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Fabrication of Compliant Micro Grippers Using SU-8 with a Single Mask

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Abstract

In this paper, we present a single-mask process for fabricating compliant micro-grippers using SU-8. The fabricated compliant grippers fit within a footprint of about 10 mm x 10 mm, and have the smallest feature size of about 5 µm. A novel aspect of the process is in using a positive photoresist, AZ-4562, as a sacrificial layer to release the gripper and make it movable. It is demonstrated that the use of AZ-4562, compared with the conventional methods; reduces the number of steps required to fabricate the grippers and similar devices. Another novel feature is off-setting the position of the substrate on a spin-coater, which makes it possible to coat the sample with the sacrificial layer for a specific region of the substrate. The effectiveness of the fabrication process is demonstrated by fabricating the grippers, and testing them to handle single biological cells. It is shown that, by using the developed process, one can obtain a sacrificial layer of 6.13±0.1 µm and an SU-8 gripper with a thickness of 44±1 µm with a good repeatability. The details of the various steps involved in the fabrication and the parameters used in these steps are described. The proposed process is amenable for batch-production.

1. Introduction

There is an increased interest in developing biomechanical assays to assess the mechanical responses of biological cells, and thereby understand their physiological status [Suresh, 2007]. Among different kinds of biomechanical assays, single-cell based manipulation is a popular approach when there is limited access to cells. For example, the number of circulating tumor cells in the early stage of cancer can be as low as one among five billion erythrocytes [Tan et al., 2010]. Although flow-based approach is popular in single-cell manipulation [Bhagat et al., 2011], this method is mostly restricted to the segregation of cells rather than assessing their mechanical properties directly. On the other hand, the miniature grippers are useful in applying and measuring forces on single cells. There are grippers reported in the literature that are shown to be effective in single-cell manipulation [Suzuki, 1996]. However, they are mostly restricted to being cantilevers where the intention is to hold the cell in place [Han et al., 2006], and the focus is on the means of actuating a pair of cantilever beams that move towards each other [Chronis and Lee, 2005]. In this regard, the compliant mechanism-based grippers provide a good alternative to the cantilever-based grippers because the former can also measure forces [Bhargav et al., 2013]. Purely mechanical forces are used in actuating the compliant mechanism-based grippers; so that no other field (e.g., thermal, optical, electrical, and magnetic, etc.) that might alter the behavior of the cells is present. A compliant gripper is a singly connected elastic body. Some portions of it are fixed to the substrate while the rest is allowed to elastically deform. This is shown in Fig. 1. In order to enable deformation, it is necessary to

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keep some part (marked by encircling with dashed lines in Fig. 1) in suspension; i.e., it should be separated from the substrate beneath it with a gap in between. It was shown by Bhargav et al. [Bhargav et al., 2013] that SU-8 based grippers can be designed to manipulate single biological cells that are trypsinized and suspended in aqueous medium. In this paper, we have presented the fabrication procedure to make such SU-8 grippers. High aspect ratio (large thickness compared to narrowest in-plane feature) possible with SU-8 makes it an attractive material for the micro-grippers that need to have high out-of-plane stiffness.

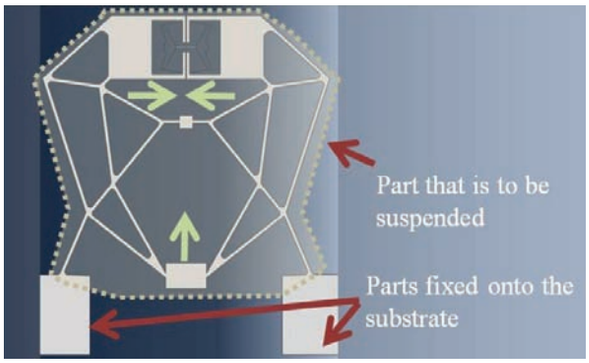

Figure 1: A compliant gripper where the parts that have to be suspended or anchored are marked.

SU-8 structures with a partial portion in suspension were reported in the past [Nordström et al., 2008]. This is quite popular in the case of SU-8 cantilevers. Photolithography was used for obtaining such SU-8 structures. Conventionally, a variant of SU-8 is spin-coated onto a substrate, and then exposed to UV light through a mask. Later, the suspended structures are obtained after micro-machining [Jack, 2001]. Using multiple layers during spin-coating has also been studied [Ling and Lian, 2007]. Different variants of SU-8 are coated during spin-coating, and later the development time is monitored so that the structures are formed. In this approach, at various stages of the fabrication; it needs to be exposed to the UV light through a mask. Thus, alignment of the mask is critical and makes the overall process tedious. Also, this process necessitates the use of multiple masks to obtain a specific geometry at different steps of the fabrication. An alternative to this is to use OmniCoat™ as a sacrificial layer.

In this case, the SU-8 layer is deposited onto the sacrificial layer and then exposed to UV light. In order to release the structures, the OmniCoat™ is dissolved using PG Remover (Microchem Corp., USA) [AiSugitani et al., 2013]. Dissolving the OmniCoat™ is an additional step, which is avoided in the fabrication process presented in this paper; here a positive photoresist is used as a sacrificial layer. Also, the layer thickness of OmniCoat™ is quite low, in the order of nm, which makes it tedious to make the structure suspended at a distance in the order of microns. However, the OmniCoat™ can still be used for fabricating these mechanisms. Further, a way to achieve suspended structures by partially coating the substrate with the sacrificial layer is presented. The proposed process unlike the other methods of fabrication requires only one mask. Thus, the number of lithography steps where the sample is exposed to UV is reduced. Also, the reduction in the number of masks makes this fabrication process cost-effective. These features led to a reliable and simple fabrication process flow for realizing the micro grippers in SU-8.

The rest of the paper is organised as follows: The details of the fabrication are presented in Section 2; the characterization of the fabricated sample is presented in Section 3; the results of the testing are presented in Section 4; and the concluding remarks in Section 5.

2. Fabrication

We will first describe the features of a device that warrant a new fabrication process. Figure 2(a) shows the design of a gripper whose overall in-plane size is 10 mm x 10 mm. Upon pushing the part labeled I upwards, the jaws of the gripper marked O, move towards each other. It may be noticed at the top that there are two Displacement-amplifying Compliant Mechanisms (DaCMs) [Krishnan and Ananthasuresh, 2008], that are 10 times smaller, embedded within the larger gripper. They serve two purposes:

- First, the two rod-like projections, one from each, act like a gripper to hold a cell. They are marked C in Fig. 2(b), which shows the magnified part of DaCMs. The stiffness of this portion is so low (60 mN/m) that a cell can be gently grasped with it without causing mechanical trauma.
- Second, portions marked F in Fig. 2(b) are the points where the displacements at C are amplified mechanically by the DaCMs. By measuring the amplified displacements at F, we can compute the forces applied by the grasped cell between C-C through computational models [Reddy and Ananthasuresh, 2013].

For these two features to work effectively, the beam segments in DaCMs must be slender. Indeed, the narrowest beam segments in it are 5 µm wide. The whole mechanism, called a composite compliant mechanism [Bhargav et al., 2013], has to be sufficiently thick so that it does not bend out of its plane. And it should have its two large pads, marked A in Fig. 2(a), anchored to the substrate while the rest is suspended

above the substrate with a gap underneath. This is clear from the side-view of the whole gripper. This is a representative design, for which a new fabrication process is developed as described next.

Usually photolithography is carried out on a silicon-based substrate. However, a cell-gripper is used in an inverted microscope where the cells and the gripper are to be seen from underneath the substrate. Therefore, a glass substrate was used in this work. The grippers were fabricated on the glass substrates and were directly used for manipulation. As explained above and as can be seen in Fig. 2(c), except the anchored pads, the rest of the mechanism must be able to move when the gripper is actuated. This requirement of suspending a large part of the mechanism above the substrate was achieved using the following steps:

(i) A glass cover slip is chosen as the substrate. It is heated to a temperature of about 250°C for about 2 min and then brought down to the room temperature, which is about 20°C.

(ii) The glass substrate is spin-coated with a sacrificial layer, AZ 4562, a positive photoresist at 4000 rpm for 40 s. The advantage of using AZ 4562 is that it dissolves in the SU-8 developer. Thus, while the SU-8 structures get developed, the sacrificial layer is dissolved almost simultaneously. This avoids an extra step of dissolving the sacrificial layer.

It should be noted that a partial coat of AZ 4562 is given on the glass substrate by strategically placing it on the chuck of the spin-coater. Figure 3 shows this schematically. Due to the centrifugal force of the spin, the sacrificial layer has a tendency to flow in the outward direction, and thus, it gets deposited on a portion of the glass substrate. During this step, placing of the glass on the spin-coater is crucial, and it depends upon the extent of the structure that needs to be suspended. In our case, the extent of offset depends on the anchoring pads. It was kept around 2.5 mm.

(iii) The glass substrate coated with the sacrificial layer is heated to a temperature of about 95°C for about 1 min, and then cooled to the room temperature. This step is optional, although it was found that this reduces the bubbling of the positive photoresist during post-exposure bake.

(iv) The glass substrate with the sacrificial layer is spin-coated with SU-8 2035, initially at 500 rpm for 5 s before reaching 3000 rpm and then on maintaining the speed for 40 s. After spinning for 40 s, it is brought back to the speed of 500 rpm, and then maintained this speed for another 5 s. After spin-coating, the glass substrate is carefully removed from the chuck, and placed on a hot plate. This step was carried out according to the datasheet provided by MicroChem Corporation [SU-8 Datasheet].

The substrate is allowed to cool to the room temperature. It is important to allow it to cool as it reduces the stress in the developed structure [Sameoto et al., 2007].

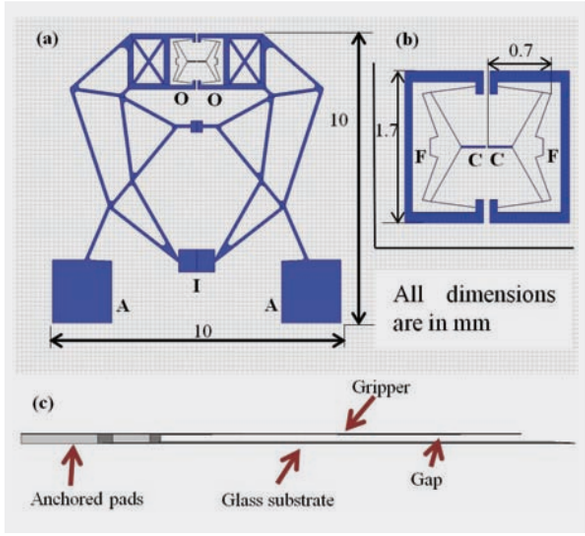

Figure 2: (a) Final design of the compliant micro-gripper. (b) The DaCM part of the gripper. (c) A side-view showing a part of the gripper in suspension, while the pads are anchored onto the substrate.

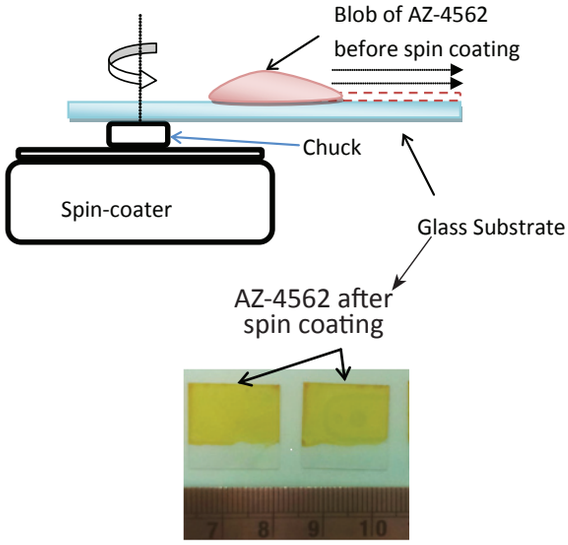

Figure 3: Spin-coating of the sacrificial layer. During this step, AZ 4562 is laid on a portion of the glass substrate away from the axis of rotation

(v) The substrate is pre-baked at 95°C for about 40 min. The duration of baking is decided based on the thickness of SU-8, which is expected to be about 40 µm [SU-8 Datasheet].

(vi) The pre-baked sample is exposed to Ultra-violet (UV) light using EVG®620 Automated Mask Alignment System. During this step, a chrome mask containing the design of the gripper is placed between the UV source and the substrate, and then UV light of 365 nm wavelength with an intensity of 375 mJ/cm² is beamed onto the substrate.

(vii) After the exposure, the substrate is baked at 95°C for about 10 min. During this step, due to the presence of positive photo resist as the sacrificial layer, bubbles may form as was observed by Bao, et al. [Bao et al.,2010]. The formation of the bubbles can be reduced as recommended in step (iii). Figure 4 shows the sample after this step.

(viii) The samples are allowed to cool to the room temperature and then dipped in the SU-8 developer solution. This step takes about 8-10 min. During this step, AZ 4562 is also dissolved giving rise to the released gripper.

2.1 A note on batch fabrication

The fabrication process described so far can be used to obtain several copies of the gripper in one step, which allows one to produce these grippers in a batch. Figure 5 shows a possible arrangement to enable batch production. It can be seen in Fig. 5 that for a 3 inch substrate, about 24 pieces can be obtained in one step. Thus, the proposed fabrication process is amenable to batch-production.

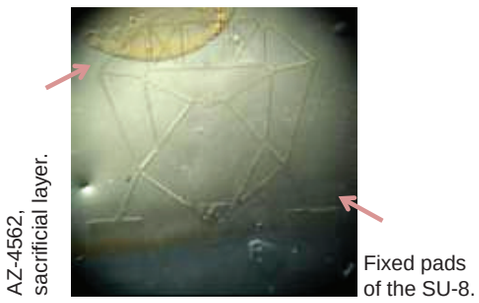

Figure 4: Sample just after the post-exposure bake.

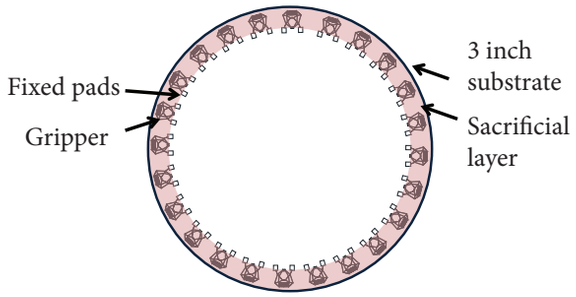

Figure 5: Conceptual diagram for batch production

The complete fabrication process is pictorially summarized in Fig. 6. The grippers obtained using this fabrication was further tested with Dektak®stylus profiler for their thickness. The characterization of the released gripper is discussed next.

3. Characterization

The samples that were fabricated using the process described in the preceding section were characterized for their thickness. In this regard, the Dektak® stylus profilers were used to test these samples. Figure 7(a) shows an outcome of one of the samples using this system. It is observed from this figure that the AZ 4562 is about 6.13 µm thick. It can also be observed that the edge-bead thickness of the profile is well within 600 nm, which is about 10% of the thickness and is considered to be low [Lee et al., 2011].

Figure 7(b) shows the profile, as reported by the profiler after the gripper is fabricated. It is observed that, with the parameters described in Section 2, the SU-8 gripper has a thickness of about 44 µm. The edge-bead is estimated to be 3.6 µm, which is about 8% of the thickness. Figure 7(c) is a representation of the average values and the error-bars in the thickness of both the sacrificial layer and the SU-8 layer in five samples. It can be observed that the error-bars are quite small, which confirms that the fabrication process has good repeatability.

Figure 8 shows the fabricated SU-8 gripper. There are places in the gripper, as marked in Fig. 8, where water vapour is accumulated. This can be attributed to the gap between the mechanism and the substrate.

4. Testing and Results

The gripper was tested using the setup shown in Fig. 10. It consists of an inverted microscope (IX81, Olympus Corporation), a micro-positioner (MP-285, Sutter Inc.) and the SU-8 gripper. The mechanism is placed in such a

way that both the jaws are within the field of view of the microscope while the gripper is actuated. An additional digital microscope is used for improved visualization of the mechanism, but it is not an essential part of the setup. A micro-positioner is used to actuate the mechanism through a rotary optical encoder (ROE) controller with a step-size of 40 nm. The gripper is actuated using an extension arm attached to the micro-positioner and, in turn, this extension arm contains a glass pipette, which comes in contact with the gripper. A camera (STC-625AS, Sentech Inc.) attached to the microscope is used to capture the images when the gripper is actuated. Figures 10(a-b) show the grippers under actuation as seen under the inverted microscope. Figure 10(a) is the picture before the gripper's actuation and Fig. 10(b) is after deformation. The gap between the jaws is about 20 µm before deformation. This gap reduces upon the actuation of the gripper, as can be observed from Figs. 10(a, b). In Fig. 10(b) the jaws are in contact with each other indicating that the gripper is actuated to the maximum extent. The experiments validate that, using the fabrication process described in Section 2, the portion of the gripper that is desired to be suspended is achieved. Figures 11(a-b) show an MCF-7 cell whose size on the average is about 10 µm, manipulated by the gripper. Figure 11(a) shows the cell placed near one of the DaCMs. This is done using a glass pipette. While Fig. 11(b) shows a close up view of the gripper jaws manipulating the MCF-7 cells. Thus, the fabrication process is successful in realizing an SU-8 micro-gripper, which can manipulate a single biological cell as small as 10 µm in size.

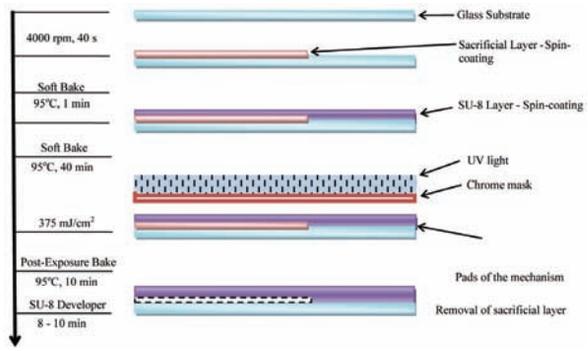

Figure 6: Steps used for fabricating the compliant micro-grippers using SU-8.

5. Closure

A novel single-mask process of fabricating the SU-8 micro-grippers is presented in this paper. The main contributions are:

- Demonstrated the use of positive photoresist, AZ 4562, as the sacrificial layer for the SU-8 micro-grippers
- Demonstrated the ability to partially coat the substrate by offsetting the position of the substrate on the chuck of the spin-coater in order to have a suspended gripper anchored to a glass substrate
- Demonstrated that the use of AZ 4562 reduces the number of steps in fabricating the micro-grippers using SU-8, as compared to the conventional processes

The design of the gripper presented in this paper had a region that is distinctly away from the fixed region. However, in some other designs of the grippers, it may not be the case. Realizing such designs is a challenge to be addressed in future work.

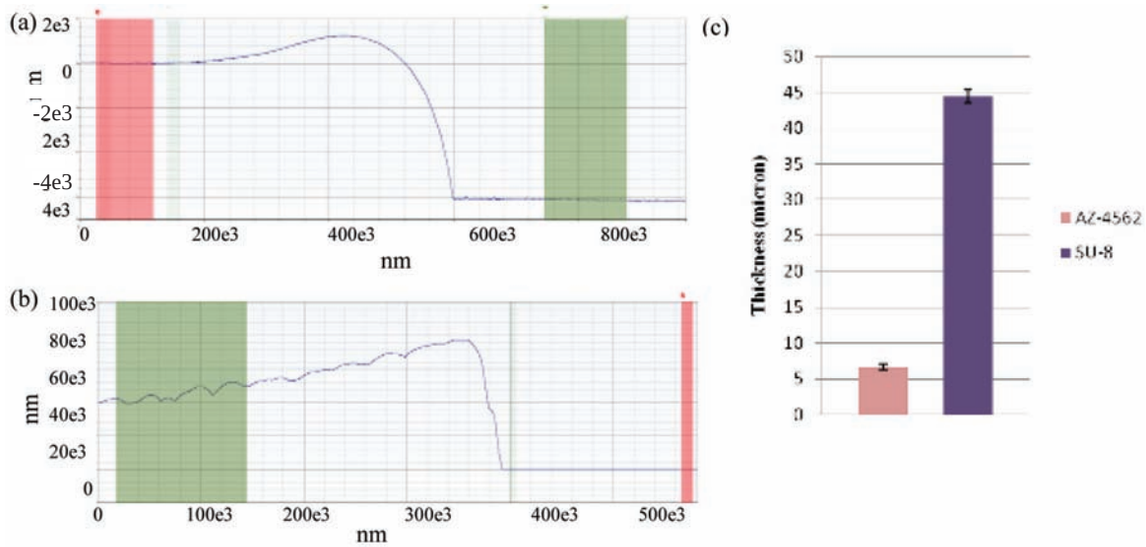

Figure 7: (a) Surface profile of the sacrificial layer. (b) Surface profile of the SU-8 layer. (c) A representation of the values of the thickness measured across 5 different samples.

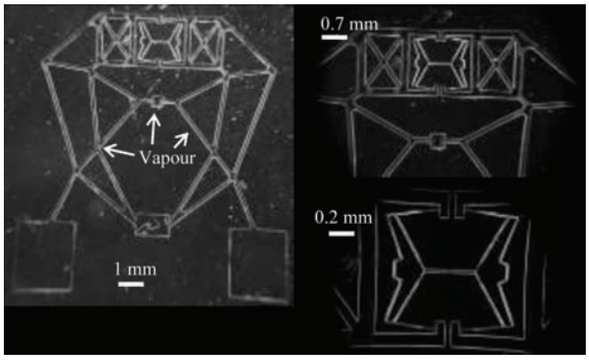

Figure 8: Sample just after the post-exposure bake.

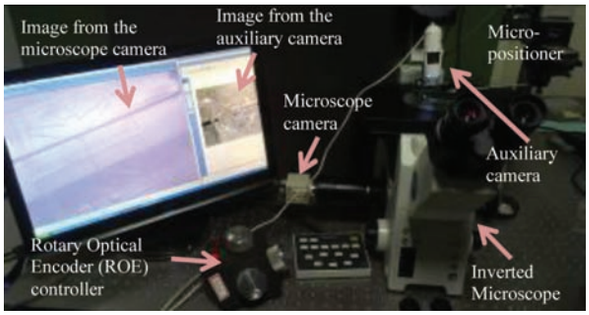

Figure 9: Setup used for testing the gripper.

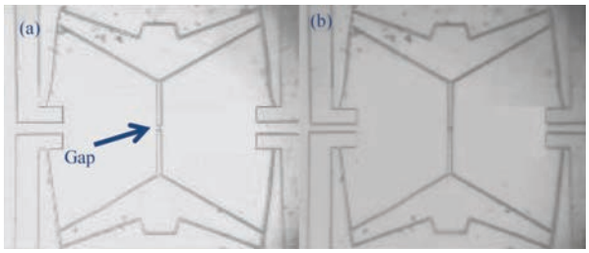

Figure 10: Jaws of the Gripper: (a) before actuation (b) after actuation.

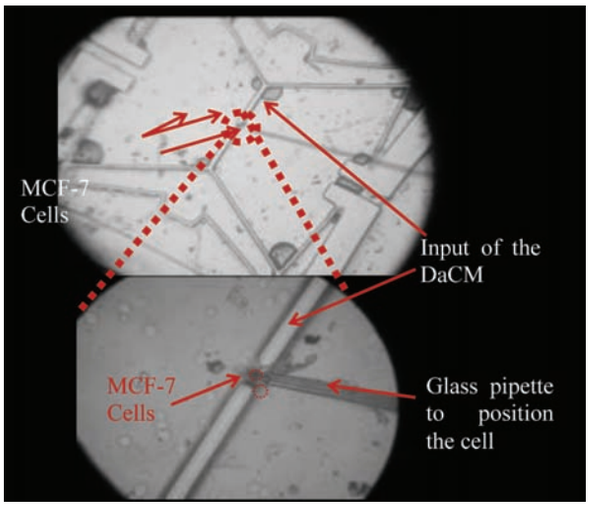

Figure 11: Manipulation of an MCF-7 cell; (a) The field of view of the microscope where DaCMs of the composite are grasping MCF-7 cells. (b) A zoomed image of grasping of MCF-7 cell.

Acknowledgement

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