A High Aspect Ratio Parylene Micro-Stencil for Large Scale Micro-Patterning for MEMS Applications

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ABSTRACT

Patterning using a Shadow Mask or Stencil technique is increasingly being utilized for creating microscale patterns on conventional and unconventional surfaces. Previously reported micro-stencils made of rigid or polymeric membranes have various shortcomings and lack precise pattern definition. In this paper, a reusable, high aspect ratio (HAR), flexible parylene-C micro-stencil technology is introduced. To realize this micro-stencil, we have also developed a high aspect ratio polymer etching technology using an ICP tool and with this process, demonstrate features as small as 4 µm. By utilizing SU-8 support pillars as alignment posts, we demonstrate multi mask alignment with a tolerance of 5-7 µm. The large Young's Modulus of the Parylene-C material allows the stencil to be reusable. This flexible parylene-C stencil technology will find applications in the fabrication of organic transistors and selective metal deposition onto fragile MEMS devices. This paper will discuss the details of the parylene micro-stencil fabrication process and describe various micropatterning applications.

1. INTRODUCTION

Classical microfabrication based on optical lithography has limitations for applications on organic substrates (lacking chemical and thermal stability) and on released MEMS (fragile) devices. Hence, Shadow mask technology has emerged as an alternative technique for micropatterning applications on conventional and unconventional surfaces. Shadow masks can be classified as active or passive shadow masks. The difference between the active and the passive shadow masks is that the aperture size of the active shadow masks are adjustable within demand [1]. For the passive shadow masks, of which most current shadow masks comprise of, have fixed aperture dimensions. Previously reported passive microstencils, which are made of rigid and polymeric membranes have various limitations. For instance, Si, Si_3N_4, TEM grid or stainless steel shadow masks are rigid and brittle, require complicated and expensive processing steps and lack the precise pattern definition and the pattern flexibility to different pattern dimensions due to the gap between the stencil and the substrate [2,3,4,5]. Elastomeric microstencils (such as PDMS), on the other hand, are not easy to handle, and have difficulty in achieving mechanical alignment and lack high resolution [6]. Shadow masks made of SU-8 polymer [7] are also not suitable for wafer scale patterning applications since their high residual stress makes them buckle. Alternatively, dry lift-off method as demonstrated by B. Ilic et al. is limited to thin films of single use and to IC compatible surfaces (silicon, glass and PDMS) [8]. In this paper, a high aspect ratio parylene shadow mask technology is demonstrated. The applications of this technology are vast some include patterning applications for organic electronics, metamaterials and micro-nano integration, and patterning on topographically rough and curved surfaces.

2. PARYLENE-C DEPOSITION

Parylene, poly-para-xylylene, has traditionally been widely utilized in the medical and electronics industries as a pin-hole free conformal coating and also increasingly been explored in the MEMS community. Up to a certain thickness (50µm) the parylene films are flexible and can conform to round surfaces. They also have high mechanical strength and robustness compared to PDMS stencils and hence are reusable. Parylene-C is a room temperature deposited polymer that is used to make the flexible shadow mask and its deposition process is detailed in the following section.

Polymerizations of polymer materials are typically done in solution form or gas/vapor phase form with/without the assistance of plasma [9]. Parylene deposition is a chemical vapor deposition (CVD) process, which is done at

25 mTorr and at low temperature (25°C). Parylene deposition process has three different stages. The first stage is vaporization process, where a solid parylene dimer is vaporized at a temperature of 175°C. The second stage is the Pyrolysis process, where vaporized parylene gas moves slowly into the Pyrolysis chamber, and the parylene gas is decomposes into parylene monomer at a temperature of 690°C. The last stage is the deposition process where parylene monomers move slowly into the deposition chamber and absorbs on the substrate surface and polymerize. The steps of parylene deposition are illustrated in Figure 1.

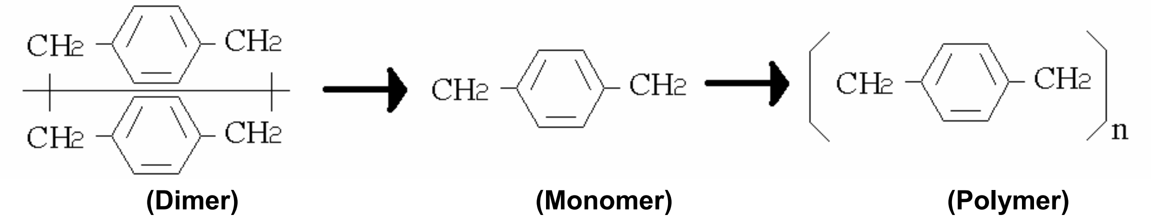

Figure 1: The Parylene Deposition Sequence. Parylene dimer first decomposes into monomer and then polymerization takes place.

During the polymerization process, the monomer in the deposition chamber is first absorbed on the substrate, then surface migration and bulk diffusion of monomers take place, finally the chemical reaction between the monomers form the film. Parylene shadow mask requires a fairly thick membrane, ~10-20 µm so that it is reusable for micro patterning applications. The mean free path of Parylene monomer in the deposition chamber is in the order of 0.1cm during this process which results in a conformal deposition. Since the polymerization process occurs at the room temperature, the deposited parylene films are relatively stress free.

3. FABRICATION

To fabricate the flexible microstencil, first, a 10-20 µm thick parylene is deposited on a silicon wafer (PDS2010, Labcoater 2, Specialty Coating Systems). Next, a 2000Å thick Aluminum hard mask is deposited using sputter deposition. After patterning the Al hard mask, the uncovered parylene areas are etched in an ICP etcher (Plasmatherm 790). After this etch, the Al hard mask is stripped. The parylene shadow mask is then peeled off the wafer and is ready for use. As a side note, prior to parylene deposition, we routinely use HMDS as the adhesion promoter. Utilizing the traditional adhesion promoter (A-174 Silane) tends to create very strong adhesion between the film and the substrate and hence causes the film to tear while peeling. We have used both 10 µm and 20 µm thick parylene sheets, and both worked well and both were flexible, yet for large scale applications and for reusability, the 20 µm thick film is recommended even though it is slightly less flexible. For larger features (dimensions > 100 µm), we fabricate the shadow mask with a room temperature ICP etch since lateral etching is not a major concern. Furthermore, while fabricating stencils with fine features (< 10 µm), one requires the most anisotropic etch and hence, we have developed a novel high aspect ratio parylene etch process which is detailed in the next section.

4. HIGH ASPECT RATIO ETCHING OF PARYLENE-C

Parylene is gaining popularity as a unique low temperature material for many biomedical or non-biomedical applications. It can also be utilized as a potential substrate for flexible devices [10]. One of the current needs for parylene micromachining is the need for a high aspect ratio etch process. Meng, utilizing a DRIE tool, obtained aspect ratios of up to 3:1 [11], moreover to create stencils with fine features one requires higher aspect ratios.

It is possible to reduce the isotropy of a reactive ion etch process by reducing the etch temperature which is commonly done by etching silicon at low temperatures (~ -100°C). Moreover, for etching polymers such as parylene-C, reducing the etch temperature down to 5°C serves a similar purpose. Using an ICP reactor (Plasmatherm 790), we developed multiple recipes (Table 1) with fast etch rates and anisotropic profiles (>9:1). The parylene structure that is shown in Figure 2(a) with a thickness of 55 µm is etched with the recipe “b” in Table 1 and the one shown in Figure 2(b) with a thickness of 10 µm is etched with recipe “c” in Table 1 and they both display almost vertical sidewalls. We were able to etch through a 55 µm thick parylene film with a hole diameter of 6 µm which is equivalent to an aspect ratio of about 9:1.

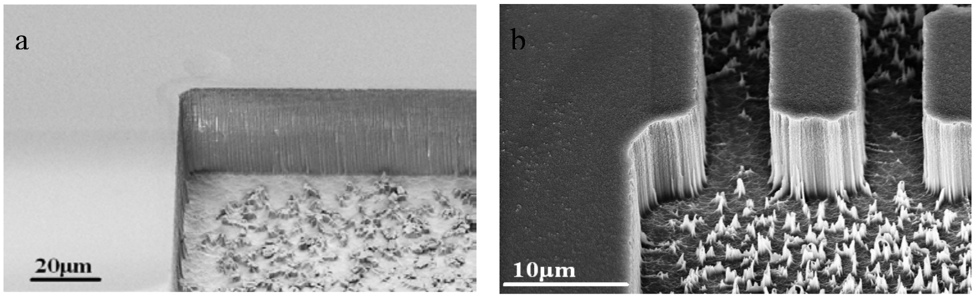

Figure 2: Anisotropic profiles of 55 μm thick parylene (a) and 10 μm thick parylene (b).

Table 1: ICP etch recipes for low temperature (5ºC) parylene etching

Etch #	*Etch Rate (μm/min)*	*RF Bias power (W)*	*Source Power (W)*	*O_2 (sccm)*	*Ar (sccm)*
a	*1.7*	*250*	*400*	*20*	*0*
b	*1.0*	*100*	*400*	*10*	*10*
c	*0.5*	*100*	*150*	*10*	*10*

5. RESULTS AND DISCUSSION

5.1 High pattern resolution and pattern flexibility

To characterize the properties of the parylene shadow mask, several parylene stencils with various dimensions, spacings and shapes were fabricated. After fabrication, these membranes were placed over silicon wafers and metal films (Al and Cr-Au) with 1500Å in thickness were sputter deposited. After the deposition, we have carefully peeled off the shadow mask from the silicon wafer and reused it multiple times without any difficulty. Due to the large dimensions of the features, one can reuse this mask many times as the holes do not get clogged up and the micropatterns were formed in a reproducible manner. As seen in Figure 3(a), we were able to pattern fine features as small as 4 μm in a reproducible manner. Utiling the same shadow mask, we also demonstrated patterning both large and small patterns as displayed in Figure 3(b) illustrating the pattern flexibility of our technology. The feature size measurements that were conducted using both Scanning Electron Microscope (SEM) and the optical microscope agree well with each other and suggest that there is very little pattern degradation or blurring during deposition indicating an exceptionally good seal between the parylene film and the substrate.

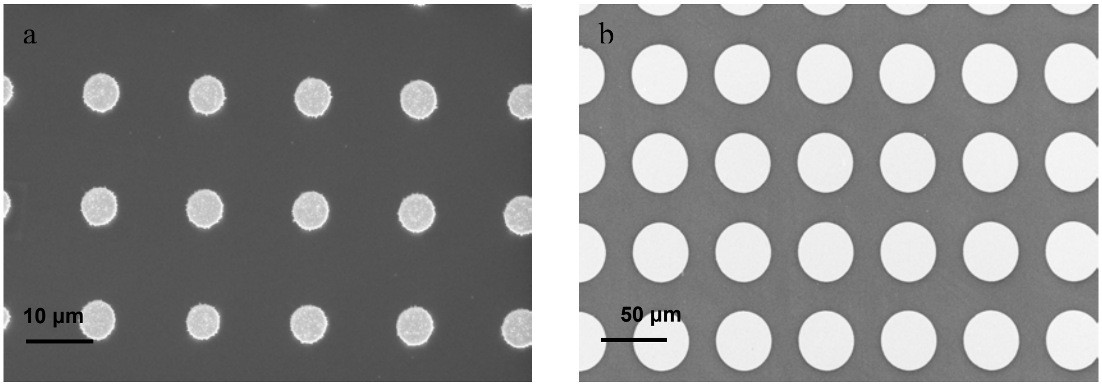

Figure 3: High pattern resolution achieved using parylene shadow mask. Feature sizes a) 4 μm b) 50 μm.

We next demonstrated pattern flexibility using our parylene shadow mask technology as illustrated in Figure.4. We have successfully patterned structures with different shapes and dimensions. Comparing the parylene shadow masks of thickness 10 μm and 20 μm, we have discovered that the 10 μm parylene membrane has a tendency to bend and forms a gap (crimpled surface) when brought in contact with the silicon wafer accordingly, one gets deformed patterns. Moreover, the 20 μm thick membrane was rigid enough so that we were able to achieve precise pattern definition (without any deformations) as seen in Figure 4(a-d).

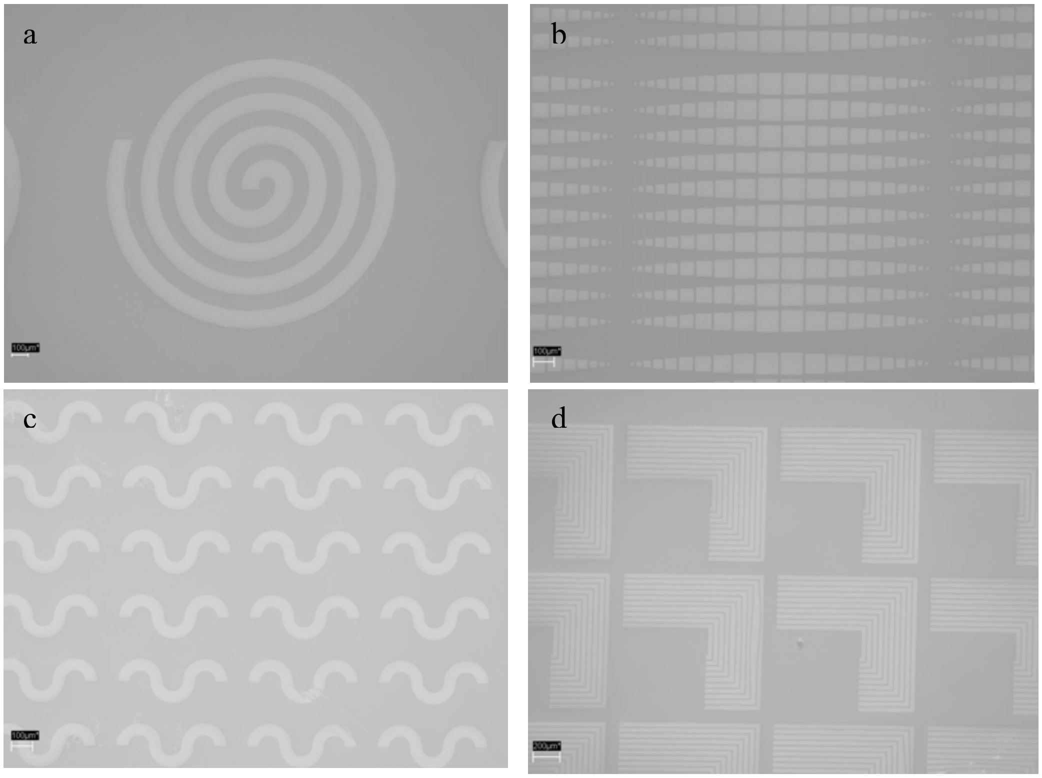

Figure 4: High pattern flexibility. a) the width of the spiral is 100 μm, b) the smallest and the biggest squares are 10 μm x10 μm and 100 μm x100 μm and the spacing between squares is 15 μm, c) curved patterns, d) the rectangular patterns where the spacing between lines is 15 μm and the width of the individual line is 25 μm.

5.2 Micropatterning on curved surfaces

Patterning on curved surfaces has potential applications in flexible electronics and biotechnology. To demonstrate patterning on curved surfaces, we have fabricated a PDMS cylinder of 17 mm height and 15 mm diameter. Then a parylene shadow mask was wrapped around this cylinder. Aluminum was subsequently sputter deposited on top of the cylinder and then the parylene shadow mask was peeled off and the generated patterns were imaged using an SEM. Figure 5(a) displays the optical photograph of the PDMS cylinder with the patterns and Figure 5(b) displays the magnified view of one of the patterns. Since the PDMS surface is very hydrophobic, the parylene sheet adhered well to the cylindrical surface and the patterns were well defined.

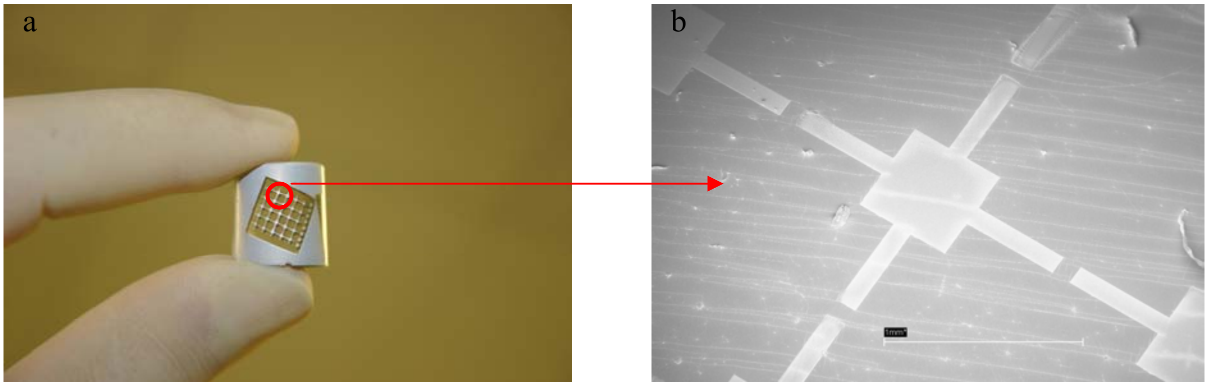

Figure 5: Micropatterning on curved surfaces. a) Optical image of the PDMS cylinder with micropatterns and b) magnified SEM micrograph of one of the patterns.

5.3 Mechanical Alignment

Most of the current shadow mask technologies are limited to single step processing. Furthermore, most microdevices require multi mask processing. In order to carry out a multi mask patterning, mechanical alignment structures are required. To realize multi mask processing, we have then designed and fabricated SU-8 alignment posts to hold the parylene shadow masks in place with the technology detailed below.

SU-8 is a fairly thick polymeric material that is being increasingly used in the MEMS and microfabrication fields. Similar to a LIGA process, one can create high aspect ratio features using a single step exposure. To create the alignment posts, we have first created SU-8 alignment walls on a silicon wafer. Then, the first parylene shadow mask was carefully placed inside these walls. The alignment accuracy was verified and corrected under an optical microscope with the fine alignment being performed utilizing a fine tip tweezer in a manual manner. A metal film was next sputter deposited onto the wafer. After lifting up the first parylene mask from the silicon wafer, a second parylene mask with complementary patterns was carefully placed inside the alignment walls. The second metal deposition was then performed and the parylene sheet was subsequently lifted off the wafer. The misalignment from the multi mask processing was then examined both under a microscope and under an SEM. To characterize the alignment accuracy in X and Y direction, we have created 2 different complementary "E-shaped" structures as seen in Figure.6. Figure 7 displays the measurements from the misalignment tests. In the x-direction, an x-offset of 4.6 µm and y-offset of 8.6 µm were measured using the complementary structures. In the y-direction, the x-offset and y-offset were 6.9 µm and 4.1 µm respectively.

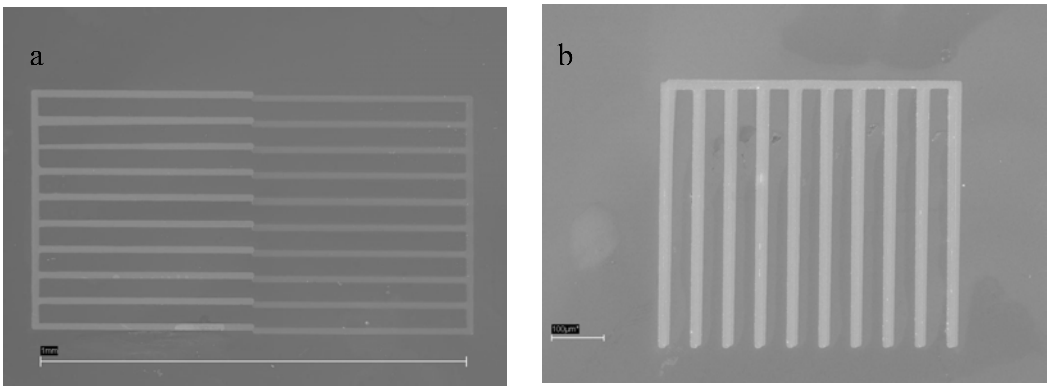

Figure 6: Test structures for misalignment measurements in X and Y directions where the width of the electrode is 10 µm and the spacing between them is 50 µm. a) alignment tests in X direction using complementary 'E' shaped structures b) alignment test in Y direction using the same structures.

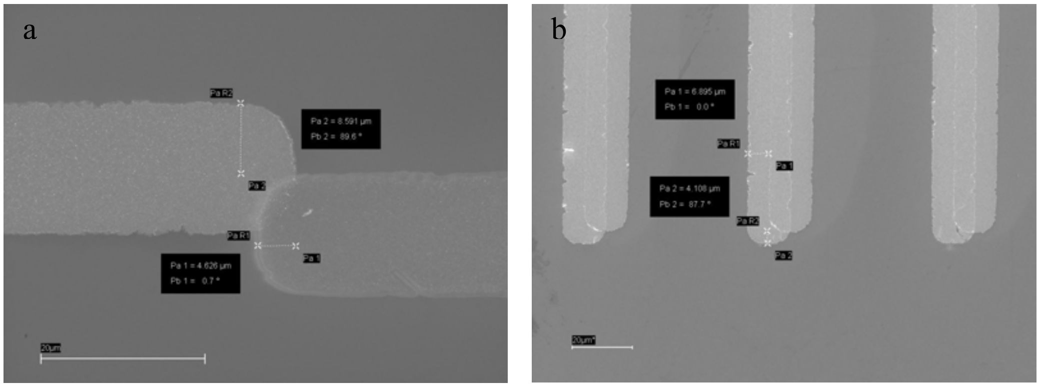

Figure 7: Measured offsets from the misalignment measurements in x and y directions.

We were able to achieve a misalignment of about 5-7 µm. During these experiments, we have utilized 2 different thicknesses for the SU-8 posts (100 µm and 250 µm). We have found out that the 100 µm posts did not hold the parylene shadow masks properly during manual manipulation (for minor adjustments) whereas the thicker versions (250 µm) hold the shadow masks in place and were the alignment posts of choice.

Figure 8: Wafer scale patterning using a flexible parylene shadow mask.

Among its many advantages, parylene shadow masks can be cleaned and reused repeatedly (at least 10 times) since parylene is a very inert material [12]. As shown in Figure 8, wafer scale patterning is easily achievable. Moreover, a thin parylene membrane (<10 µm) has the tendency to fold while being held by tweezers, which makes it difficult to precisely position the shadow mask on the sample. Thus, a thick membrane of at least 20 µm is required for multi use and for large scale patterning applications. Patterning for heterogeneous device integration can be another area where the flexible and transparent parylene shadow mask technology can be utilized. Since parylene is a biostable and biocompatible material, other applications include patterning proteins and cells for BioMEMS applications.

As-deposited Parylene-C, similar to PDMS, has a hydrophobic surface with a contact angle of ~98 ºC. Furthermore, with a brief O_2 plasma treatment becomes hydrophilic and it stays hydrophilic for many days. The hydrophobic parylene surface seals extremely well to other hydrophobic surfaces, moreover, the hydrophilic surface does not adhere well to other surfaces, a property that is important while using the parylene-C as a shadow mask. Accordingly, we have characterized the contact angle and the stability of parylene sheets in aqueous environments over time. The parylene sheet was submerged into DI water for 3 days (which may be the case for multiple rinsing experiments) and its bottom hydrophobic surface remained hydrophobic during this period. Moreover, Al is used as the hard mask while etching parylene and to improve its adhesion to the parylene surface, we routinely roughen the parylene surface prior to depositing the Al metal which makes the top parylene surface hydrophilic, and hence our stencil to be single sided (one side sticks better than the other side).

6. CONCLUSIONS

In this paper, we present a high aspect ratio, flexible, reusable parylene shadow mask for large scale micropatterning applications. Features with dimensions of 4 µm was demonstrated. A low temperature (5°C) parylene etch process is also developed to fabricate the fine structures with anisotropic profiles. Utilizing this flexible shadow mask technology, micropatterning on curved surfaces (PDMS cylinder) was also demonstrated. The parylene shadow mask is biocompatible, chemically inert and hence reusable. Multi mask processing is demonstrated with the addition of SU-8 support pillars, and the misalignment between masks was measured to be around 5-7 µm. The parylene stencil method has high pattern flexibility; as shapes with different dimensions can be achieved on the same mask.

ACKNOWLEDGEMENTS

The authors would like to thank for the support by the Air Force Research laboratory, Hanscom, MA, contract # FA8718-06-C-0045.

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