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Suspended Microstructures of Epoxy Based Photoresists Fabricated with UV Photolithography

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Abstract

In this work we present an easy, fast, reliable and low cost microfabrication technique for fabricating suspended microstructures of epoxy based photoresists with UV photolithography. Two different fabrication processes with epoxy based resins (SU-8 and mr-DWL) using UV exposures at wavelengths of 313 nm and 405 nm were optimized and compared in terms of structural stability, control of suspended layer thickness and resolution limits. A novel fabrication process combining the two photoresists SU-8 and mr-DWL with two UV exposures at 365 nm and 405 nm respectively provided a wider processing window for definition of well-defined suspended microstructures with lateral dimensions down to 5 µm when compared to 313 nm or 365 nm UV photolithography processes.

1. Introduction

The epoxy-based photoresist SU-8 is well established for the microfabrication of 3D microstructures for various applications such as tissue engineering, microelectromechanical systems (MEMS) and microfluidics [1]–[6]. Furthermore SU-8 is also the most common polymer template for the fabrication of pyrolytic carbon electrodes using the Carbon MEMS (C-MEMS) process [7]. The resist allows fabrication of high aspect ratio microstructures with high mechanical and chemical stability using standard UV photolithography due to the low absorption of UV wavelengths above 350 nm [8]. At the same time, the low UV absorption results in challenges for fabrication of overhanging or suspended features by subsequent steps of SU-8 photolithography. In the past, different fabrication processes have been proposed for the fabrication of suspended 3D SU-8 microstructures. Advanced methods such as X-ray, e-beam and two-photon lithography have been proposed for fabrication of high resolution 3D microstructures [9]–[12]. The limiting factor for these techniques is the low throughput.

Alternatively, several approaches using UV photolithography have been introduced. The most common process involves adding a polymerization-stop-layer between the structures to be suspended and the substrate [13], [14]. Alternatively lamination of a polymer foil on top of a patterned template followed by patterning of the foil has been proposed [15], [16]. The complexity of these fabrication processes increases as the structures become multi-layered (i.e. more 3D). Another method includes doping of SU-8 with nanoparticles or tailoring of the photoinitiator concentration to control the thickness of suspended layers. However adding nanoparticles such as Fe_2O_3 or increasing the concentration of photoinitiator requires an additional preparation step [17], [18]. Furthermore, suspended macrostructures have been fabricated with grayscale photolithography, but without achieving micron or submicron resolution [7].

Recently, fabrication of suspended SU-8 layers by partial exposure at a wavelength of 365 nm has been demonstrated [19]–[21]. The limiting factor of this fabrication process is the narrow processing window (5±1 sec UV exposure) for the partial exposure [22]. We observed that minor variations in parameters such as the baking temperature, humidity and exposure dose resulted in cracks and difficulties to control the suspended layer thickness (Figure 1.A). Furthermore, instability of the features with a size smaller than 10 µm was seen (Figure 1.B). Alternatively, the use of a lower wavelength (313 nm) to crosslink or pattern the suspended layer has been proposed [14]. At this wavelength, the absorption by the SU-8 is increased resulting in lower penetration depth of the UV radiation.

In this work, we introduce a third approach for fabrication of suspended layers of epoxy based photoresists with UV photolithography using a higher wavelength of 405 nm. The combination of two different photoresists (SU-8 and mr-DWL) is exploited to fabricate suspended layers with a precise lateral and longitudinal resolution. The novel approach is compared with a process using partial exposure at wavelengths of 313 nm to crosslink the suspended layers. Compared to earlier work, all the processes were carried out with a low temperature baking profile to minimize the thermal stress [23], [24]. After optimization of the exposure dose, both fabrication processes result in a well-defined suspended layer in lateral direction. However, the fabrication process with 405 nm and mr-DWL provides a wider processing window and improved control of the thickness of the suspended layer.

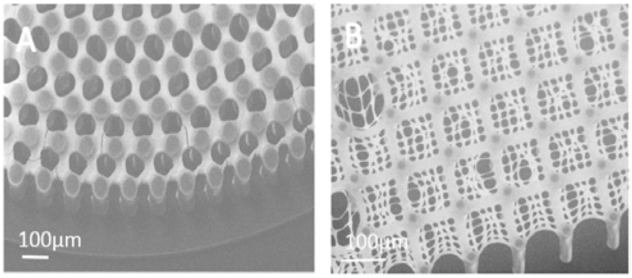

Figure 1: Defects in suspended SU-8 layer fabricated with 365 nm partial UV exposure according to [22] (A) Cracks on the suspended layer (B) Unstable suspended SU-8 microstructures

2. Methods

2.1. 313 nm UV photolithography

The fabrication of suspended microstructures using 313 nm photolithography is illustrated in Figure 2. Approximately 5 ml of SU-8 2075 (MicroChem, USA) were manually dispensed on a 4-inch Si/SiO_2 substrate and coating was performed using a two-step spin process on a RCD8 T spin-coater (Süss Micro-Tec, Germany). A spread cycle of 30 s at 700 rpm with 100 $rpms^{-1}$ acceleration was applied, followed by a thinning cycle at 1600 rpm for 60 s with 100 rpms^{-1} acceleration yielding a uniform 98 μm thick film. The edge bead was removed by dispensing propylene glycol methyl ether acetate (PGMEA) at the edge of the rotating wafer at 300 rpm for 30 secs (Figure 2.A). To minimize the thermal stress low temperature baking steps were used [24]. The wafers were placed on a programmable hotplate (Harry Gestigkeit GmbH, Germany) at room temperature and ramped to 50 °C at 2 °Cmin^{-1} followed by a soft bake (SB) for 5 h at 50 °C and natural cooling for 2 h. The SU-8 layer was patterned by UV exposure on an EVG620 aligner (EVGroup, Austria) equipped with a mercury lamp and a long pass filter (SU-8 filter), adjusted to a constant intensity of 7 mWcm^{-2} at 365 nm in soft contact mode through a mask. The intensity was measured with a UV-Optometer (SUSS UV-Optometer, SÜSS MicroTec AG, Germany) using a probe 365/405 channel 365, which is sensitive between 345 nm and 385 nm, where 365 nm intensity is the maximum for a mercury lamp. The SU-8 filter blocks all wavelengths below 345 nm. The mask (M_1) includes designs of micropillar arrays with various pillar diameters (d = 10–50 μm) with a varying pitch (a = 25–250 μm). The first UV exposure with a dose D_1= 210 mJcm^{-2} (Figure 2.B) was followed by a second partial UV exposure at 313 nm with dose D_{313} through a second mask (M_2). For the partial exposure, the filter was changed to a 313 nm (250 nm to 350 nm) short pass filter. A constant intensity of 1.05 mWcm^{-2} was measured with a UV-Optometer using a 320 nm probe which is sensitive between 290 nm and 345 nm including the predominate line for a mercury lamp at 313 nm. The partial exposure dose D_{313} was optimized to obtain well resolved microstructures on the suspended layer connecting the pillars (Figure 2.C). The mask (M_2) includes distribution of holes with diameters (w= 10 µm-50 µm) and varying pitch (y= 5 µm- 200µm) which defines the suspended layer. For the post exposure bake (PEB), a baking temperature of 50 °C for 5 h with a ramp of 2 °Cmin^{-1} followed by a natural cooling down to room temperature was used. The development in PGMEA was performed in two steps of 10 min followed by rinsing in isopropanol for 30 s and drying in air (Figure 2.D).

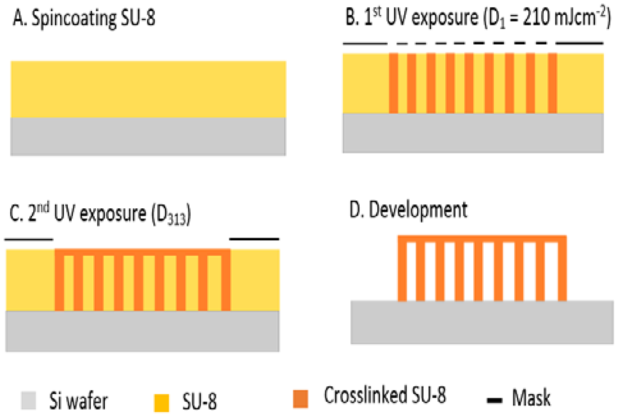

Figure 2 : Schematic of the 313 nm UV lithography process: (A) SU-8 is spin coated on a Si/SiO_2 substrate and soft-baked; (B) 1st UV exposure at 365 nm; (C) 2nd partial UV exposure at 313 nm and post-exposure bake; (D) Development in PGMEA

2.2. 405 nm UV photolithography

The fabrication of suspended microstructures with 405 nm UV photolithography is shown in Figure 3. The supporting SU-8 pillars were fabricated as described in section 2.1 (Figure 3.A and B). After the first SU-8 exposure (Figure 3.B), approximately 5 ml of mr-DWL 40 (Microresist technology GmbH, Germany) were spin coated on the SU-8 at 4000 rpm for 60 s with 100 rpms^{-1} acceleration yielding a uniform 17 µm thick film. The polymer stack was SB at 50 °C for 1 h (Figure 3.C). The aligner was equipped with two filters: The 365 nm broad band filter described above (SU-8 filter) and a 10 mm thick PMMA sheet (SPMMA0050NR00, NordiskPlast, Denmark) mainly to filter out the i-line at 365 nm wavelength. With this configuration the constant intensities at 313 nm, 365 nm and 405 nm were 0 mWcm^{-2}, 0.33 mWcm^{-2} and 10.50 mWcm^{-2} respectively. The intensity at 405 nm was measured with the UV-Optometer using probe 365/405 channel 405, which is sensitive between 345 nm and 460 nm, including three dominate lines at 365 nm, 405 nm and 435 nm. The 365 nm intensity is half the intensities at 405 nm and 435 nm, hence the measured intensity at 405 nm was obtained by subtracting the intensities at 365 nm and 435 nm. The exposure dose for mr-DWL 40 D_{405} was optimized to obtain well resolved microstructures on the suspended layer (Figure 3.D).

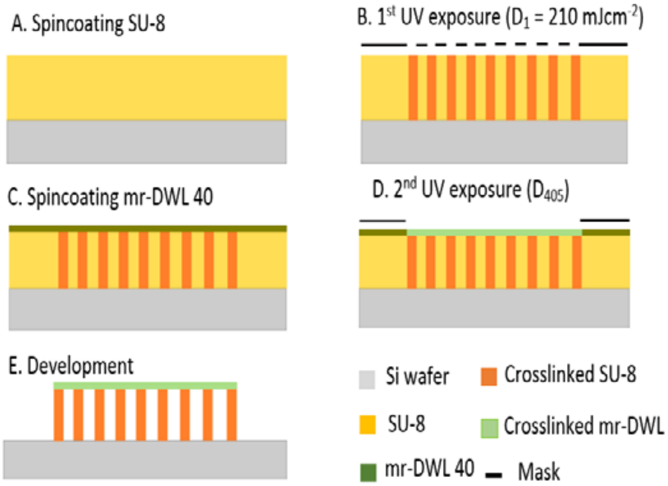

Figure 3 : Schematic of 405 nm microfabrication process: (A) SU-8 is spin coated on a Si/SiO$_2$ substrate and soft-baked; (B) 1st UV exposure at 365 nm; (C) mr- DWL 40 spin coating on SU-8; (D) 2nd UV exposure at 405 nm and post-exposure-bake; (E) Development in PGMEA

This step was followed by a PEB at 50 °C for 5 h and development in PGMEA in two steps of 10 mins each, rinsing in isopropanol for 30 s and drying in air (Figure 3. E).

3. Results and discussion

3.1. 313 nm UV photolithography process

For UV photolithography with 365 nm wavelength both the lateral dimensions and the thickness of the suspended layer have been difficult to control and reproduce. Here, a low wavelength (313 nm) was used to limit the cross-linking to the top surface. SU-8 absorbs considerably more UV radiation at wavelengths below 350 nm [8]. Therefore, activation of the photoinitiator in the bulk of the resist film is reduced and crosslinking can be limited to the top surface when using lower wavelengths for the partial exposure [8], [14].

We optimized a low temperature process to successfully fabricate suspended SU-8 layers with UV exposure at 313 nm wavelength for a large range of exposure doses D_{313} (Figure 4). The UV exposure at 313 nm limited photoiniator activation to the top surface and allowed to reduce the thickness of the suspended layer (approximately 11 µm) compared to exposure at 365 nm. However, the high absorption at 313 nm combined with diffusion of the photoinitator resulted in overexposure and complete crosslinking of the top surface without any patterns for an exposure dose D_{313}= 10 mJcm^{-2} (Figure 4. A). Even for a lower exposure dose of 5.25 mJcm^{-2} (5 s of UV exposure) the structures were still over exposed and no replication of the mask design M_2 was achieved (Figure 4.B). With an exposure dose of

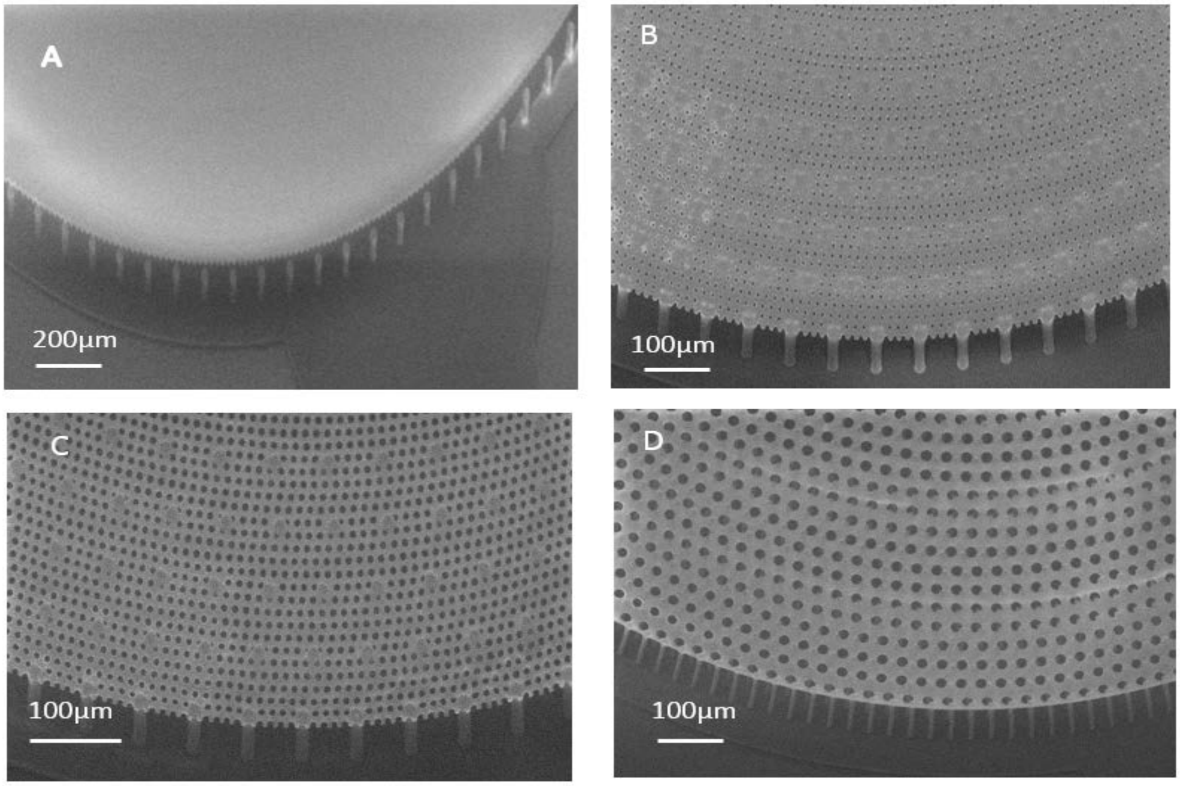

Figure 4: Second partial UV exposure optimization with D_{313} (A) 10.50 mJcm^{-2} (B) 5.25 mJcm^{-2} and (C) and (D) 3.15 mJcm^{-2}

3.15 mJcm^{-2} (3 s of UV exposure) the patterns on M_2 were replicated (Figure 4.C and D). The thickness of the suspended layer was approximately 11 µm for all three exposure doses (D_{313}). The holes with 10 µm diameter and pitch 5 µm was successfully fabricated on the suspended layer as showed in Figure 4.C. This demonstrates that the processing window for fabrication of suspended SU-8 structures with high lateral photolithographic resolution remains quite narrow when using UV exposure at 313 nm. As a major drawback, it is not possible to control lateral resolution and thickness of the suspended layer independently, because both parameters depend on the exposure dose. This results in a less flexible process for fabricating patterned suspended layers with different thicknesses.

3.2. 405 nm UV lithography process

The limitation to control both lateral resolution and the suspended layer thickness precisely, lead us to explore a new fabrication process. The negative epoxy photoresist mr-DWL 40 has a photoinitiator which can be activated at 405 nm. At the same time, SU-8 should not be crosslinked after UV exposure at 405 nm wavelength. First, the SU-8 crosslinking at 405 nm was evaluated by exposing 98 µm thick SU-8 layers with an exposure dose of 220.5 mJcm^{-2} (21 s of UV exposure). After development no SU-8 structures remained on the substrate. Next, the complete fabrication sequence illustrated in Figure 3 was performed. Figure 5 shows that suspended layers with a well-defined thickness of 17 µm were obtained

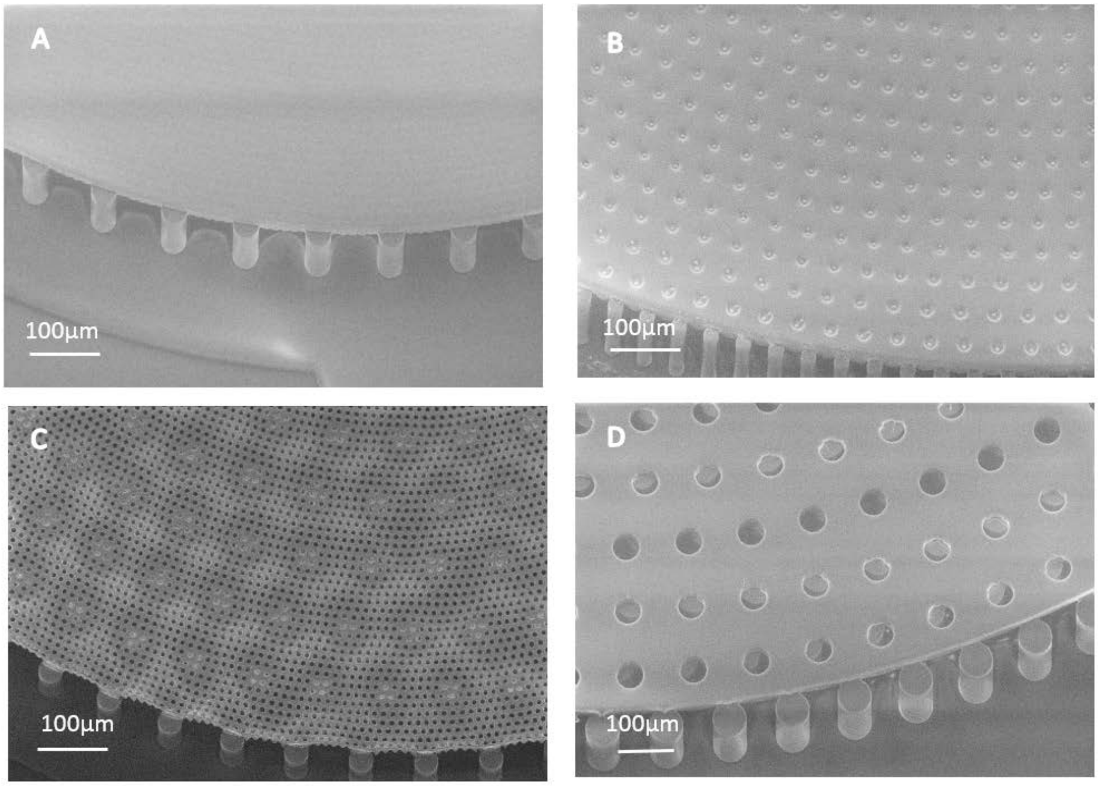

Figure 5: Second UV exposure D_{405} optimization (A) 105 mJcm^{-2} (B) 52.5 mJcm^{-2} (C) and (D) 31.50 mJcm^{-2}

for a large range of exposure dose D_{405}. Exposure doses of 105 mJcm^{-2} (Figure 5.A) and 52.5 mJcm^{-2} (Figure 5.B) resulted in overexposure and the mask (M_2) patterns were not replicated. For an exposure dose D_{405}= 31.50 mJcm^{-2} (3 s of UV exposure) well-defined suspended layers were fabricated.

With this fabrication process it is possible to define the pattern only in the mr-DWL polymer (suspended layer) without affecting the supporting SU-8 structures. The thickness of the suspended layer is defined by a spin coating step and the lithographic resolution of the suspended layer is defined by the UV exposure dose at 405 nm. This increases the processing window for patterning the suspended layer and allows independent tailoring of the two parameters.

4. Conclusion

Suspended SU-8 microstructures were fabricated with UV photolithography using two different wavelengths (313 nm and 405 nm). For the process using 313 nm, the optimized partial exposure dose D_{313} = 3.15 mJcm^{-2} for a low temperature baking process was used to fabricate a well-defined suspended layer with 5 µm suspended structures. This approach limited crosslinking to the top layer of the SU-8 film and increased the processing window for the exposure dose compared to earlier work performed with 365 nm [22]. However, simultaneous control of the thickness of the suspended microstructures was impossible. To achieve this, a novel process using UV lithography at 405 nm was optimized after spin coating a layer of a second epoxy based photoresist mr-DWL 40. The filtering of the lower wavelengths was achieved by simply inserting a PMMA sheet in a standard UV aligner. The optimized exposure dose for well resolved microstructures on a mechanically stable suspended layer of mr-DWL was D_{405} = 31.50 mJcm^{-2}. In conclusion, a change in wavelength and the introduction of an additional spin coating step allowed optimal control of both thickness and lateral resolution and thereby improved processing flexibility. In future work, the suspended SU-8 structures will be used as a polymer template for C-MEMS to fabricate 3D carbon microelectrode.

Acknowledgements

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