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Multi-layer lithography using focal plane changing for SU-8 microstructures

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Abstract

In this paper, we report on a type of SU-8 microstructure with vertical sidewalls used for polydimethylsiloxane (PDMS) microchannels. Multi-layer lithography using focal plane changing approach is proposed to expose the SU-8 photoresist based on a digital micromirror device (DMD) maskless lithography system. We used a light-emitting diode source with a wavelength of 405 nm. The thickness of the SU-8 is divided into multi-layers according to the depth of focus. Each layer corresponds to a depth of focus, and then, a virtual mask is designed for the layer. Finally, each layer is exposed to changes in the focal plane. The results indicate that the actual profile of the SU-8 mold shows good agreement with the design profile without any T-profiles. Additionally, there is better linewidth in the proposed method compared with multi-exposure by a single fixed focal plane. The PDMS microchannels result also demonstrate the stability of the SU-8 mold.

1. Introduction

SU-8 is a negative, ultraviolet (UV) photoresist based on epoxy resin. Because thick SU-8 has excellent mechanical properties, resistance to solvents, chemical stability and optical properties, it has become a popular photoresist material for the fabrication of many microelectromechanical system (MEMS) structures and devices [1–6]. Polydimethylsiloxane (PDMS) [7] microfluidic channels are an application of SU-8 microstructures [8]. SU-8 masters are frequently used for molding microfluidic channels [9]. Similarly, the quality of the SU-8 master can be verified through the PDMS microchannel. Several researchers have reported on SU-8 microstructures with different technologies [10–16]. Among them, digital micromirror device (DMD) maskless lithography eliminates the cost of mask production and increases lithography flexibility as compared to typical mask-lithography. The exposure light source for SU-8 is usually the I-line (365 nm) [17–20] of a high-power mercury lamp which has the disadvantages of a large spectral range, short life, high power consumption, and pollution. The light-emitting diode (LED) is widely used in DMD lithography because of the characteristics of a single spectrum, energy saving, long life and no pollution. The DMD chip has the best light transmission efficiency for light with a wavelength from 400 to 420 nm [21]. The common wavelength used in the DMD system is 405 nm [22] because many photoresists are sensitive at this wavelength. For a thick SU-8 film, according to Beer–Lambert’s law [23], when an ultraviolet light with a short wavelength (350–365 nm) propagates from the top to the bottom of the photoresist, the exposure intensity will be attenuated. The absorption of SU-8 photoresist at these wavelengths causes a non-uniform light intensity distribution across the resist film. The top of the photoresist is easily overexposed and the bottom is underexposed resulting in lithographic features with pronounced T-profiles and non-vertical sidewalls [1, 24–26]. Scan-exposing photonic energy of 405 nm only once on such thick film may not reach the required amount of total energy required to polymerize the photoresist along the thickness [14]. Multiple rounds of exposure with a fixed focal plane at the surface of the photoresist can reach the total energy, but will let the linewidth of the pattern increase which affects the accuracy of the lithography.
In this study, a method of multi-layer lithography via focal plane changing was proposed to achieve the total energy required for polymerization and maintain the linewidth accuracy simultaneously. The results show that the sidewalls of the SU-8 mold are nearly vertical without any T-profiles. The linewidth of the SU-8 mold shows good agreement with the design profile. The PDMS microchannels result also demonstrates the stability of the SU-8 mold.

2. Experimental section

Figure 1 (a) presents a schematic of a DMD-based maskless lithography system. The device model used was MLL-C900, which was purchased from the Hefei Chip and Electronic Equipment Company, China. The core components of this system are the exposure light source, DMD chip and projection system. The DMD chip acts as a spatial light modulator and is manufactured by Texas Instruments. A magnified schematic of the DMD chip is shown in figure 1 (b). The linewidth of the DMD micromirrors is 13.68 μm. The DMD chip is integrated with a microlens array (MLA). The function of the MLA is modulating the exposure light, which allows the light to be distributed evenly. A magnified schematic of the MLA is shown in figure 1 (c). We used the homogenized and collimated light from an ultraviolet LED source as the exposure light. The light source is packaged by six CBT-39-UV LED chips, which are purchased from LUMINUS. The central wavelength is 405 nm and the total power is 4.5 W. There is a condenser lens between the LED and DMD chip, which can convert the light from the LED into exposure light with uniform illumination and a high degree of collimation. The exposure light is cast onto the DMD chip after a reflecting mirror. Then, the incident light is reflected by the DMD, through the MLA and objective lens, and then focused onto the photoresist surface. A refining system is placed on top of and below the objective lens that can modulate the light path. Light through the MLA can form an intermediate image, which is a bright dot array plane [27], as shown in figure 1 (d). The working stage can move along x, y, z axes, which provides a basis for our experiment.

The DMD chip in our system acts as a high-speed dynamic virtual mask and generates optical patterns according to the image flow from a computer in real time. When the corresponding DMD micromirror causes a deflection of +12°, the corresponding dot in the intermediate image is bright. When the corresponding micromirror causes a deflection of −12°, the corresponding dot is black. The DMD chip in our system is tilted at \( \theta = 7.125° \). The space of the projected dot array in the coaxial direction was 5 μm. The scanning rate is the rate at which the platform moves. In every time exposure process, the platform moved along the plane formed by the x and y axes from the initial position to the end position. The bright dot forms a line, and the lines form the wafer-scale pattern. There is no need to consider the stitching process between the stitched patterns, as in masked lithography. When there is only one dot coincident in the scanning direction, we obtain the linewidth accuracy limit of our system which is equal to 0.62 μm. Additionally, we can control the focus plane at different positions along the thickness of the photoresist by adjusting the height of the platform in the z-axis.
We used a glass substrate with a chrome layer (2 inch × 2 inch), and SU-8 2050 from MICRO CHEN Corporation. To allow the SU-8 photoresist coat the substrate uniformly, the substrate was baked at 120 °C for 10 min. The substrate was then cooled for 5 min. After cooling, the substrate was spin-coated with SU-8 at 600 rpm for 10 s, and then, spun at 2600 rpm for 40 s. The substrate was left to rest for 1 min prior to prebaking. Next, the substrate coated with photoresist was soft-baked at 65 °C for 1 min, then at 95 °C for 6 min, and finally at 65 °C for 1 min. The purpose of this prebaking process is to improve the SU-8 adhesion for full exposure. After the soft baking process, the substrate was left to rest and cool for 20 min. As a result, an SU-8 photoresist layer with a thickness of approximately 45 μm was obtained.

To ensure sufficient exposure of the SU-8, the depth of focus (DOF) of the system objective lens must be considered. If the SU-8 thickness is greater than the DOF, the spatial resolution rate will be reduced, and the actual and design profiles may contain errors, thereby reducing the exposure quality. The DOF is defined by equation (1) [28],

\[
\text{DOF} = \frac{K_2}{\lambda^2 NA^2}
\]

where NA is the numerical aperture of the 20× objective lens, which is 0.75. λ is the wavelength of the light source. K_2 is a constant that is equal to 4 in our system. We designed multi-layer lithography with multiple patterns by changing the focus plane to reach the required amount of total energy needed to polymerize along the thickness. The schematic is shown in figure 2.

This method is that for a structure, multiple virtual patterns are used for exposure at different focal plane positions. First, the structure is layered based on the thickness of the SU-8, where each layer corresponds to a DOF, a virtual pattern is designed for each layer, and finally, each layer is exposed by moving the focal plane. Figure 2(a) shows the beginning of the exposure process; the focus plane is at the top of the photoresist. Then the focus plane moves down layer by layer, and the SU-8 is cured at each layer. Figure 2(b) shows the focus plane when it is in the middle of the SU-8, and figure 2(c) shows the focus plane is at the bottom of it.

To evaluate the validity of the method proposed above, an SU-8 mold with a thickness of approximately 45 μm was experimentally fabricated. First, multilayer virtual patterns must be drawn for multiple exposures during the fabrication process. A schematic of the multilayer patterns is shown in figure 3. Figure 3(a) shows the whole pattern drawn using the L-Edit software (commonly used software for designing an integrated circuit layout developed by Tanner Research). The cell filter is a type of microfluidic channel that is widely applied in the biological field. Most microchannels in the cell filter are straight, which is not conducive for cell separation into the reservoir. Figure 3(a) shows a type of cell filter with arc channels and branches. The size of the chip is 1 × 1.2 mm². The width of the microchannel was 30 μm. The diameter of the circles on the top is 130 μm, and the diameter of the circle on the bottom is 250 μm. Figure 3(b) shows the pattern corresponding to each layer. Different colors indicate different layers. In the digital lithography system, the DMD chip converts these patterns into a binary image to replace the traditional physical mask. Each layer from the top to the bottom corresponds to the 1st to nth layer.
Assuming that the design SU-8 mold has height H, which is the thickness of the SU-8 photoresist, we divide H into n layers according to the DOF. The height of the ith layer is $h_i$, as described in equation (2),

$$
\sum_{i=1}^{n} h_i = H
$$

$h_i$ is equal to the DOF, which is 3 μm in our system. H is equal to the thickness of the SU-8, which is 45 μm in our experiment. To ensure the cross-linking of the overall SU-8, each layer needs to be fully exposed but not overexposed. When the exposure dose is greater than the threshold, the width gradually increases as the exposure dose increases [29]. Therefore, the exposure dose we used for each layer was 150 mJ/cm² which is the exposure threshold $E_{th}$ for SU-8 2050.

The scanning rate is set at 0.7 mm s⁻¹, which is the rate of platform movement. For each layer exposure process, the platform moved along the plane formed by x and y axes from the initial position to the end position. Additionally, the bright dot array forms a line, and the lines form the complete pattern on the SU-8 photoresist.

For all layer exposure processes, we only expose the layer once to form a 2D pattern. The system has an automatic alignment centering function. After a complete pattern for one layer is exposed, the platform can return to the same initial position to ensure the alignment accuracy of different layer patterns. The time for the platform to return from the end position to the initial position can be regarded as the resting time. No partial development or exposure occurs during this resting time.

Moreover, the z-axis of the platform can move by setting the offset parameter, which is the defocusing amount. For the first layer (the top layer) exposure, the offset parameter was set as 0. At this time, the focus plane was at the top of the SU-8 photoresist, due to the DOF of the system being 3 μm. After this layer is exposed, 3 μm thick SU-8 was cured. For the second layer exposure, the offset parameter was set as 3, and the focus plane moved down 3 μm from the top and so on, until the nth layer is exposed. For every layer exposure, the exposure of the SU-8 beyond the DOF is ignored. Therefore, after one layer was exposed, a 2D pattern was cured inside the SU-8 photoresist with a thickness of 3 μm. As multiple exposures progress, these cured 2D patterns in different layers are automatic-alignment and stack repeatedly inside the SU-8 and finally form a 3D structure. For a 45 μm thick SU-8, the number of multi-exposure times should to be 15.

Following the exposure process, the sample was post-baked at 65 °C for 1 min and heated to 95 °C for 30 min. The sample was then soaked in an SU-8 developer solution for 5 min, and rinsed with isopropanol until the white floccule disappeared. After development, the pattern was preserved. Finally, the samples were dried with nitrogen and hard baked at 150 °C for 30 min to increase the stiffness of the SU-8 mold. To demonstrate the stability of the SU-8 mold, the SU-8 mold was used to fabricate PDMS microchannels. The PDMS and curing
agent were mixed at a ratio of 10:1. This mixture was then stirred with a precursor for 1 min to ensure complete combination. The resulting mixture was then cast into the SU-8 mold sample and cured in an oven at 65 °C for 12 h. The PDMS slice with microfluidic channels was gently peeled from the molds and subjected to ultrasonic cleaning with N, N-dimethylformamide for 1 min. Finally, the PDMS slice was bonded to a glass slide.

3. Results and discussions

The morphologies of the fabricated SU-8 microstructure were evaluated by changing the focal plane using the confocal laser scanning microscopy (CLSM) (OLS4100, Olympus, Japan). The results are presented in figure 4.

A confocal 3D laser image of the SU-8 microstructure is presented in figure 4(a). Notably, the pattern is intact free from damage and convex. Figure 4(b) presents a confocal 2D laser image of the entire SU-8 mold. From the result, we can see that the size of the SU-8 mold is approximately 1 × 1.2 mm² which is the same as our design. The corner joints of every branche are clear and free of damage. The same color in figure 4(b) indicates the same height, which means that the height of the entire pattern is consistent. Furthermore, the edge of the profile is sharp. The cross-section profile of the SU-8 microstructure was measured, as shown in figure 4(c). The red line in figure 4(b) is the measurement line. Figure 4(c) shows that the height of the microstructure is 45 μm, which demonstrates that the thickness of the SU-8 photoresist is 45 μm. The results also demonstrate that the SU-8 microstructure has nearly vertical sidewalls without any T-profiles, and the actual profile of the SU-8 mold shows good agreement with the design profile. A magnified confocal 2D image of the microstructure is shown in figure 4(d), where the scale bar is 50 μm. From these results, it can be observed that the width of the microchannel is 30 μm, which is the same as our design.

The morphologies of the PDMS microchannels were investigated using CLSM, as shown in figure 5. A confocal 3D laser image of the PDMS microstructure is presented in figure 5(a). Notably, the channels in the pattern are clear and that the pattern is concave. Every channel in the chip is clear and free of impurities. Additionally, the confocal 2D optical image in figure 5(b) shows that the branches and trunk couple perfectly. Figure 5(c) shows a confocal 2D laser image of the entire PDMS microchannel. The same color in figure 5(c)
represents the same height, and the darker color means the deeper position. The cross-section profile of the PDMS microchannels was measured as shown in figure 5(d). The blue line in figure 5(c) is the measurement line. The depth of each channel was 45 μm, which perfectly matches the height of the SU-8 mold. There is no residual SU-8 in the microchannel. In addition, the sidewalls of the PDMS microchannels were nearly vertical. The PDMS microchannels result demonstrates the good quality and stability of the SU-8 microstructure.

For a more intuitive observation, the SU-8 mold after being used to fabricate the PDMS microchannels, and the PDMS microchannels are investigated by scanning electron microscopy (SEM), as shown in figure 6. Figure 6(a) shows a 15° angled view of the entire SU-8 microstructure. It can be observed from the figure 6(a) that the side walls of the SU-8 mold are nearly vertical. For each branch channel, the top and bottom width are the same, which are equal to 30 μm. The results show that the quality of the SU-8 mold after being used to fabricate PDMS microchannels was stable without overexposure or underexposure. A cross-sectional SEM image of the SU-8 microstructure is shown in figure 6(b). The height of SU-8 is measured to be 44.6 μm which is almost similar to the CLSM results. Figure 6(c) shows a 15° angled view of the PDMS microchannels. There is no residual SU-8 in the microchannels. The results demonstrate that the process of PDMS casting and peeling was successful and SU-8 reached full polymerization. Figures 6(d) and (e) show the 15° angled view of the magnified single PDMS microchannels at the top and in the middle, respectively. From the results, it can be noted that the sidewalls of the PDMS microchannels are nearly vertical, which indirectly proves that the sidewall of the SU-8 microstructure is nearly vertical. The branches are useful for cell-migration applications. The purpose of the arc channels is to allow the test solution to flow to the branches easily and quickly. This type of PDMS microchannel is applicable to the field of cell migration and medicine analysis.

Additionally, the quality of the SU-8 mold is compared with another SU-8 mold (referred to as sample B) fabricated by multi-exposure with a fixed focal plane at the surface of the photoresist. The CLSM 2D image of sample B is shown in figure 7(a). Notably, the edge of SU-8 is blurred and the profile was deformed. The red line in figure 7(a) is the measurement line, which is the same position relative to figure 4(c). Both the SU-8 mold and sample B were measured by Profiler (PG1240, Taylor Hobson Limited). The results are shown in figure 7(b). The red line represents the profile of the SU-8 mold. The black line represents the profile of sample B. The height of the black line is higher than that of the red line. This is due to the coated thickness error. The overall profile of
the black line is wider than that of the red line. This indicates that the method of multi-exposure with a fixed focal plane at the surface affects the accuracy of the lithography. The method proposed in this study can effectively achieve better results.

Figure 6. SEM images of SU-8 microstructure and PDMS microchannels. (a) 15° angled view of the entire SU-8 microstructure; (b) cross-sectional image of the SU-8 microstructure, (c) 15° angled view of the entire PDMS microchannels, (d) 15° angled view of a magnified single microchannel at the top; (e) 15° angled view of a magnified single microchannel in the middle.

Figure 7. (a) SU-8 microstructure fabricated by multi-exposure with constant focal plane, scale bar: 500 μm; (b) Diagram for comparing the cross-sectional profile where DOF is changed relative to the cross-sectional profile where DOF is unchanged.
The SU-8 photoresist is composed of resin, photoactive compound (PAC) and cyclopentanone solvent. During the exposure process, PAC produces H$_2$SbF$_6$, which is a strong acid that acts as a catalyst and provides protons for the cross-linking reaction \([30]\) of the resin during post-baking. Under multi-exposure with a fixed focal plane condition, the SU-8 in the focal plane is overexposed resulting in the diffusion of PAC to form a cross-linking reaction in advance, while the SU-8 fields out of the focal plane are not fully exposed. During the post-baking process, a collapse occurs, resulting in a widening of the linewidth, as shown in figure 7(a). In this study, using the method of multi-layer exposure with the focal plane changing, each layer of SU-8 is fully exposed, the resolution of SU-8 is improved and no T-shaped profile is observed.

4. Conclusions

An SU-8 mold was fabricated using multi-layer exposure with the focal plane changing method during DMD-based maskless lithography with an LED source at a wavelength of 405 nm. The multi-exposure times and the step of moving the focal plane for each instance were theoretically analyzed. The results show that the actual profiles of the SU-8 mold show good agreement with the design profile without any T-profiles. Moreover, the PDMS microchannels result demonstrates the stability of the SU-8 mold. This method provides another way to fabricate the SU-8 mold, and it will expand the application field of the 405 nm LED source.

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Author contributions

Conceptualization, Q M Chen and J Y Zhou; Methodology, Q M Chen and J Y Zhou; Formal Analysis, Q M Chen, Q Zheng and Y M Hu; Investigation, Q M Chen, Q Zheng and Y M Hu; Writing—Original Draft Preparation, Q M Chen; Writing—Review and Editing, J Y Zhou; Supervision, Project Administration and Funding Acquisition, J Y Zhou.

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Conflicts of interest

The authors declare no conflict of interest.

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