Moving-mask Lithography for 3D Microstructure Molding

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Backside lithography with a moving mask UV exposure technique is proposed. A novel moving-mask exposure apparatus was developed and evaluated both experimentally and through exposure simulations. The backside exposure using this technique was validated and is capable of producing tapered microstructures of thick photoresist for molding. The shape of the structure can be modified by the trajectory of the stage movement. It was confirmed that the shape of the processed structure could be successfully predicted using the proposed simulation method.

Keywords: moving mask exposure, backside exposure, molding

1. Introduction

Tapered 3D microstructures have been fabricated using micromachining since the mid-1980s. Among these structures, microneedles have many promising applications. A pioneering study on microneedles was conducted by Prausnitz and colleagues, where etching of micrometer-size silicon needles was proposed for creating conduits for transport across the stratum corneum, the outer layer of the skin [1]. They also proposed polymeric microneedles that contain a drug matrix for controlled release [2]. Such microneedles have been formed by molding, in which control of the sidewall inclination angle of the microstructures is very important. For this purpose, techniques such as inclined deep X-ray lithography [3], double-exposure deep X-ray lithography [4], moving mask X-ray lithography [5-7], gray-scale lithography [8], inclined UV lithography [9], moving-mask UV lithography [10-12], backside lithography [13,14] and deep UV lithography using diffraction [15-18] have been investigated.

X-ray lithography requires a synchrotron, which is prohibitively expensive for many microsystem laboratories [3-7,9,10].

To obtain tapered 3D microstructures in a timely manner and with affordable cost, grayscale and moving-mask UV lithography are promising techniques. However, conventional UV exposure

from the surface side of the photoresist can only be adopted for positive tone resists to produce inclined microstructures. The thickness of the positive tone resist restricts the microstructure height to less than 50 μm [10], which is too thin for microneedle applications. Therefore, backside lithography using a thick negative-tone photoresist is a more promising technique.

Miki and colleagues proposed to make a mold of a tapered hole by backside exposure utilizing diffraction from a mask pattern. The sidewall inclination angle of the mold was controlled by changing the distance between the mask and the resist surface. However, the inclination of the mold cannot be significantly modified by only the effect of diffraction [18].

Moving-mask UV lithography can be used to modify the UV light intensity distribution significantly by the mask movement, and thus has a wide range of flexibility for inclination [10].

Here, we propose a moving-mask UV lithography technique with backside exposure to form tapered microstructures with a wide range of inclination angles.

2. Method

The concept of moving-mask UV lithography with backside exposure is straightforward. The moving-mask trajectory blurs the UV light

patterned by the photomask. This exposure process works as a grayscale mask by illuminating a thick negative-tone photoresist from the backside through a transparent substrate to produce a 3D microstructure with a positive taper.

2.1 Novel moving-mask UV lithography apparatus with backside exposure

Figure 1 shows the moving-mask UV lithography apparatus with backside exposure developed in this study, which includes a UV spot light source (LC6, Hamamatsu Photonics K. K.) with an i-line (365 nm) transmittance filter. The UV light is guided by a light guide from the source to illuminate the photomask using a uniform irradiation unit (E5147-06, Hamamatsu Photonics K. K.). The mask holder can be moved up and down with a long-stroke motorized stage (ALZ-115, Chuo Precision Industrial Co., Ltd., 150 mm stroke with 2 μm resolution) to contact with the substrate and adjust the proximity gap. The substrate was flipped over and placed on top of a 2-axis precision piezo-scanning stage (MS-150LCV3, MESS-TEK, 150 μm stroke with 2 nm closed-loop resolution) on a poly(dimethylsiloxane) (PDMS) slab with a 35 mm diameter hole as a cushion and suction pad. The movement trajectory of the stage was controlled with a 2-channel function generator

Fig 1 Overview of the moving mask UV lithography apparatus.

(AFG320, Tektronix). The signals from the function generator were applied to the stage through a stage controller (M-2689, MESS-TEK). The trajectory of the stage was monitored using a digital oscilloscope (TSD224, Tektronix).

2.2 Resist preparation, exposure and development

A custom-made soda lime glass wafer (50 mm in diameter, 170 μm thick, Matsunami Glass Ind., Ltd.) was spin-coated with a negative-tone photoresist (SU-8 3050, MicroChem) using a spin-coater (1H-D7, Mikasa Co., Ltd). The main spin speed and spin time used to produce a 200 μm thick coating were 1100 rpm and 5 s, respectively. After spin-coating and a 1 h relaxation step at room temperature, the sample was heated at 95 $^{\circ}\text{C}$ for 40 min on a hotplate to evaporate the solvent.

The glass wafer coated with photoresist was set upside down on the PDMS cushion. The substrate stage was then moved in a circular motion (50 $\mu\text{m}/150 \mu\text{m}$ in diameter, 2 Hz). The mask holder was lowered to achieve tight contact of the photomask and glass substrate, which was confirmed by the stage trajectory monitor. The mask holder was then raised up 10 μm to provide a proximity gap. The UV light source was used to irradiate the photomask for 18 s with an exposure energy of 300 mJ/cm^2 at the center of the pattern. A post-exposure bake was conducted at 95 $^{\circ}\text{C}$ for 40 min and the sample was allowed to cool down to room temperature for 2 h. The polymerized resist was developed by spraying developer (SU-8 developer, Microchem) for 1 h and was then rinsed with isopropyl alcohol (IPA).

2.3 Molding of epoxy resin

Epoxy microstructures were fabricated using PDMS (Sylgard 184, Dow Corning Toray) molds that were made from SU-8 microstructure. The volume ratio of PDMS-base and curing agent was 10:1. The PDMS mixture was poured over SU-8 master microstructure and cured by placing in a 60 $^{\circ}\text{C}$ oven for 3 h. The cured PDMS mold was then peeled off from the master.

The PDMS mold was then filled with epoxy resin (Epok 812, Oken-shoji) and cured in a 60 $^{\circ}\text{C}$ oven for 12 h. The volume ratio of Epok was 46 ml, 30 ml, 24 ml and 1.5 ml for Epok 812, DDSA, MNA and DMP-30, respectively. After the solidification, the epoxy microstructures were removed from the PDMS mold. The PDMS molds could be reused to make additional microstructures.

3. Simulation of 3D microstructure shape

The intensity of UV light at the interface of the glass substrate and resist layer can be calculated

Fig 2 Calculated exposure dose at the interface and final shape of the microstructure with (a) a moving trajectory of 50 μm in diameter, and (b) a movement trajectory of 150 μm in diameter.

from the convolution of the light intensity modulated with the mask pattern and the movement trajectory of the substrate, as follows:

$$I_1(x, y) = I_0(x, y) * T(x, y), \quad (1)$$

where $I_1(x, y)$ is the light intensity at the interface between the glass and the resist, $I_0(x, y)$ is the light intensity beneath the photomask, and $T(x, y)$ is the moving trajectory.

The intensity of the light propagating in the resist can be calculated from the UV absorption of the resist [19]:

$$I_2(x, y, z) = I_1(x, y)e^{-\alpha_{SU-8}z}, \quad (2)$$

where $I_2(x, y, z)$ is the light intensity at an arbitrary location in the resist layer, and α_{SU-8} is the absorption coefficient of SU-8 for the i-line. The exposure dose can be expressed as,

$$D(x, y, z, t) = I_2(x, y, z) t \quad (3)$$

where t is the exposure time. The critical exposure dose of SU-8 (D_c) was estimated from Ref. [19] to be 95 mJ/cm^2 . Thus, the shape of the microstructure can be expressed as:

$$z(x, y) = -\frac{1}{\alpha_{SU-8}} \log \frac{D_c}{I_1(x, y) t}. \quad (4)$$

The microstructure shape was simulated using image processing software (ImageJ 1.84q, NIH) [20]. In the first step, 2048×2048 pixel 8-bit monochrome graphics files filled with black were prepared, where 1 pixel corresponded to 1 μm . One

Table 1. Dimensions of the calculated microstructures

Diameter of trajectory (μm)	Diameter of top (μm)	Diameter of bottom (μm)	Inclination angle of sidewall ($^\circ$)
50	202	263	78–86
150	107	300	53–78

file had a filled white circle with a diameter of 250 pixels as the photomask and another file had a 50 pixel or 150 pixel diameter circle as the movement trajectory. In the second step, the convolution of these two images was calculated. The shape of the

Fig 3 Shape of microstructures calculated with (a) a movement trajectory of 50 μm in diameter, and (b) a movement trajectory of 150 μm in diameter.

Fig 4. SEM images of the SU-8 masters fabricated (a) with a movement trajectory of 50 μm in diameter, and (b) with a movement trajectory of 150 μm in diameter.

Table 2. Dimensions of the fabricated microstructures

Diameter of trajectory (μm)	Diameter of top (μm)	Diameter of bottom (μm)
50	242	294
150	197	387

microstructure was then calculated using Eq. (4). Figure 2 shows the calculated exposure dose profile at the interface and the final shape of the microstructures. The thickness of the resist was set at 200 μm and the resist was fully exposed in the vicinity of the center of the pattern; therefore, the maximum height of the microstructure was 200 μm . Table 1 shows the dimensions of the calculated microstructures. Figure 3 shows 3D images of the calculated shapes.

4. Results and discussions

The geometry of the SU-8 masters, the PDMS molds and the epoxy microstructures were examined by scanning electron micrographs. Figure 4 shows SEM images of patterned photoresist 3D microstructures exposed through a circular (250 μm diameter) opening photomask with a moving-mask trajectory of (a) 50 μm and (b) 150 μm . The overall shape of the structure was in good qualitative

Fig 5 SEM images of the PDMS molds fabricated (a) with a movement trajectory of 50 μm in diameter, and (b) with a movement trajectory of 150 μm in diameter.

Fig 6 SEM images of the PDMS molds fabricated (a) with a movement trajectory of 50 μm in diameter, and (b) with a movement trajectory of 150 μm in diameter.

agreement with the prediction. However, the difference in the dimensions of the fabricated structures was not negligible. The dimensions of the fabricated microstructures are shown in Table 2. Compared to the analytical prediction, the diameters of both the microstructures were expanded by 11.8–29.0%. These results suggest that the effect of diffraction should be considered. According to the literature [21], the proximity gap has a significant effect on the pattern size, especially in the case of ultra thick resist exposure, where calculations predicted that a 100 μm proximity gap would expand the mask pattern 25 μm in the radial direction. In the present study, the thickness of the glass substrate and proximity gap acted as an actual proximity gap of at least 180 μm . Therefore, for more precise prediction, the effect of Fresnel diffraction should be considered.

Figure 5 shows the SEM images of PDMS molds. The microstructures of SU-8 master were precisely transferred to PDMS molds. Figure 6 shows the epoxy resin microstructures of the final products of this series of fabrication. The microstructure of the epoxy resin shows good agreement with the SU-8 master.

5. Conclusion

A newly developed moving-mask exposure apparatus with backside exposure technique was demonstrated to produce a variety of sidewall inclination angles for a 3D microstructure. The microstructures of SU-8 master were successfully transferred to the epoxy resin by using PDMS molds. An image processing technique was employed to qualitatively predict the final shape of the microstructure. The results indicate that the effect of Fresnel diffraction should be considered for quantitative predictions.

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