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High Aspect Ratio Sloping and Curved Structures Fabricated by Proximity and UV-LED Backside Exposure

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1. Introduction

Fabrication technique for micro three-dimensional structures has been in wide demand in various devices in MEMS, micro optics, and the biomedical field. However, high aspect ratio sloping and curved structures of a few hundred micrometers height are generally difficult to fabricate by using the conventional method. The injection molding method is not suitable for small-lot production because the die assembly is expensive. The thermal reflow method does not provide high controllability of profile because the size depends on the surface tension. In the case of the gray scale mask method, the mask cost is high and it does not provide a high aspect ratio in the size of a few hundred micrometers. In this study, a new fabrication technique has been developed using a novel lithography process. This process provides structures with high uniformity over a large area and also high flexibility of design by only one exposure process. In this paper, details of the process and experimental results are described.

2. High aspect ratio sloping structures

2.1 Exposure system

Micro three-dimensional structures have been fabricated by a layer-by-layer process[1], a UV-LIGA process[2][3], moving mask UV lithography[4], and gray-scale lithography[5]. Another fabrication method has been proposed that utilizes chemically amplified epoxy-based negative resist(SU-8 etc.) and backside exposure[6]. The backside exposure is effective in creating a negative resist structure. It prevents resist peeling off from the substrate because the exposure and the photochemical reaction are occuring at the interface of the glass substrate.

However, the high aspect ratio sloping structure is still difficult to fabricate using these lithography techniques. In this chapter, a fabrication method for this type of structure is proposed based on use of the proximity exposure technique[7]. The method exposes the SU8 resist from the backside of the glass substrate to change the amount of exposure using a conventional mask. By using backside exposure, the exposure amount can be transformed into a resist structure. The top layer of the resist is removed in the developing process so that the uniformity and roughness of the resist during the coating process do not affect the final resist structure.

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2.2 Simulation of and results for the L&S structure

Diffraction phenomena can be positively used to change the amount of exposure at the boundary of the mask. In this study, a glass substrate 150 µm thick was used for the threedimensional fabrication. The gap between the mask and the resist makes the lithography process in the proximity region dominated by Fresnel diffraction. The light intensity on the resist surface could be calculated based on the model proposed by Dill et al. (the "Dill model") [8]. The Dill model calculates the light intensity on the resist surface through numerical calculations of all elements of the processes of resist exposure and development. Grindle et al. have proposed a method (the "Grindle model") in which the light intensity distribution is obtained by numerical calculations, but the simulation of development is performed based on the actually measured dissolution rate values [9]. The lithography simulator ProxSim-2 (Lithotech Japan) is based on the Grindle model and designed for proximity lithography using a mask aligner.

The light intensity through the slit pattern from 20 μ m to 100 μ m in width was calculated by the lithography simulator. The simulation was preformed for the exposure dose of 90mJ/cm² at wave length of 365 nm, with a collimation angle of ±3°. The light intensity in the resist changed according to the glass thickness and mask opening. The light beams passing through the mask opening were diffracted on the Hopkins equation[10]. Figure 2 (a) shows the calculated UV intensity in SU8 resist. The UV intensity and actual exposure amount is changed depending on the slit width. The final resist structure was determined by the chemical reaction occurring during post-exposure bake and the resist development process. The simulator calculates the final strucuture based on the calculated light intensity distribution and the actually measured dissolution rate values for each intensities of SU-8 3000 resist. Figure 2 (b) shows simulated results for the final resist profile. The simulation predicts that the height changes depending on the slit width and that a slope is formed in the resist sidewall.

As described above, the SU-8 resist structures were fabricated with a mask in which the slit width changed between 7 μ m and 35 μ m. SU-8 10 resist was dip-coated with a thickness of around 500 μ m on a 150 μ m thick glass substrate. After the prebake process, the glass substrate was backside-exposed for 5 s by the mask aligner LA310k(Nanometric Technology Inc., Japan). The light intensity of the wave length at 365 nm was 18mW/cm² with a collimation angle of ±3°. The glass substrate was post-exposure baked for 5min at 100°C. An SEM photograph of the fabricated SU-8 resist structures is shown in Fig. 3. The UV dose and the photochemical reaction changed based on the slit width under the proximity condition. The height of the structures is measured in Fig. 4. The height changes nearly constantly if the slit width is less than 30 μ m.

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Fig. 3. SEM photograph of different height resist structures for different L&S pattern masks.



Fig. 4. Relation between slit width and the height of the SU8 resist.

A smooth sloping structure was fabricated by changing the exposure amount using the triangle mask pattern. The mask pattern design is shown in Fig. 5.

Lithography



Exposure time 5 s

Exposure time 15 s



The exposure times are 5 s, 7.5 s, and 15 s by the mask aligner LA310k(Nanometric Technology Inc., Japan). The fabrication results are shown in Fig. 5. These structures had a smooth sloping formation because the width was changed continuously in a triangular mask pattern. A micro sloping structure up to 200 μ m was realized. As shown in Fig. 5, the structure height was controlled by adjusting the exposure time. Structures with a height of 250 μ m were obtained when the exposure time was 15 sec. The SU-8 structures were transferred to metal by a molding technique for application in MEMS and biomedical engineering.

2.3 Simulation of and results for cylinder structure

Taper cylinder structures with a diameter of several tens of μ m were obtained by using the diffraction phenomenon that occurred at the edge of the mask pattern. Figure 6 provides an example of the mask pattern.

The effect of the diffraction was calculated by ProxSim-2. Precise calculations for the mask pattern of Fig. 6 should be performed with a three-dimensional simulator. Because the ProxSim-2 is a two-dimensional simulator, the diffraction effect for the L&S pattern is calculated as shown in Fig. 7. The simulation results predict that taper structures will be formed by the diffraction phenomenon at the side of structure.





-80.0 -60.0 -40.0 -20.0 0.0 20.0 40.0 60.0 80.0 x position /micrometer

Fig. 7. Simulations result for exposure dose and resist structure The SEM photograph obtained after backside exposure using the mask

The SEM photograph obtained after backside exposure using the mask is shown in Fig. 7. Sloping hollows were formed under the diffraction in proximity condition.



Fig. 8. SEM photograph of resist structure .

The structure shown in Fig. 8 can be used as a mold component. PDMS (Polydimethylsiloxane) was poured onto the structure and polymerized, and the resulting PDMS structures were easy peeled away from the SU-8 resist structures because of the tapered shape. An SEM photograph of the structures that were transferred to PDMS is shown in Fig. 9.

However, the height of Fig. 9 is approximately half of the calculated result of the L&S pattern in Fig. 7. The axisymmetrical diffraction effect should be large at the edge of the circle mask pattern in the experiment. The diffraction UV light forms a resist layer on the masking region. The resist layer reduces the hole depth of the resist and the height of the PDMS cylinder structure.

2.4 Application for super-hydrophobic surface

Super-hydrophobic surfaces have attracted much attention due to their practical application potential such as in micro TAS applications. The PDMS structures form a super hydrophobic surface that depend on the micro relief structures on the PDMS surface. The contact angle of the PDMS surface is measured by using a contact angle measurement apparatus. The normal PDMS surface of the contact angle was 105 degrees, and the super hydrophobic PDMS surface was achieved at over 160 degrees[7]. The size of the fabrication structure was changed in this study, and the relation between the size and the contact angle was measured, as shown in Fig. 10. The contact angle increases as the fabrication structure becomes smaller until reaching a size of 20 μ m. However, a taper structure is not fabricated by the diffraction phenomenon when the size of the structure is less than 20 μ m. Therefore, the contact angle becomes small. The repellency was highest at a diameter of 20 μ m, and the maximum contact angle was 172° and, on average, 165°.

3. High aspect ratio curved structures

3.1 Exposure system

Another fabrication technique for high aspect ratio curved structures has been developed using a UV-LED array and a rotary stage[11]. The high aspect ratio curved surface structures are needed for optical devices such as micro lenses, light-guiding devices, and so on. Smooth surface structures can be fabricated with this technique because the UV-LED makes the difference of the UV dose with its wide directivity characteristics. In addition, the

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(d) Scale of the 20 μ m diameter structure

Fig. 9. SEM photographs of PDMS structures.



Fig. 10. Mask diameter versus contact angle.



(b) NS370L-7SFF.

Fig. 11. Photograph of the UV-LED array light source.

structures can be formed with high uniformity by only one exposure process because the rotation reduces the unevenness of exposure. This technique can control the height and curvature of structures by changing the exposure time. Large devices can be fabricated by increasing the number of UV-LED array. Furthermore, this technique also provides high

flexibility of design; for instance, the semi-cylinder shape is fabricated with the mask patterned rectangular aperture. Because the incidence range of UV rays depends on the aperture size, the use of apertures of various sizes allows for structures of various heights to be fabricated by only one exposure process.

Two UV-LED arrays shown in Fig. 11 were used in this experiment. The UV-LED NS370L-5CFA (Nitride semiconductors Co. Ltd.) is the round type without a collecting lens. The center wavelength is 370 nm, and the directional characteristics angle is 50 deg. The light intensity is 1.8 mW, and the light intensity tolerance is 10%. The pitch of the UV-LED array is 12.5 mm, and the array is arranged in 32 lines and 25 rows. The light intensity of the UV-LED array was 0.315 mW/cm². The UV-LED NS370L-7SFF (Nitride semiconductors Co. Ltd.) is a surface mount device type. The center wavelength is 370 nm, and the directional characteristics angle is 50 deg. The light intensity is 1.0 mW, and the light intensity tolerance is 10%. The pitch of the UV-LED array was 0.315 mW/cm². The UV-LED NS370L-7SFF (Nitride semiconductors Co. Ltd.) is a surface mount device type. The center wavelength is 370 nm, and the directional characteristics angle is 50 deg. The light intensity is 2.0 mW, and the light intensity tolerance is 10%. The pitch of the UV-LED array is 10 mm, and the array is arranged in 30 lines and 30 rows. The light intensity of the UV-LED array was 0.830 mW/cm².

The rotary stage was located in parallel to the UV-LED array. The distance between the rotary stage and the UV-LED array was determined within a few cm by measuring the uniformity of the UV intensity. Exposure was performed while the stage was rotating. The exposure system is shown in Fig. 12.



Fig. 12. Exposure system for fabrication of a curved surface structure.

3.2 Fabrication process

A negative photoresist of SU-8 10 was utilized in this technique. SU-8 resist was dip-coated with a thickness of around 500 μ m on a 150- μ m thick glass substrate. After the prebake

process, the lithography process was performed with a UV-LED array. The mask was set on the glass substrate coated with SU-8 resist, and they were fixed on the rotary stage. They were set at a 5 cm radius of rotation. The rotation speed was 100 rpm. SU-8 was exposed by UV light through the glass and apertures of the mask by the UV-LED array. The amount of UV light depends on the mask pattern and the directional characteristics of the UV-LED. The distributions of light arriving at the resist were simulated by the lithography simulator ProxSim-2 (Lithotech Japan). Figure 13 shows the calculated results for the UV intensity and the resist structure at wave length of 365 nm, with a collimation angle of ±50°. The width of the opening windows is 300µm. If the opening windows is circle, the axisymmetrical diffraction effect should be large at the edge of the mask pattern in the experiment.

The structure shape is determined by the UV dose; therefore the curved surface shape can be formed after the development process. The shape can be controlled by the mask pattern, exposure time, intensity, and directivity of the light source.



Fig. 13. Simulation results for the exposure dose and structure

3.3 Fabrication results

Semi-cylindrical structures were fabricated using this technique. In this technique, the structure height depends on the distance from the edge of the aperture. A semi-cylindrical structure with a smooth surface can therefore be fabricated using the mask with a rectangular pattern. The mask pattern and the fabrication results for the semi-cylindrical structures are shown in Fig. 14 (a). A semi-cylindrical structure bent at 90 degree pattern was fabricated. The mask pattern and fabrication results are shown in Fig. 14 (b). By using a gray-scale method, a semi-cone pattern was also fabricated. The gray-scale mask of the rectangular pattern and the fabrication results are shown in Fig. 14 (c). A narrow, pointed structure was obtained.

Hemisphere structures with smooth surface were fabricated as shown in Fig. 15(a). The diameters of the structures were 400 μ m, and the maximum heights were 200 μ m. Hemisphere structures of various sizes were fabricated by only one-step exposure. The exposure time was 18 min. The various diameters of the mask pattern and the fabricated structures are shown in Fig. 15(b). The structure diameters were 270, 380, 480, and 600 μ m, in increasing order. The maximum heights were 110, 170, 220, and 250 μ m.

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(a) Line pattern and semi-cylindrical structure.



(b) Pattern and semi-cylindrical structure bent at 90 degree.



Fig. 14. Mask pattern and SEM images of SU-8 structures.

Hemisphere structures of various sizes were fabricated by 16 min exposure. They are shown in Fig. 16. The mask pattern was used the same one shown in Fig. 15(b). The heights of the structures were lower and the curvatures were smaller than the results shown in Fig. 15(b). The structure diameters were 210, 350, 450, and 570 μ m. The maximum heights were 50, 100, 130, and 150 μ m.

Figure 17 shows the schematic diagram of the shape change versus exposure time.



(c) Side view.

Fig. 15. Mask pattern and SEM image of SU-8 structure



Fig. 17. Relationship between exposure time and shape of resist.

3.4 Micro lens fabrication on another substrate

Micro lenses of UV curable resins were fabricated on another substrate such as a silicon wafer using the above-described hemisphere resist structures. The fabrication process is shown in Fig. 18. Fabricated structures were put into a Petri dish, and PDMS was poured. After defoaming in the vacuum desiccators, the PDMS was cured at room temperature for 6 h and peeled off from the glass plate. UV curable resin (Opster PJ3001, JSR Co.) was then dropped on the silicon wafer, and the PDMS-formed micro lens pattern was pressed on it. The exposure was performed with a mask aligner to penetrate the PDMS. The surface tension was 150 mN/m for Si, over 300 mN/m for SiO², and 20 mN/m for PDMS so that PDMS was easily peeled away from the silicon wafer. As a result, micro lenses of UV curable resin were obtained. The fabrication result is shown in Fig. 19.



Fig. 19. Micro lenses of UV curable resin.

The focusing property of the fabricated micro lenses was simulated by the lay trace simulator Light Tools (Optical Research Associates). Figure 20 shows the calculated results for the focusing property for 240 μ m and 440 μ m diameter lenses. The lenses effectively collected a laser beam of 550 nm wavelength under the glass substrate.

The focusing property of the fabricated micro lenses was evaluated by irradiating laser beam. The lenses collect laser beam to 12.9-68.5 μ m spot diameter and 70.0-380 μ m collective distance from the 150 μ m thick glass substrate. These results show the same tendency as the ray trace simulation and indicate that the focal length of the fabricated micro lens was shorter than that of the conventional micro lens for optical communication. Therefore, the size of the optical device can be reduced by using fabricated micro lenses.



Parameters

Lens diameter: 240 [µm] Lens curvature radius: 120 [µm] Thickness of lens: 120 [µm] Thickness of glass substrate: 150 [µm] Refractive index of lens: 1.51 Refractive index of substrate: 1.52 Number of lays: 100



Parameters Lens diameter: 440[µm] Lens curvature radius: 220 [µm] Thickness of lens: 220[µm] Thickness of glass substrate: 150 [µm] Refractive index of lens : 1.51 Refractive index of substrate: 1.52 Number of lays: 100

Fig. 20. Lay trace simulation results for Microlenses.

Furthermore, a micro fly eye lens was fabricated by reducing the pitch distance of mask circular apertures. Micro lenses with diameters of 200 μ m, 300 μ m, 400 μ m, and 500 μ m were linked to each other in the pitch at distances less than 50 μ m, 450 μ m, 570 μ m, and 690 μ m.



Fig. 21. SEM photograph of micro fly-eye lens.

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Lithography, the fundamental fabrication process of semiconductor devices, plays a critical role in micro- and nano-fabrications and the revolution in high density integrated circuits. This book is the result of inspirations and contributions from many researchers worldwide. Although the inclusion of the book chapters may not be a complete representation of all lithographic arts, it does represent a good collection of contributions in this field. We hope readers will enjoy reading the book as much as we have enjoyed bringing it together. We would like to thank all contributors and authors of this book.

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