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Fabrication of suspended micro-structures using diffsuser lithography on negative photoresist

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Abstract

We report the results of diffuser lithography applied to a negative-type thick photoresist to fabricate 3-dimensional microstructures suspended on supports. When UV light passes through a diffuser film, the direction of the light is randomized because of the irregular surface of the diffuser. By exposing through a diffuser on a Cr-mask, a circular or an elliptical cross-section of exposed region can be formed on a spin-coated photoresist. When applied to a negative-type thick photoresist, diffuser lithography gives a 3-dimensional circular cross-section of the exposed and cross-linked regions, which could be used for making suspended microstructures. The size of the exposed region has been controlled by the dose of the UV light. The current study clearly shows that the depth of exposed region of photoresist is affected by the geometry of the pattern. By controlling the depth of the exposed region using different pattern size, beam structures suspended on the support structures could be fabricated by single exposure process. The characteristics of the diffuser lithography process were investigated on a negative type photopolymer, SU-8, with different doses of UV-light and different geometry.

Keywords: Diffuser lithography; SU-8; 3-D micro structure

1. Introduction

Recently, with enhancements of MEMS/NEMS technology, the need for the fabrication of 3-dimensional microstructures with special functions has increased. Photo-lithography is a common method for making microstructures, but it has a limitation in making three-dimensional microstructures such as bridge-type structures which are supported on both ends or cantilever-type structures supported on one end by support structures.

Yu et al. [1] reported a scanning laser technique to fabricate 3-D structures, e.g., cantilevers and bridges, on SU-8. Suzuki et al. [2] reported an inclined UV exposure method to make an embedded microchannel with single mask process. Chang and Yoon [3] proposed a diffuser lithography, which uses UV exposure through a diffuser film on a positive-type photoresist to make rounded cross-section of micro-lens array mold. Because the diffuser lithography proposed by Chang uses the conventional lithography process with addition of a diffuser film on Cr-mask, it showed some advantages of process simplicity, reproducibility and various shapes of cross-section. The cross-section shape varies by changing the sort of diffuser, exposure dose, mask pattern width, and proximity gap. However, in Chang's report, because they were interested in optical device application which requires uniform pattern size, the investigation about the effect of mask pattern size and geometry was not reported.

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In order to get the rounded cross-section on photoresist by using diffuser lithography, the process parameters are controlled so that the light is diffused in the resist and does not reach the bottom surface of the substrate. When diffuser lithography is applied on a positive type photoresist, only the part of the resist exposed by diffused light is removed and the other part remains on the substrate. This remaining photoresist can be used as a mold structure for replication of various micro patterns with rounded shapes. On the other hand, at negative type photoresist, exposed parts are cross-linked and other unexposed parts are removed by development. This means the exposed parts are not on the substrate and will be washed away from the substrate if they have no support structures on the substrate. Therefore, in the diffuser lithography on a negative type photoresist, investigations on the relations between the depth of exposure and process parameters are necessary in order to ensure the connection of microstructures on the substrate surface.

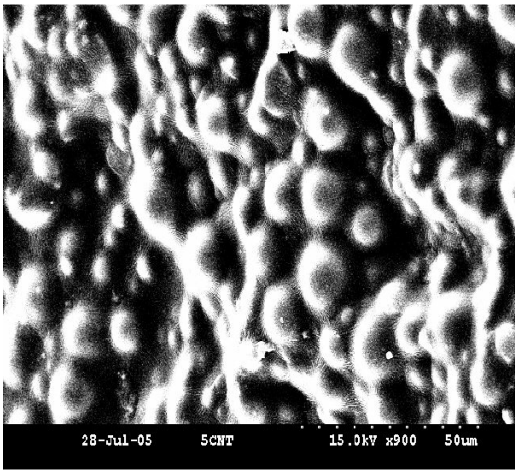
In this study, we applied diffuser-lithography to negative type photo plastic, SU-8, to fabricate various 3-D structures. Tests on various conditions of dose and mask pattern size were performed to investigate the effect of mask pattern size and geometry. It was observed that the depth of exposure depends on the pattern size and geometry of the mask pattern as well as exposure dose. By using the difference of exposure depth according to the size of the metal mask pattern during diffuser lithography, free-standing 3-D microstructures and support structures could be fabricated in a single mask process.

2. Diffuser lithography

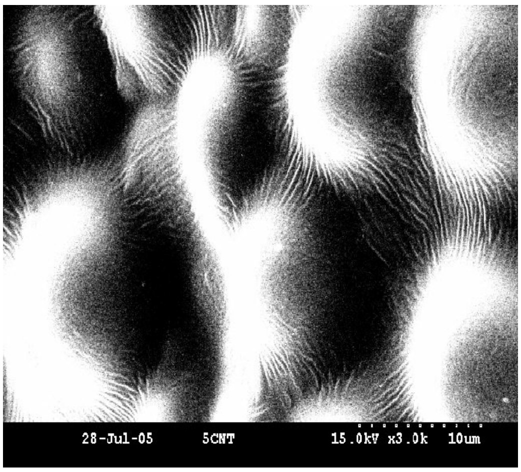
2.1 Optical diffuser film

When UV light passes through an optical diffuser film, UV light refracts resulting in diffused light. Because diffused lighting is often used in many illumination applications, common types of sand-blasted or opal-coated diffusers are commercially available. Another application of the diffused film is LCD (liquid crystal display). Diffuser films are one of the basic elements of the back light unit (BLU). The diffuser film diffuses the light from the light guide plate for the purpose of homogenous light distribution. In this study, diffuser film in the back light unit of an LCD monitor was used for the experiments. Usually, diffuser film is based on polycarbonate resin or polyethylene resin. The diffuser used in this study is polyethylene resin based diffuser (H-102A, Heesung Chemical LTD.). The total light transmittance of the diffuser is 55% and the haze is 99.6%.

Fig. 1 shows SEM images of the surface of the diffuser film. Refraction of UV light passing through the diffuser is caused by the various protrusions irregularly distributed on the surface. The total amount of UV light is reduced as it passes through the diffuser film according to the light transmittance. Moreover, as the light diffuses, the light density decreases and the path of the light deviates from the vertical direction.



(a)



(b)

Fig. 1. The SEM image of the surface of diffuser: (a) overall view (500X), (b) closed view (3000X).

2.2 Basic principle of diffuser lithography

Normal photo-lithography uses UV light passing straight through the metal pattern on a Cr-mask. The straight UV light exposure allows a vertical side-wall of exposed pattern when applied to a negative-type epoxy photo-resist, SU-8. On the other hand, by putting a diffuser film on a Cr-mask during the UV light exposure step, UV light is refracted by the rough surface on the diffuser film, changing the angle of light from vertical direction when exiting the diffuser film. Fig. 2 shows the path of UV light passing through a diffuser and a Cr-mask according to Snell's law. Because the exit angle of light, θ_{diff} , is changed, the photoresist is exposed to the slanted UV-light. The entrance angle of UV to the SU-8 increases as θ_{diff} increases. The direction of UV after diffusion is governed by the protrusion of the diffuser film surface. After exposure, the exposed pattern is larger than the designed pattern on the Cr-mask due to the diffusing effect.

The diffusing effect on the exposed pattern can be observed in the SEM images in Fig. 3. Fig. 3(b) shows an SU-8 pattern made by normal photolithography. Fig. 3(c) shows diffuser lithography in the same Cr-mask pattern. The exposed pattern in the diffuser lithography is bigger due to diffusion of the light. The change of exposed area due to the diffusion effect is affected not only by the dose of light, but also by the pattern geometry (e.g., corner, slit) and size. In Fig. 3(c), the center part A, which has a sharp corner of metal pattern on the photo-mask, shows more diffusion than the pad corner B. This geometry effect, or size effect, is attributed to the difference in the number of photons received at a certain point due to different geometry. A point at a sharp corner, A, receives more photons because the small region is covered by metal (45°) in Cr-mask. Diffused photons come from many directions. On the other hand, a point around pad corner, B, is blocked around 270°, and receives fewer photons. As observed above, the shape of the SU-8 structures exposed by diffuser lithography can be affected by pattern shape and pattern size as well as exposure dose.

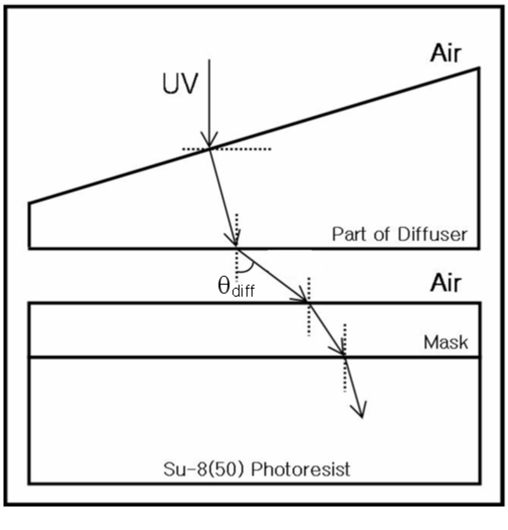
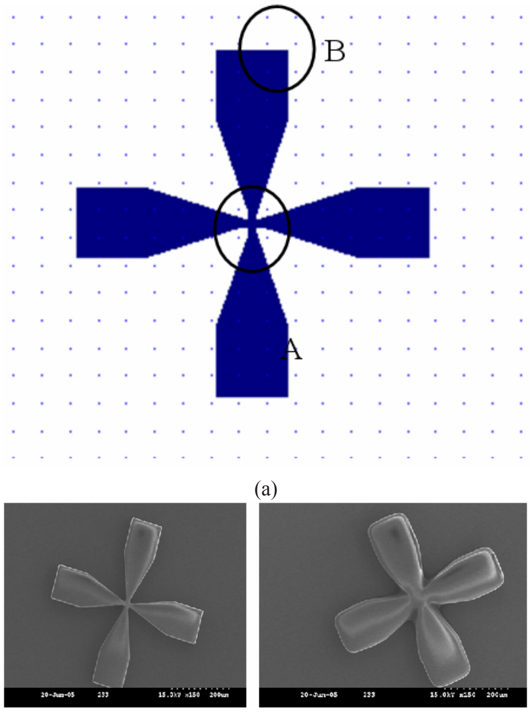


Fig. 2. The path of UV light passing through a diffuser.



(a)

(b) (c)

Fig. 3. Example of diffuser lithography: (a) mask pattern (b) without diffuser (b) with diffuser.

2.3 Exposure depth variation according to pattern size and dose

Tests on various conditions of dose and mask pattern size were performed to investigate the effect of mask pattern size and geometry. Because negative type photoresist is difficult to observe the cross-section of exposed area, positive type photoresist, AZ 9260 was used instead in the test. After spincoating of 45 μm-thick photoresist layer (1500 rpm, 25 sec) on the substrate and soft-baking (110 °C, 10 min), the

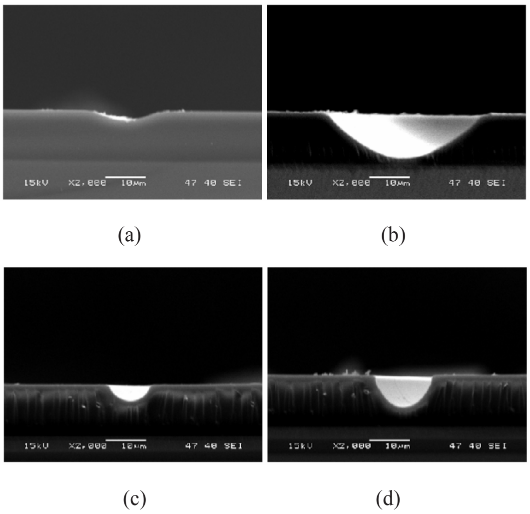


Fig. 4. Cross-sectional SEM images of photoresist under various test conditions: (a) 600 mJ/cm^2, 7-μm-wide line, (b) 600 mJ/cm^2, 20-μm-wide line, (c) 2000 mJ/cm^2, 5-μm-wide line, (d) 2000 mJ/cm^2, 7-μm-wide line.

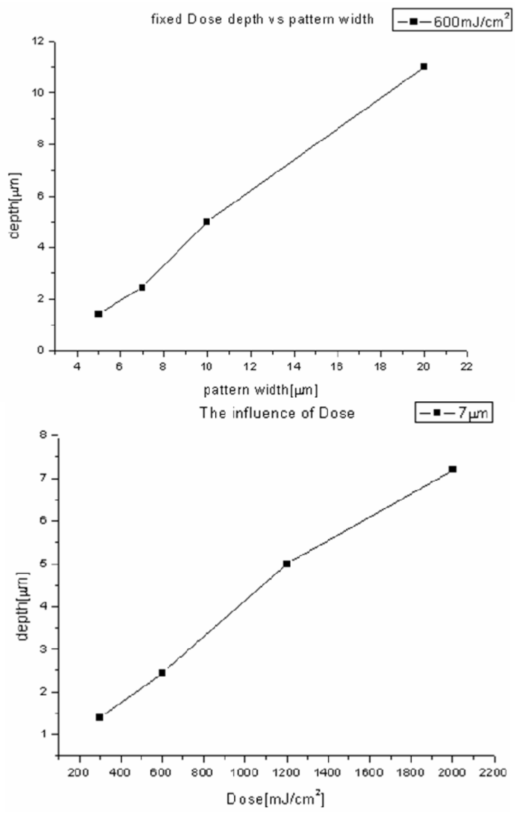


Fig. 5. Variation of exposure depth of diffused light on positive type photoresist: (a) according to the pattern width (dose: 600 mJ/cm^2), and (b) according to dose change (7 μm wide line).

photoresist layer was exposed by UV light through diffuser lithography under various dose and mask pattern size conditions. Doses of 300, 600, 1200 and 2000 mJ/cm^2 were used in tests. Test mask patterns were 5, 7, 10 and 20 μm wide slit lines. Depth of exposed area by diffuser lithography was measured from cross-sectional SEM images of the photoresist layer. It was observed that the depth of exposure depends on the pattern size and geometry of the mask pattern as well as exposure dose. As shown in SEM images of Fig. 4, cross-sectional shapes of exposed area varied according to the dose and pattern size. Fig. 5 shows the variation of the measured exposure depth according to the dose and line width. At higher dose and bigger patterns, we obtained deeper exposure of diffused light on the photoresist. Because varying the dose of light has limitations due to optochemical properties of resist and facility limitation, the size effect will be more effective in changing the exposure depth. This effect of pattern size on the depth of exposure can be used for fabrication of 3-D structures by designing a mask with different pattern sizes.

3. Fabrication of 3 dimensional structure

Fig. 6 shows a schematic diagram of the difference of exposure depth according to the pattern size in the diffuser lithography. When the open part of the metal layer on the Cr-mask is small, the light diffuses and the light cannot reach the bottom of the resist, which means that the cross-linked region would be suspended after developing. On the other hand, when the open pattern of the Cr-mask is big, the UV lights diffused from different point are superposed and finally get enough of a dose to make depth of exposure large enough to reach down to the substrate, which allows it to form a support structure in a negative-type resist.

The current study used test patterns having 1,2,5,10

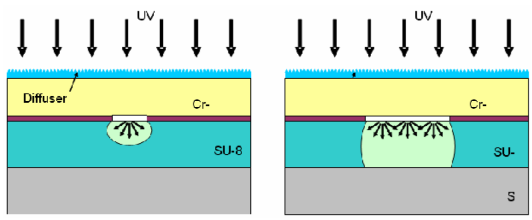


Fig. 6. Size effect of diffuser lithography: (a) at small pattern, (b) at large pattern.

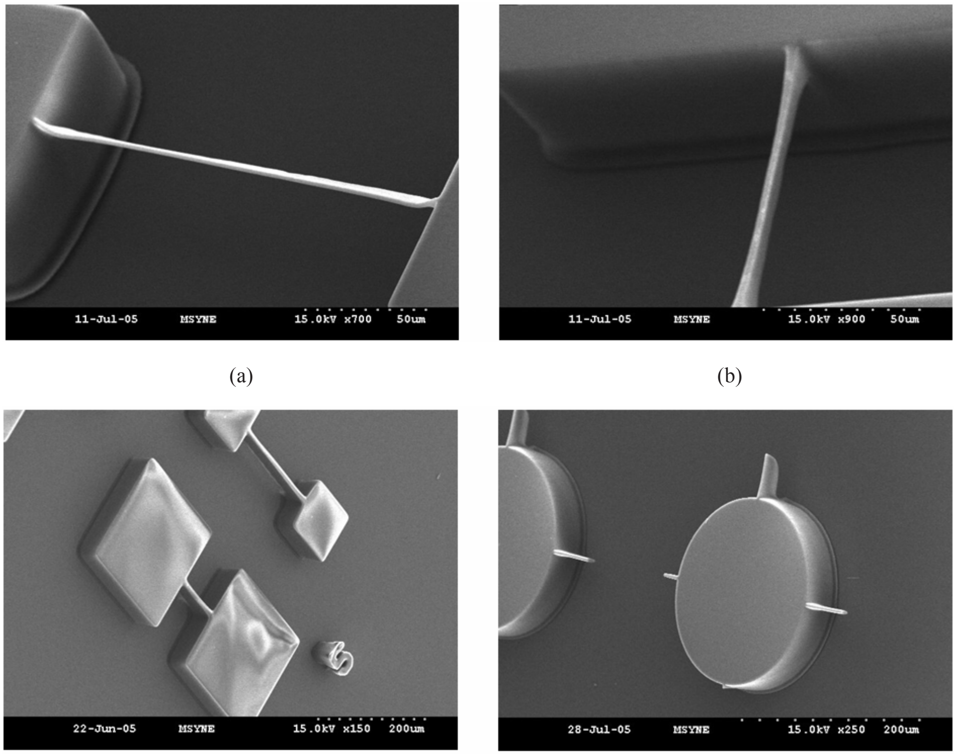


Fig. 7. SEM images of fabricated 3D microstructures: (a) 1 μm-wide bridge, (b) 2 μm-wide bridge, (c) 5 μm-wide bridge, (d) 5 μm-wide cantilever.

μm-wide slits and 100×100, 200×200 μm squares to fabricate free-standing micro structures by diffuser lithography. Fig. 5 shows test patterns in a Cr-mask and SEM photos of the fabricated 3-D micro structures. The thickness of the SU-8 photo-resist layer was 50 μm. After a single exposure using a diffuser film and after development, a slit part in the mask pattern resulted in a free-standing micro-beam and a square part in a support structure due to difference of the exposure depth.

As shown in Fig. 7, a wider slit pattern in the Cr-mask gave a bigger beam width and thickness because more UV-light could go through the wider slit of the Cr-mask. When comparing the width and thickness of the beam structure at the both ends and at middle point of the bridge, the beam had a bigger width and thickness at both ends than in middle point of the bridge structure. This is attributed to geometry effect. In the corner part, where slit and square meet, the number of photons is larger than in the middle of slit because it has more directions for diffused photons to come. In the middle point, apart some distance

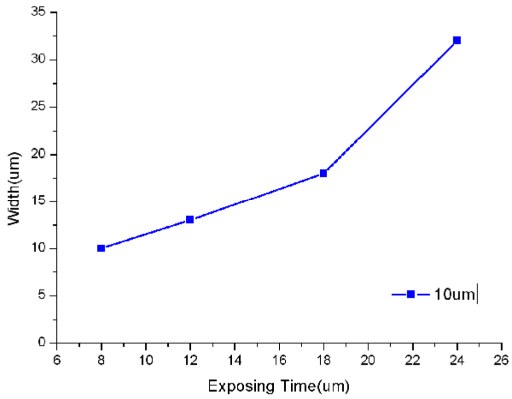


Fig. 8. Variation of width of free-standing beam according to different exposure time.

from the junction of slit and square, the beam width and thickness could be kept uniform. Fig. 8 shows the exposure width according to exposure time. As the exposure time increases, the width increases. Fig. 9 shows the exposure depth measured by beam thickness according to the exposure dose and slit width.

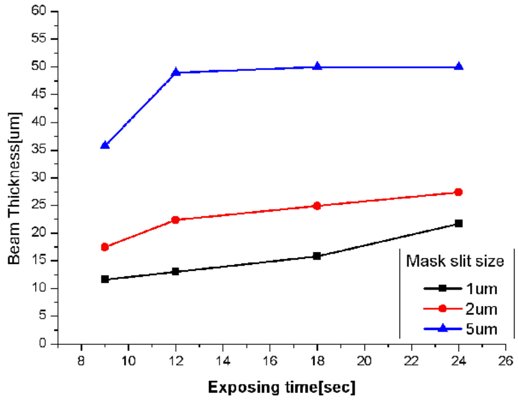


Fig. 9. Variation of thickness of free-standing beam according to the exposure time and slit size.

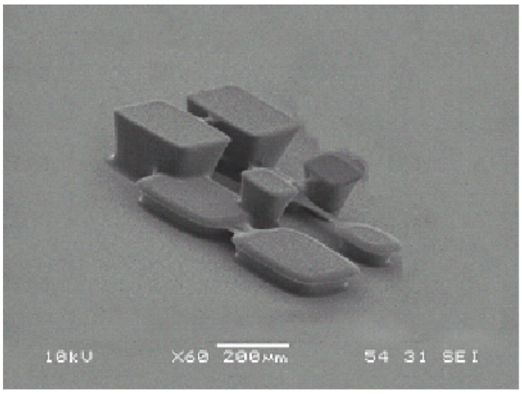


Fig. 10. Complex 3D microstructures fabricated by multi-layer diffuser lithography.

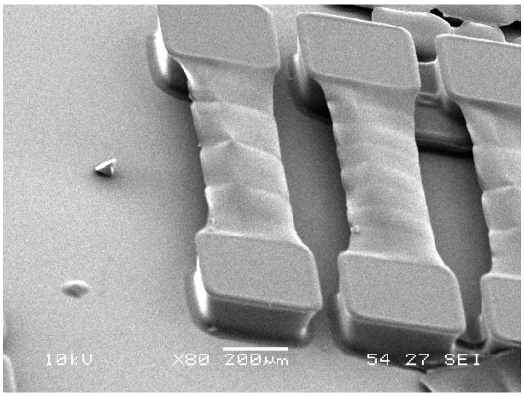


Fig. 11. Freestanding 3-D structures of large width.

The beam thickness increased as the exposure dose and the width of slit increased. It is noteworthy that the geometrical effect of the pattern size showed more effect on the exposure depth than the exposure dose. The test results showed the feasibility of the diffuser lithography for the fabrication of 3-D micro structures by using single exposure process.

Variation of the diffuser lithography could be extended to fabrication of more complex structures. Fig. 10 shows an example of complex structures using diffuser lithography on the multi-layer. Two layers of 50-µm-thick SU-8 were used. A first layer was spin-coated and exposed with a diffuser. Without developing the first layer, a second layer was spin-coated and exposed in the same procedure. Finally, both layers were developed together. Precise alignment between the two layers was not performed because the test was focused on the feasibility.

Fig. 11 shows another prospective example of diffuser lithography. Because freestanding structures can be made only in the narrow slit pattern, very wide structures freestanding from the substrate need other fabrication method. However, by using an array pattern of slits on photomask and diffuser lithography, a very wide freestanding structure can be made as shown in Fig. 11. More study on relations of pattern design of the slit array and lithography parameters will be necessary for the dimension control of the fabricated structures in this case.

4. Conclusions

The feasibility of diffuser lithography on a negative photo-resist was studied for the fabrication of 3-dimensional micro-structures, such as free-standing beams and cantilevers. At negative type photoresist, investigations on exposure depth are necessary because microstructures should be connected to the substrate. The relation of exposure depth with exposure dose and pattern size was studied by cross-sectional analysis of SEM images and by measuring the thickness of a free-standing beam fabricated with diffuser lithography. It was found that pattern geometry has more effect on the exposure depth than does the exposure dose. Therefore, by controlling the geometry of Cr-mask pattern, various free-standing 3-D micro-structures and support structures could be made in a single exposure process. The fabricated 3-D micro structures can be used in a variety of applications including light guide and bio-related devices.

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