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Fabrication of Three-Dimensional Structures by Image Processing

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In this paper, we propose a novel lithography technique for fabricating three-dimensional (3D) structures by applying image processing, which markedly reduces prototyping effort and time, and allows high flexibility for design. We employed two types of lithography techniques that are compatible with image processing: gray-scale lithography and binary optics technique. The former provides high flexibility to 3D figuration of photoresist with only a single exposure step using a special photomask: gray-scale mask. The latter requires several exposure steps, but provides high controllability of resist height and low surface roughness. We prototyped several structures such as a Fresnel lens profile using two types of photoresists: AZ-p4620 and SU-8. In particular, SU-8 allowed distinctly tall 3D structures with high aspect figures.

1. Introduction

In the field of Bio-MEMS (Micro-Electro-Mechanical System) and Optical-MEMS, sensor devices have a crucial role as an interface. 3D structures such as lens and capillary are the main components of sensor devices, and their fabrication techniques are also significant factors affecting their industrial applications. Various micromachining techniques have recently been developed to accommodate various applications and amount of production. Generally, in the development stage of the product, it is crucial to reduce the number of processing steps and time from designing to prototyping. A higher frequency of prototyping is critical.

In this study, a novel fabrication technique for a 3D microstructure was developed by incorporating image processing into lithography. It simplifies the generation of a photomask pattern considerably, and provides a high flexibility of design by applying various functions that are available in image processing. We utilized an image processing software, “Adobe Photoshop”, which is commonly used and contains many beneficial functions for mask pattern generation. For the subsequent fabrication processes, two different lithography techniques, namely, gray-scale lithography and the use of binary optics, were em-

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ployed and compared. In this paper, the compatibility of 3D fabrication and image processing is mentioned first, and then the details of the two types of lithography process and the results of the test fabrication are described.

2. Three-Dimensional Fabrication and Image Processing

In the lithography process of a conventional semiconductor industry, monochrome (opaque or transparent) patterns on a photomask are transferred onto photoresist to provide a selectivity to subsequent processes: to etch a substrate or a metal layer just under the photoresist layer or not, to dope ions or not, and so on. 3D structures can also be fabricated by repeating the conventional lithography and etching processes, but it requires a high accuracy for mask alignment. However, it is not suitable for a small lot or on-demand production because much effort and time are required for prototyping.

Performing variable-UV-intensity exposure for a thick photoresist layer enables fast prototyping. Briefly, the structures are formed directly on a photoresist layer, and the structures can be transferred to a substrate material. Reactive ion etching (RIE) transfers the resist structures vertically down to the substrate at a very high accuracy. Alternatively, casting the resist structure to PDMS has also been developed as a common technique.[1]

A problem that may occur during the first step of the process is the generation of a photomask pattern that accommodates an aimed structure figuration. Since the most common GDS-II format has been optimized for circuit pattern, it is difficult to apply it to 3D fabrication, because the aimed height of the structure and mask data can hardly be correlated.

Bitmap data by image processing can conform to 3D fabrication. For instance, gray-scale value can correspond to the aimed height of the structures. Figure 1 shows a procedure of mask pattern generation for a Fresnel lens profile. A cross-sectional profile of the lens is calculated by a C-code program, and saved as an 8-bit gray-scale image. Then, the image is converted into a polar coordinate by using the filter function of Adobe

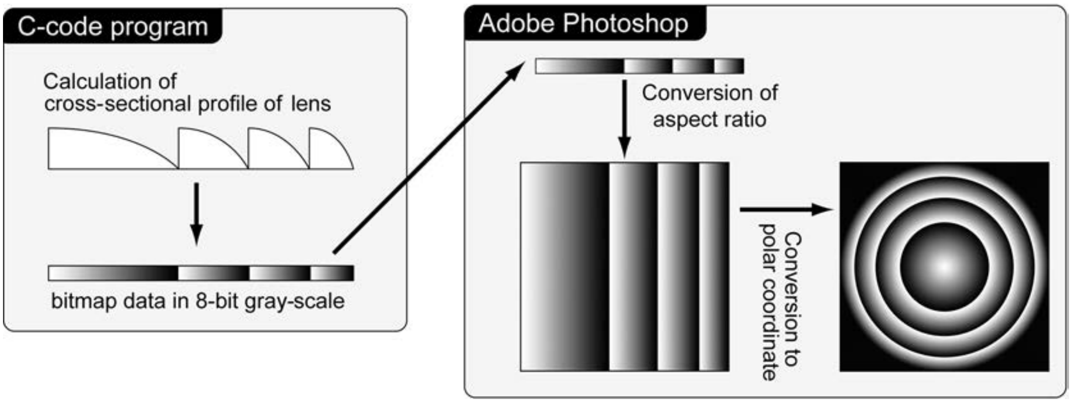


Fig. 1. Concept of mask pattern generation with image processing. The cross-sectional profile of a lens calculated in C-code program is converted into a gray-scale mask pattern using several image processing functions.

Photoshop. The first stage of the mask pattern generation is completed at this stage. Then, the image is transferred again into the final mask data that are suitable for each lithography process, as described hereinafter.

3. Experimental Methods of Gray-Scale Lithography

Gray-scale lithography is a relatively new technique for fabricating 3D resist structures by changing the exposure intensity of UV light with a special photomask, "gray-scale mask", which has not only the opaque or transparent regions but also the "gray zone" of transmittance of the UV light.[2,3] Gray-scale lithography is also called one-step lithography or gray-tone lithography. It requires only a single exposure step, and provides multiple 3D structures at once. It is necessary to accurately control gray-scale level and exposure intensity according to the aimed structures. Because resist height corresponds to the transmittance of the mask directly determined by the gray scale of the mask image, gray-scale lithography is very suitable for image processing.

In general, three kinds of mask are known and used as gray-scale mask. HEBS (high-energy beam-sensitive) glass mask has been reported as the most advanced gray-scale mask with an extremely high accuracy: less than 0.1 μm for horizontal resolution, more than 256 gray-scale levels.[4-6] The HEBS glass mask is supplied exclusively by Canyon Material, Inc. Its surface is chemically treated, where opaque molecules emerge when a high-energy beam such as EB (electron beam) illuminates. Its transmittance changes exactly according to intensity with a high linearity.

Emulsion glass and films are also used as gray-scale mask.[7-9] They can be fabricated in a very short time and easily processed, however, they are less accurate than the HEBS glass mask. According to the literature, the horizontal resolutions of both are 20 μm when used as gray-scale mask, and the available number of gray-scale levels is about 10–20.

The last mask, a half-tone chrome mask, that we employed is described in the next section.

3.1 *Half-tone chrome mask and mask pattern generation*

In this study, a conventional chrome mask was employed as gray-scale mask. A chrome mask is widely used and compatible with various lithography systems. In particular, only a chrome mask with a quartz substrate can be applied to a recent projection stepper with a deep-UV light source.

Since chromium on a mask takes only two states of "on" or "off," a pseudo-gray-scale of a half-tone pattern was attached on the mask. Adobe Photoshop provides various filters of image processing, including a "half-tone filter". The filter converts the original 8-bit gray-scale image into a half-tone of the monochrome two-value mode in a burst, even if the image contains a complex pattern. A half-tone pattern expresses a gray scale by changing the diameters of circles located in a lattice with uniform intervals, as shown in Fig. 2. With a bitmap format, the circles consist of many square pixels as a mosaic tile picture as shown in Fig. 3, and the diameter of a circle changes discontinuously because the number of the pixels is finite. For this reason, the available number of gray-scale levels is limited and also becomes discontinuous. A deficient interval of circles causes posterization (or tone jump),

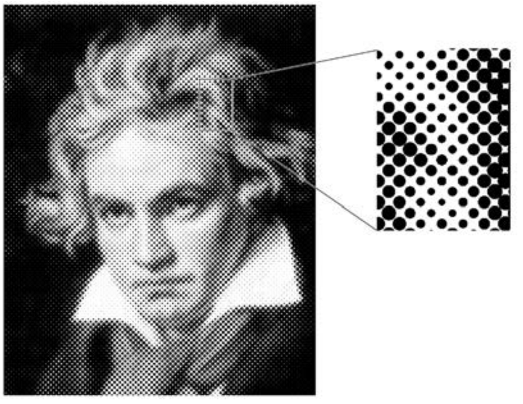


Fig. 2. Half-tone pattern that can easily be converted from 8-bit gray-scale image using "half-tone filter." The state of the image is the monochrome 2-value mode.

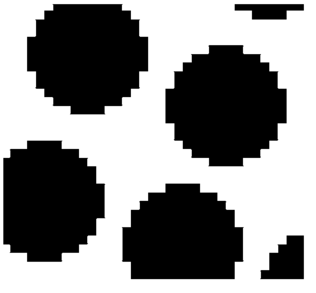


Fig. 3. Zoomed half-tone circles consisting of many square pixels as mosaic tile picture.

as shown in Fig. 4. This image contains only 13 gray-scale levels, where the interval is set to 8 pixels. On the contrary, too large an interval of circles decreases horizontal resolution. In other words, a trade-off occurs between horizontal resolution and vertical resolution. It is necessary to choose the appropriate interval of circles to balance both resolutions according to the targeted size and shape. In this work, the interval of the circles was optimized at 17 pixels (1.7 μm on the mask; determined by subsequent EB lithography), and the number of available gray-scale levels became about 40.

A schematic flow of the mask fabrication is shown in Fig. 5(a). An EB resist (ZEP-520) was spin-coated on a plane chrome mask with a thickness of 0.4 μm. The mask patterns were transferred on the mask using an EB lithography system ('Beam Draw,' Tokyo Technology). This equipment is based on FE-SEM ('S-4300SE, 'HITACHI), and has some plug-in modules such as an EB amplifier and a stage controller. The maximum resolution for a single field is 10,000 pixels square, and the bitmap data of the monochrome two-value mode is available. After EB lithography and development, the pattern on EB resist was transferred to a chromium layer by RIE. A gas mixture of CCl_4 and O_2 (mixture ratio = 5:1) was used as the etching gas. Figure 6 shows the completed chrome mask.

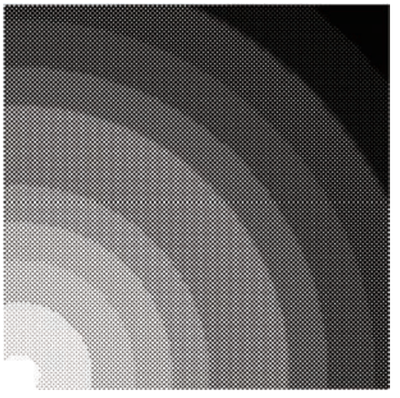


Fig. 4. Posterization (tone jump) caused by lack of interval of half-tone circles. This image contains only 13 gray-scale levels with an interval of 8 pixels.

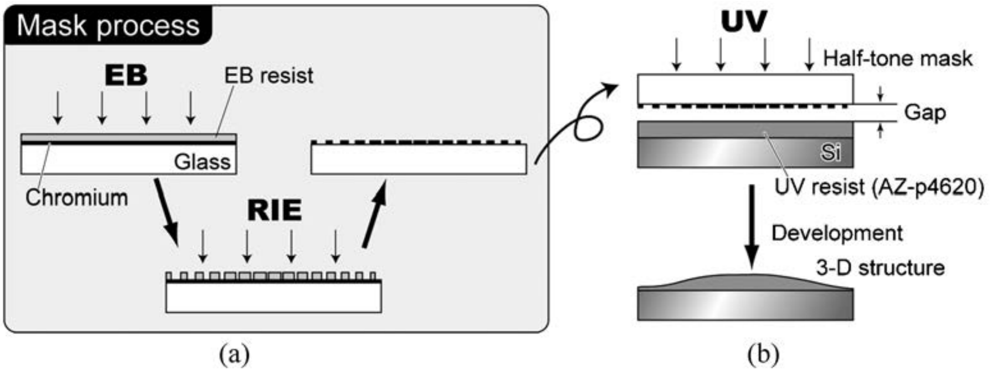


Fig. 5. (a) Fabrication of half-tone chrome mask and (b) subsequent lithography: defocus exposure method.

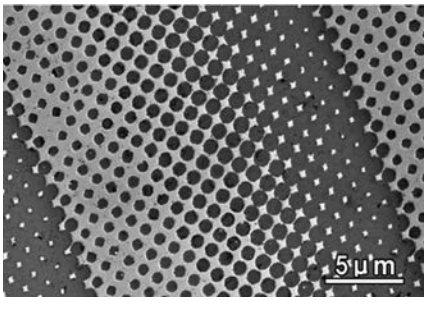


Fig. 6. SEM image of completed half-tone chrome mask of Fresnel lens pattern.

3.2 *Defocus exposure method and process conditions*

Proximity UV exposure was performed using a mask aligner ('LA-310k' Nanometric Technology Inc.) onto positive tone photoresist of AZ-p4620 that was spin-coated with a thickness of 10 μm on a silicon wafer. The reason for utilizing the proximity method is not to protect the photomask from contamination or abrasion, but to purposely give a defocus to blur the half-tone pattern. Therefore, a relatively large gap was produced between the mask and the resist surface as shown in Fig. 5(b). The optimum defocus amount is dependent on a half-tone interval and parallelism of the light source.

With a half-tone interval of 1.7 μm, the defocus amount was optimized at 80 μm, where the half-tone pattern was sufficiently blurred. The intensity of the UV light should also be optimized to gain a wide range of gray scale. A positive-tone photoresist has a characteristic versus UV intensity that consists of two portions: linear portion and saturating portion. Intensity at the 100% transparent area of the mask should be equal to the border of the two portions. In this study, the intensity was optimized using a "gray-scale test pattern", as shown in Fig. 7. The widest effective gray-scale range of 20–90% was obtained at a UV intensity of 2.2 J/cm^2. The relationship between the gray-scale value and the resist depth measured by DEKTAK is shown in Fig. 8. This curve can be used to compensate the relationship at the generation of gray-scale image using a tone-curve filter.

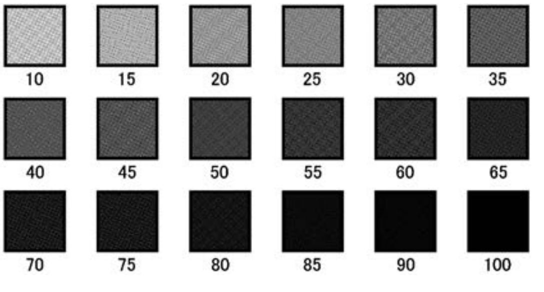


Fig. 7. Gray-scale test pattern. Numbers for each gray box indicate gray-scale value in percentage.

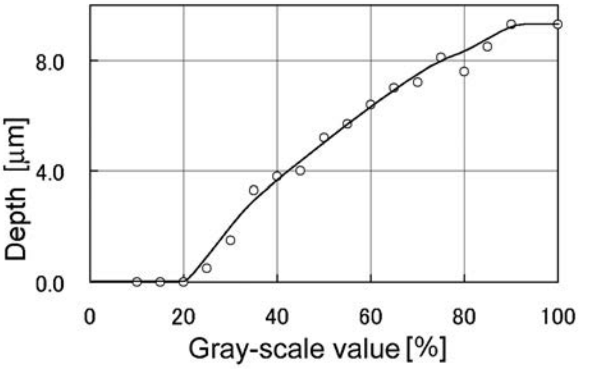


Fig. 8. Relationship between gray-scale value and resist depth measured using gray-scale test pattern shown in Fig. 7.

3.3 *Substrate penetration method*

The negative tone photoresist of SU-8 has recently been attracting attention as a material for sensor devices, because it provides high aspect structures with a height of more than 500 mm.[10] However, gray-scale lithography cannot be applied for SU-8 by a conventional exposure method SU-8 firms from the exposed surface side, and the unexposed area dissolves during the development process.

Substrate penetration method enables the application of gray-scale lithography to SU-8.[11] As shown in Fig. 9, UV light irradiates the SU-8 layer from the backside of a substrate. A thin glass plate of 150 μm was used as a substrate to allow UV light to penetrate it. This method allows a relatively large surface roughness and tolerance of height so long as the initial thickness is lager than the maximum height of the aimed structure. Consequently, a much easier coating process can be used, and an initial thickness of more than 500 μm can easily be obtained, while the initial thickness of a positive tone photoresist is restricted by spin coating.

In this process, it is also necessary to blur the half-tone. The defocus amount can be controlled by changing the thickness of the glass plate or the gap between the plate and the mask. The optimum defocus amount of the optical path from the bottom surface of the mask to the SU-8 layer was obtained at 450 μm.

4. Experimental Method Using Binary Optics

4.1 *General information on binary optics technique*

Gray-scale lithography requires a high accuracy for light intensity and transmission rate at each gray-scale level to control resist height. The use of binary optics is an alternative lithographic technique for fabricating 3D structures with a higher controllability of resist height.[12] Complex structures can be fabricated using binary optics, where exposure and etching processes are repeated, replacing the photomasks at each cycle. Thus, the power-of-two selectivity is provided by doubling the etching depth also at each cycle at the same time, such that the N cycles provide 2^N levels of a structure.

In this study, binary optics were used in the substrate penetration method. Since the height of SU-8 changes in relation to a given exposure energy, the power-of-two levels can also be obtained by doubling the exposure energy at each cycle. Figure 10 shows the case of three cycles. The finest pattern is exposed at first, then the second finest pattern of the doubled pitch is exposed also with a doubled time after alignment of the mask, and finally a four-fold energy exposure is performed with a pattern of a four-fold pitch. A structure with 8 levels is obtained by this procedure. More cycles will make the surface smoother, but it always requires only a single development process.

4.2 *Binary optics technique by image processing*

The generation of a mask pattern for the binary optics technique is difficult, particularly with a complex pattern, because the patterns must correspond to each exposure cycle. In this study, we developed a new method of mask pattern generation for the binary optics technique by image processing.

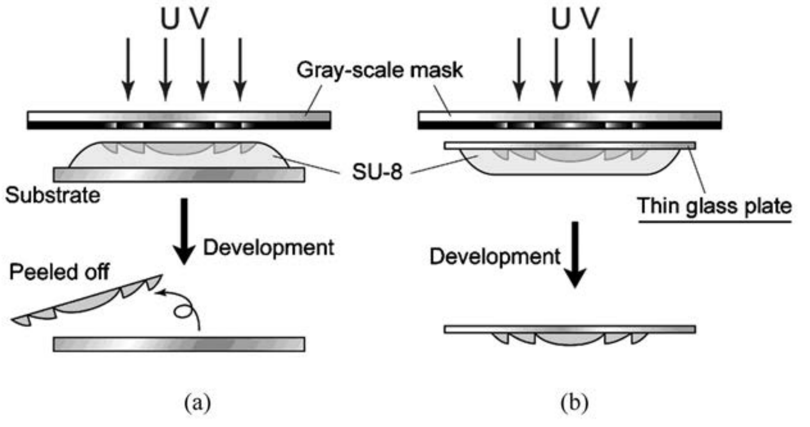


Fig. 9. Gray-scale lithography for SU-8: (a) case of failure with conventional exposure method; (b) substrate penetration method. UV light penetrates the thin glass plate and SU-8 does not peel.

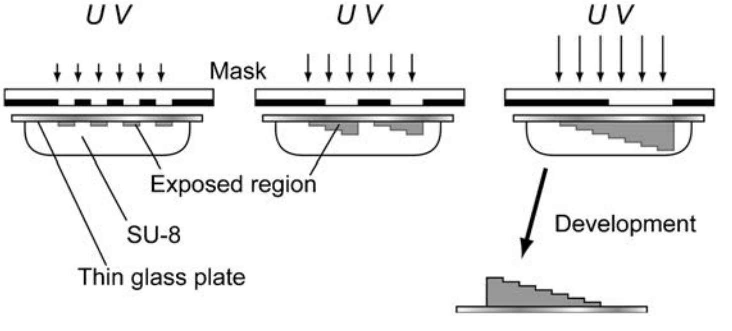


Fig. 10. Binary optics technique of three cycles and substrate penetration method. Only a single development process is required.

The mask pattern generation procedure is shown in Fig. 11, where all processes were performed using Adobe Photoshop. At first, the number of gray-scale levels is reduced to an aimed number which is determined by cycle time, that is, the constructive use of posterization. Then, the patterns for each mask are extracted from the original gray-scale image using a selection tool that picks up all the regions of a certain gray-scale level from a whole image field. Table 1 shows the allocation of 8 gray-scale levels for the three masks, where each mask behaves just as a “bit” of “binary notation.” Opaque and transparent states alter per 1, 2 and 4 levels for masks A, B and C, respectively. The mask was fabricated by an emulsion glass mask using a reduction projector for a photomask (‘MM-605,’ Nanometric Technology Inc.) and OHP film. A finer mask can be fabricated using a chrome mask and EB lithography.

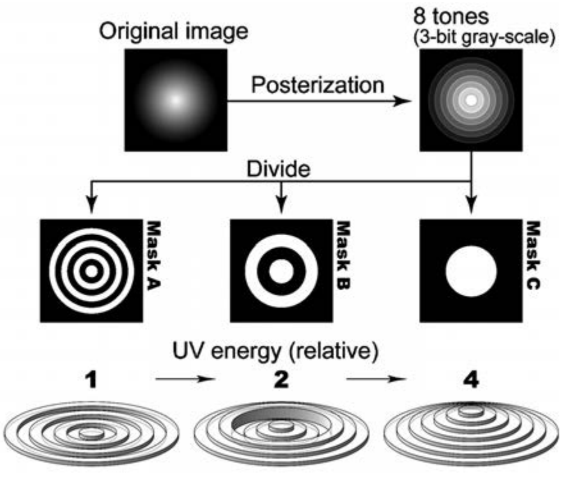


Fig. 11. Division of pattern from original gray-scale image into each mask using "tone extraction" tool after reducing tones. All of these processes can also be perfomed by image processing.

Table 1
Schematic of dividing eight tones to three masks.

Tone	0	1	2	3	4	5	6	7
Mask A		✓		✓		✓		✓
Mask B			✓	✓			✓	✓
Mask C					✓	✓	✓	✓

4.3 *Exposure process of binary optics technique*

Figure 12 shows the relationship between resist height and total exposure time. Resist height saturated gradually after the exposure time exceeded 2 s. It was considered that the higher the resist, the more UV light was absorbed in the SU-8 layer and the more contrast decreased. On the basis of this result, structures for test fabrication were designed.

Exposure of several steps was performed by the substrate penetration method as shown in Figure 10 using a mask aligner ('LA-310k' Nanometric Technology Inc.). A glass plate of 150 μm thick was used as a substrate on which a crisscross alignment mark was preliminarily attached by aluminum evaporation.

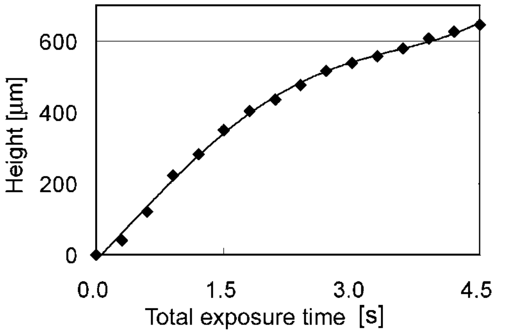


Fig. 12. Relationship between resist height and total exposure time.

5. Experimental Results and Discussion

5.1 *Gray-scale lithography for positive resist*

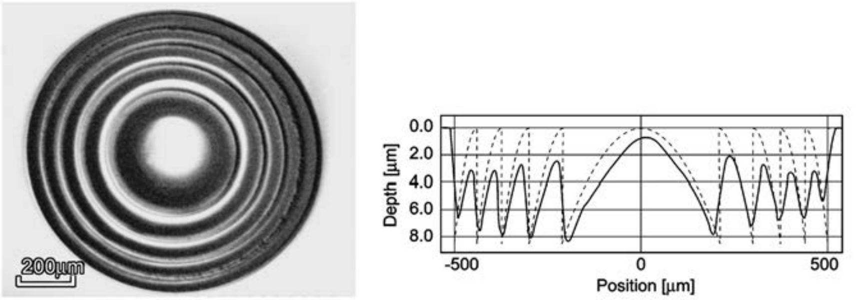
By gray-scale lithography and defocus exposure, a Fresnel lens profile was fabricated on AZ-p4620. The SEM photograph and the measurement results by DEKTAK are shown in Fig. 13. A smooth surface with a roughness of less than 0.5 μm in Ra was obtained. Resist height changed continuously according to the gray-scale value.

A sharp edge was rounded off with a diameter of 8 μm, where the mask image had a high contrast pattern. This is the result of defocus whose amount is obviously defined by the half-tone condition of the interval of circles, and also the size of a pixel in the EB lithography. Defocus amount can be decreased by reducing the half-tone interval, but the gray-scale levels may become insufficient. According to the targeted size and shape, the appropriate interval should be chosen. Linking plural fields on EB lithography increases total bitmap fields and allows high resolution and sufficient gray-scale values. Reduction-projection steppers with deep UV may also improve resolution.

5.2 *Gray-scale lithography for negative resist*

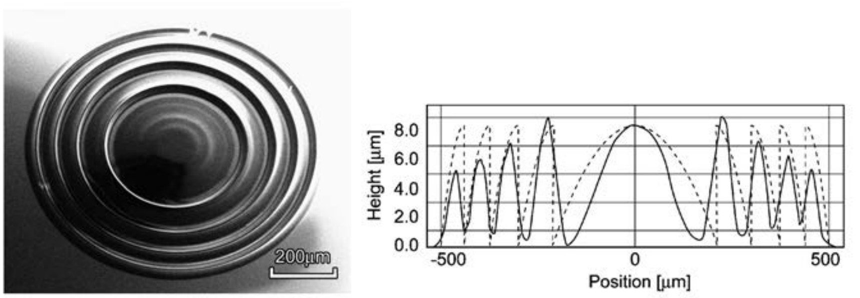
By gray-scale lithography and substrate penetration, Fresnel lens profile were fabricated as shown in Figure 14. The maximum height was 8 μm, and the exposure energy was optimized at 122 mj/cm^2 so that the maximum height is equal to each aimed height. The surface roughness at an approximately horizontal area was about 0.15 μm in Ra. As shown in Fig. 14(b), the error of the configuration was intensive particularly at the region where the height changes drastically and the UV intensity was mingled with the neighbor by defocus. The walls desired to be perpendicular tilted to 20 degrees at maximum, and the edges were also rounded off with a diameter of 4 μm. Although the reproducibility of resist heights by gray-scale test pattern was acceptable, the middle height region of the Fresnel lens, particularly around 50% of gray-scale, had comparatively large error. It is considered that the mingling of UV intensity by defocus mainly affected the middle range where the resist had a high sensitivity. This problem is expected to be corrected not only by the feedback of the relationship between gray-scale and resist height but also by compensating the undesirable and complex modification of the height caused by defocus.

A tall structure, which is hardly achieved with positive resist, was fabricated with SU-8 by the substrate penetration method. Figure 15 shows a tall fly-eye lens profile. The



(a) (b)

Fig. 13. Fresnel lens profile on AZ-p4620 by gray-scale lithography and defocus exposure: (a) SEM image, (b) measurement result by DEKTAK. A dotted line shows an aimed profile.



(a) (b)

Fig. 14. Fresnel lens profile on SU-8 by gray-scale lithography and substrate penetration method: (a) SEM images, (b) measurement result by DEKTAK. A dotted line shows an aimed profile.

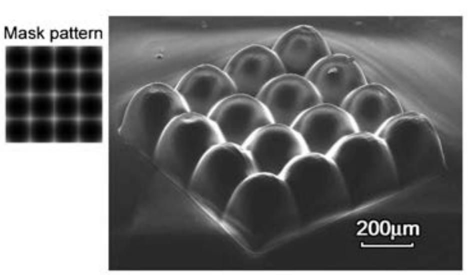


Fig. 15. A tall fly-eye lens profile.

maximum height was 300 μm, and the exposure energy was 720 mj/cm^2. Although the gray-scale was quantized into only 40 levels for this high aspect structure where height would be anticipated to change discontinuously, a very smooth surface was obtained. It is considered that defocus exposure made the UV intensity continuous, and provided the smooth surface. Naturally, resolution decreased with increasing height. According to a structure by the gray-scale test pattern, resolutions were approximately 72, 49 and 37 μm for the heights of 295, 213 and 110 μm, respectively.

Although this technique is not suitable for perpendicular walls in a tall profile, defocus exposure effectively makes a smooth surface. Therefore, this technique can be applied for fabricating a practicable lens with a single curved surface. With these accuracies and process conditions at the present stage, this technique can be applied to nonimaging lenses, such as a microlens array directly mounted on a CCD chip where each lens simply correct light to a single pixel.

5.3 *Binary optics technique*

Figure 16 shows the fabricated structures of a coin-surface profile and a whirlpool-like structure using binary optics technique and the substrate penetration method. The maximum height was 250 μm and the surface roughness was 1.2 μm in Ra. The horizontal resolution was 20 μm, which was mainly restricted by the capability of the emulsion photomask. However, in comparison with gray-scale lithography, this technique provides a much higher resolution because no intentional defocus is required.

With these process conditions, the use of this method is limited for application with a relatively low accuracy such as in microcapillaries. The resolution of the configuration can be improved using a chrome mask, a higher parallelism of light source, and a projection exposure system that focuses the mask pattern in the resist layer.

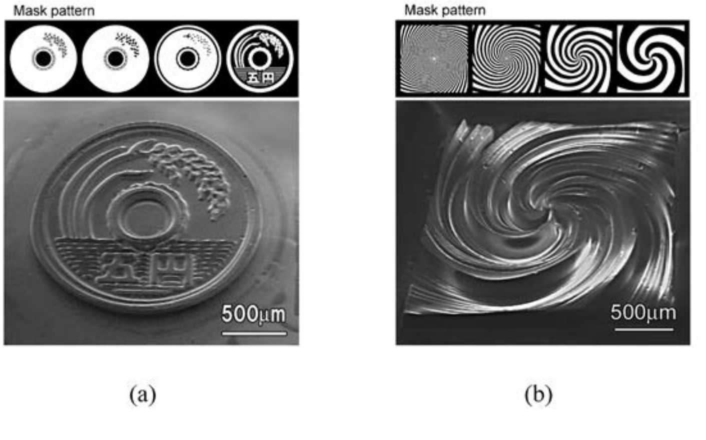


Fig. 16. SEM images of SU-8 structures by binary optics technique with four steps of exposure and mask patterns above them that were also generated by Adobe Photoshop: (a) Japanese coin and (b) whirlpool-like structure.

6. Conclusion

Novel 3D fabricating methods of gray-scale lithography and the use of binary optics were demonstrated with image processing that reduced time and effort of mask pattern generation. Through these methods, prototyping can be performed much easier and faster, which is significant for small-lot and on-demand productions.

In gray-scale lithography with half-tone mask and defocus exposure, the resolutions were restricted according to resist height. On the other hand, very smooth surfaces were obtained by defocus exposure. Furthermore, the substrate penetration method allowed the fabrication of an extremely thick SU-8 layer of more than 300 mm and very tall structures that were impossible to fabricate by conventional gray-scale lithography with positive resist. Although a problem of the controllability of a resist profile still remains at this stage, it is considered that it can be improved by compensating the undesirable modification of the UV intensity caused by defocusexposure. Therefore, this method is expected to be applied for the actual fabrication of optical devices, such as a tall lens with a high NA or a tall fly-eye lens among others.

Binary optics technique using SU-8 requires several exposure steps and yields stepwise surface. Instead, resolutions can be much highly improved compared with gray-scale lithography using a chrome mask because no intended defocus is needed, and the controllability of resist height is also better. This method is expected to be utilized for fabricating microcapillaries and diffractive optical devices.

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