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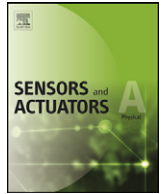


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Photolithography system with liquid crystal display as active gray-tone mask for 3D structuring of photoresist

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ABSTRACT

Layer manufacturing is generally utilized for the development of micro electromechanical systems (MEMS) and micro total analysis systems (μ TAS). However, the preparation of multiple masks and repetitive exposure procedure prevents the rapid fabrication of 3D microstructures. An active mask fabrication by using a liquid crystal display (LCD) as an electrically controllable photomask can simplify the layer manufacturing process. In addition, the gray-tone photolithography is available by using LCD lithography system, since the exposure distribution is easily controlled by an LCD. We have developed the LCD mask exposure system by using UV light source. Firstly, the patterning characteristics of the UV photoresist by exposing line and space patterns are evaluated, and then, a fundamental step shape is produced in order to verify the feasibility of gray-tone UV photolithography by using LCD. A shape with a different height can be fabricated without any repetitive exposure and development procedures. Finally, we confirmed the high patterning resolution such as 11 μ m using check patterns and fabricated 3D step shapes by using the LCD as a gray-scale photomask.

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1. Introduction

Rapid and accurate fabrications of 3D microstructures have been applied to the development of devices for microelectromechanical systems (MEMS) and micro total analysis systems (μ TAS) [1–3]. The miniaturized systems are generally fabricated using etching and deposition procedures [4]. However, multiple photomasks and a time-consuming repetitive exposure procedure are then required to fabricate the complex microstructures.

Maskless lithography that utilizes a liquid crystal device (LCD) or a digital micromirror device (DMD) [5,6] as an electrically controllable spatial light modulator (SLM) has been developed in order to simplify the conventional photolithography [7–10]. A computer-generated photomask serves as a reconfigurable mask in the lithography system. A mask alignment procedure is unnecessary because the position of the photomask is fixed. Active-mask photolithography makes the pattern alignment precise at the exposure plane and allows rapid fabrication of microstructures as well. Gray-tone photolithography is also possible by using a gray-scale

image as the computer-generated photomask. The 3D structure can be fabricated without repetitive exposure by using a gray-tone photomask [11–14]. The intensity of the gray-tone exposure can be easily calibrated by controlling the gray level of the SLM to be used as a photomask. Gray-tone photolithography could be very useful for manufacturing MEMS devices with 3D features such as microlens arrays and microchannels with tapered shapes.

Comparing the typical SLMs performance in terms of utilization in maskless lithography, the LCD has a disadvantage in optical efficiency rather than a DMD. The optical efficiency of a DMD is as high as 61% in the pixel level [5]. Therefore, a DMD based projection system is superior in terms of preventing the absorption of incident light with high power and short wavelength. On the contrary, the LCD is advantageous for high-resolution lithography. The minimum pixel size of commercially available LCDs is as small as 9.5 μ m, compared to that of the DMD pixel, 17 μ m [5,15]. Thus, an LCD based system is superior in terms of achieving high-resolution exposure by applying a low optical power projection system. In addition, the LCD based maskless lithography system has been developed typically using visible light sources in order to prevent its damage caused by UV light irradiation [16,17]. Fasari et al. have proposed a stereolithography system employing LCD as an adaptive electro-

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Table 1
Specification of LCD with microlens array

Screen size	18.5 mm × 13.9 mm
Pixel size	18 μm × 18 μm
Number of pixels	1028 × 772
NA	>54%
Microlens	Built-in

optic mask. They have pointed out that wavelengths longer than 350 nm do not cause any damage to the LCD [8].

This paper describes an LCD based high-resolution maskless lithography system using a UV light source of 365 nm without causing any damage. The system proposed here will provide a 3D microfabrication technique for structuring commercially available near-UV photoresists. To realize such a system, the optimum optical configuration of the lithography system was investigated. The low optical power density irradiation helped maintain a high mask contrast and improve the mask stability under UV exposure when the incident light passing through the LCD mask. The reduction optics increased the optical power density and improved the resolution at the exposure plane. By using the developed lithography system, we demonstrate the ability of the system with the LCD as an active mask for patterning photoresists with high resolution as small as 11 μm, and the possibility for fabricating 3D microstructures by employing the LCD as a gray-scale photomask.

2. Design of the LCD lithography system

We developed a photolithography system with an LCD as an active mask using a high-pressure mercury lamp as an ultraviolet (UV) light source in order to fabricate microstructures. The maximum exposure area was 2.8 mm × 2.1 mm in our lithography system with an 85% optical reduction. Although the exposure area depends on the reduction ratio and panel size of the LCD, the reduction in the designed system is limited to values less than 85% due to considerable distortion and other aberrations. The optical configuration of the LCD lithography system was determined from the following experiments. First, the contrast of the LCD mask to the UV light was evaluated as a function of the irradiated light intensity. Next, an appropriate incident angle for the UV light on the LCD mask was investigated in order to obtain the highest contrast in the system. We also examined the optical aberrations on the image plane of the system with the LCD mask in order to improve the resolution.

2.1. Contrast of LCD mask against UV light of 365 nm

The specifications of the monochrome LCD (Seiko Epson Co., L3P09X-25G01) used as the active mask are described in Table 1. The LCD is categorized as an active matrix type of twisted nematic. Polysilicon thin-film transistors (TFTs) are used as the switching elements for the pixels in the LCD. The switching speed of the TFT LCD was more than 50 ms [18]. The UV light irradiation on the TFT substrate part should be reduced in order to avoid damaging the LCD [8,17] under UV exposure. We selected an LCD integrated with a microlens array, resulting in a high numerical aperture (NA) of more than 54%, which is greater than that of a conventional LCD. This type of LCD has an advantage: the microlens decreases the UV light irradiation on the TFT substrate part, which in turn reduces the above-mentioned problems to a minimum. In addition, the loss of UV light through the LCD mask effectively decreases.

The contrast of the LCD mask to the UV light centered at 365 nm, obtained using a high-pressure mercury lamp (Ushio Inc., SX-UI 500HQ) through an optical filter, was investigated by varying the irradiation conditions with the basic configu-

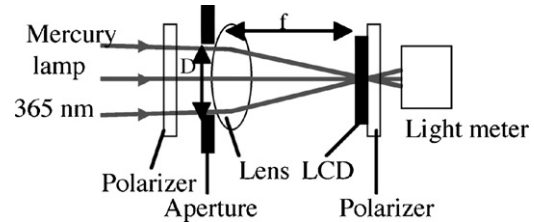


Fig. 1. Experimental setup for evaluation of LCD mask contrast. A polarizer changes the incident light from the mercury lamp into linearly polarized light. The polarized light is focused by a lens with a variable aperture and then passed through the LCD mask. A pair of polarizers is placed in the orthogonal polarization direction at the front and back of the LCD mask.

ration, as shown in Fig. 1. Two important factors, the light intensity and incident angle, are considered since they would affect the LCD mask contrast. The contrast is defined as I_{255}/I_0 ; I_{255} and I_0 denote the transmitted light intensity when LCD mask gray levels are 255 (open) and 0 (close), respectively.

Fig. 2 shows the influence of the light intensity on the LCD mask contrast as a function of the F -number. The F -number ($F = f/D$) expresses the diameter of the entrance pupil in terms of the effective focal length of the lens; in simpler terms, the F -number is the focal length (f) divided by the aperture diameter (D) [19]. It expresses the divergence angle of focused light rays, that is, an increase in the F -number corresponds to a decrease in the divergence angle. The mask contrast increased slightly with the light intensity decreasing below 150 mW/cm². In order to maintain a high contrast, excess UV irradiation is undesirable because it causes damage to the LCD [8,16,17]. The mask contrast also increased markedly with the F -number. At a light intensity of 150 mW/cm², the mask contrast at $F = 6.3$ was approximately three times larger than that at $F = 2.7$. These results suggest that the effect of the divergence angle (corresponding to the F -number) on the improvement in the mask contrast was greater than that of the light intensity. LCD mask contrast is shown in Fig. 3. The maximum contrast is regulated by the extinction ratio of the polarizer, i.e., 0.01 at the wavelength of 365 nm. The contrast was estimated to be high, above 150, within a tilt angle of 5°. From these results, it was confirmed

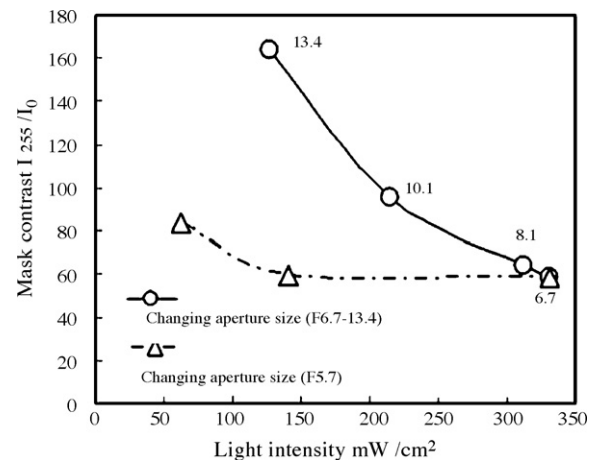


Fig. 2. Influence of light intensity on LCD mask contrast as a function of F -number. An F -number of 5.7 corresponds to a divergence angle with respect to an optical axis, which is a maximum value in this experiment. The data (denoted by a Δ symbol) were obtained by changing the optical density of a neutral density (ND) filter at the same aperture diameter in order to change only the light intensity. On the other hand, the LCD mask contrast (denoted by a $\circ$ symbol) was measured at varying F -numbers for different aperture diameters.

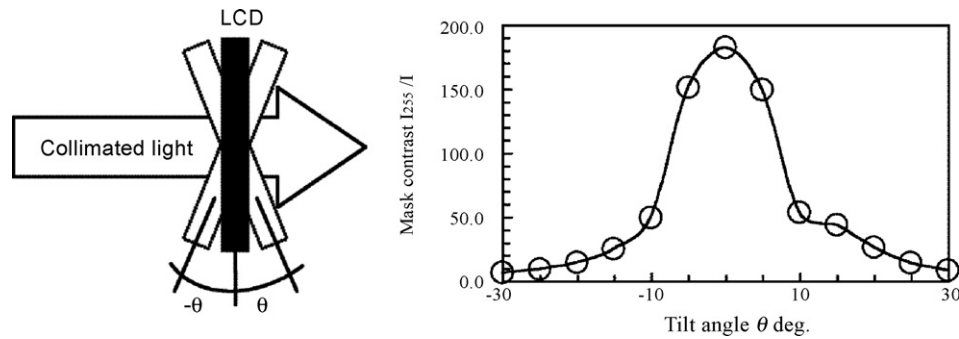


Fig. 3. LCD mask contrast at varying tilt angles θ of collimated light. The LCD mask contrast measured at varying the tilt angles θ of collimated light irradiated onto the LCD in order to evaluate the characteristics of the contrast in oblique illumination.

that the incident angle on the LCD should be less than 5° . Therefore, the perpendicular incident direction to the LCD mask with a well-collimated incident light is required to obtain a high contrast.

2.2. Optical design of UV lithography system with LCD active mask

As mentioned above, a pattern projection system with a high-contrast LCD active mask was achieved by using low-intensity, collimated UV light source that illuminates the LCD mask perpendicularly. We designed the optical configuration of the UV lithography system with an LCD active mask as shown in Fig. 4. The LCD mask can be placed just behind the mercury lamp, and consequently, will be illuminated by well-collimated light of a relatively low intensity. The energy density of the light passing through the LCD mask can be intensified on the exposure plane by the reduction optical system. This will enable patterning using conventional UV-sensitive photoresists. Moreover, the pattern exposure resolution can be improved since the reduction image of the mask pattern is projected on the exposure plane.

The lens arrangement and specifications were determined by considering the balance of optical aberrations based on ray-tracing simulation results. In order to reduce the light absorbance to a minimum, we used anti-reflection coated lenses with a transmittance of 99.0% and a mirror with a reflectance of 99.0% at 365 nm. The lens specifications are summarized in Table 2. In this system, the LCD mask, consisting of a pair of polarizers and the LCD itself. The total transmittance of the LCD mask becomes 1.1%. As a result, the overall transmittance of the optical system (from the mercury lamp to the exposure plane) was estimated to be as low as 0.8%. However, as the LCD lithography system designed here is a projection system with

Table 2

Lens specifications

Lens no.	Focal length (mm)	Thickness (mm)	Diameter (mm)	Lens type
L ₁	250	5.8	50	Plano-convex
L ₂	40.8	4.8	20	Convex
L ₃	80	5.2	30	Plano-convex
L ₄	150.6	3.6	30	Convex
L ₅	150.6	3.6	30	Convex
L ₆	80	5.2	30	Plano-convex

a 6.5:1 reduction, the UV light intensity on the exposure plane can be maintained at approximately 35% of that of the mercury lamp.

The majority of the incident light, i.e. 88%, is cut off at the first polarizer. The transmittance of the LCD itself is 34%, and the absorbance of the incident light by the LCD itself is as less as 8%. Therefore, the LCD mask is stably under appropriate UV exposure and the long term drifting is negligibly small. In addition, the beam efficiency is expected to be improved by replacing a pair of polarizers used here with a pair of calcite polarizers, which has a high transmittance of 41% at 365 nm. As a result, the transmittance of the LCD mask will be improved by up to 14%.

3. Evaluation of pattern resolution on the LCD lithography system

Fundamental experiments were conducted by using a binary image displayed on the LCD in order to achieve a high resolution using the LCD lithography system. In this section, we discuss the effect of the aperture on the pattern exposure resolution. Three apertures A, B, and C were set as shown in Fig. 4. They will strongly determine the optical aberrations on an exposure plane.

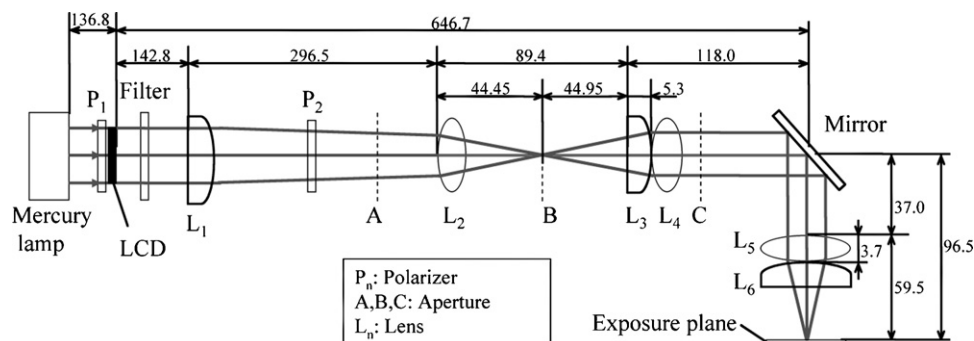


Fig. 4. Configuration of the LCD lithography system. The optical system was composed of three parts, namely, a uniform irradiation optical system that generates collimated light with low energy density, reduction optical system that reduces the LCD mask pattern at 15%, and relay lens optical system that transfers the LCD mask image to the exposure plane. A wavelength of 365 nm was selected from the mercury lamp using an optical filter with a transmittance of 82.7% before illuminating the LCD mask.

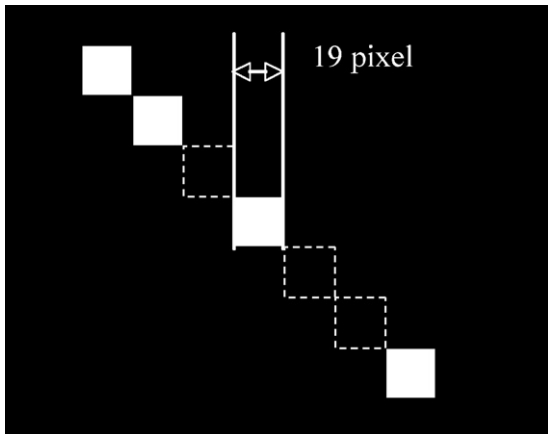


Fig. 5. LCD mask image composed of squares with 19×19 pixels ($342 \mu\text{m} \times 342 \mu\text{m}$) for evaluation of exposed area.

3.1. Effect of apertures on pattern exposure resolution

Fig. 5 shows a computer-generated mask image on the LCD, composed of four square patterns with a size of 19×19 pixels ($342 \mu\text{m} \times 342 \mu\text{m}$). The squares are located diagonally with a gradually increasing interval. This mask image is reduced by 85%, and consequently, the size of each square pattern will be of $52.3 \mu\text{m} \times 52.3 \mu\text{m}$ on the exposure plane. Fig. 6a shows a typical photoresist pattern formed by using the LCD mask image without any aperture on the LCD lithography system. A positive photoresist (Tokyo Ohka Kogyo Co. Ltd., OFPR-800) layer with a thickness of about $1.4 \mu\text{m}$ was spin-coated onto a silicon substrate, and then exposed to 365 nm UV light. The resulting square-shaped photoresist patterns (width W_a) were equivalent to the transparent image area of the LCD mask. However, in the neighbourhood of each square pattern, interference fringes were observed. Since the interference fringes originated due to the change in the photoresist thickness, this region (width W_b) can be also considered as a light-irradiated area, but the photoresist still remained underdeveloped probably due to underexposure. Such a geometric error is mainly caused by optical aberrations on the exposure plane. Therefore, the pattern resolution must improve as the width W_b of the exposed area approaches the width W_a of the patterned area by adjusting the position and diameter of the apertures.

Exposure results obtained with and without aperture C are shown in Fig. 6a and b, respectively. An interference fringe is observed, as shown in Fig. 6a. The resolution is considered to improve as W_b approaches W_a . The resolution of pattern exposure is optimum when aperture C is used with a diameter of 8 mm, as shown in Fig. 6b; in this case the exposure area is the minimum.

Fig. 7 shows the relationship between the aperture diameter and the exposed area. The exposure area is kept constant despite the addition of aperture A, as shown in Fig. 7a. The area remained unchanged even when the aperture diameter of B was decreased. However, the area decreased with the aperture diameter of C, as shown in Fig. 7b. These data were taken at the same exposure energy for different aperture sizes. The exposure energy was measured at the exposure plane by using a UV power meter.

From the above result, it is confirmed that the exposure area could be optimized by adjusting the aperture diameter of C. The aperture A is worked as a field stop for the image at the position of the aperture B. The aperture B is worked as spatial frequency filter in order to remove the stray light before reduction optical system, and the aperture C is worked as a field stop in the reduction optical system to adjust a field of the image at exposure plane. Therefore,

the aperture diameter of C is the dominant parameter for achieving the appropriate irradiation conditions at exposure plane.

3.2. Evaluation of resolution using line and checkered patterns with different aperture sizes of A, B, and C

Line patterns and checkered patterns were produced in order to investigate the resolution of patterning using the LCD lithography system. The resolution of the line patterns with different line widths is shown in Fig. 8. The line pattern with a $10 \mu\text{m}$ gap could be transferred when aperture C was set to a diameter of 8 mm. The pattern resolutions corresponded to the contrast of light intensity between the exposed area and its surroundings. The resolution decreased significantly with an increase in the exposure line width due to overexposure.

It was confirmed that line patterns with a line width of $10.8 \mu\text{m}$ could be precisely fabricated using the OFPR-800 as shown in Fig. 9a and b. Furthermore, the checkered patterns with $10.8 \mu\text{m}$ side can be transferred, as shown in Fig. 10. Thus, it was confirmed that the optical system, which uses UV light as a light source, is useful for 2D device fabrication.

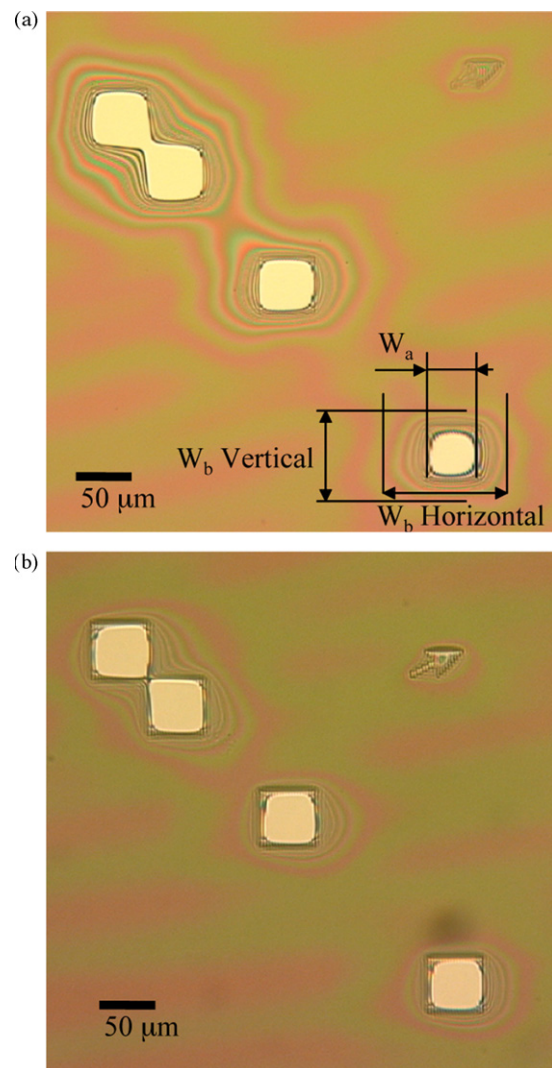


Fig. 6. Typical positive photoresist patterns formed by using LCD mask with LCD lithography system: W_b is the width of the exposed area and W_a is the width of the patterned area, respectively. (a) Exposed to an energy of $66 \text{ mJ}/\text{cm}^2$ ($0.168 \text{ mW}/\text{cm}^2 \times 390 \text{ s}$) without aperture C; (b) exposed at exposure energy of $15 \text{ mJ}/\text{cm}^2$ ($0.025 \text{ mW}/\text{cm}^2 \times 600 \text{ s}$) with 8 mm diameter aperture C.

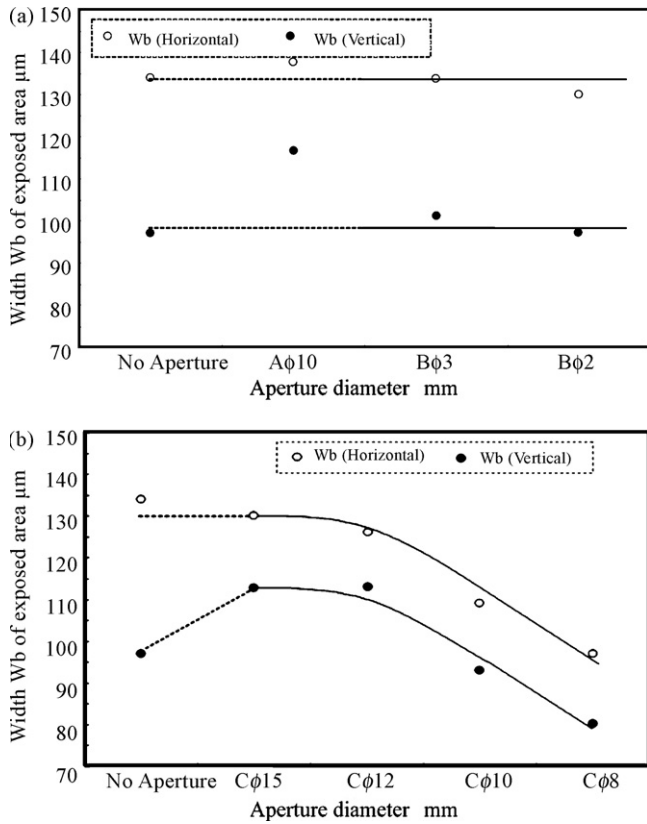


Fig. 7. Relationship between aperture diameter and exposed area: (a) effect of aperture A or B; (b) effect of aperture C.

4. Gray-tone photolithography using LCD active mask lithography system

An advanced feature of the LCD active mask exposure system is gray-tone photolithography. The percent transmittance of an LCD pixel can be linearly adjusted by changing the gray level of the computer-generated mask pattern. This pattern can be easily applied to gray-tone photolithography by using our proposed system. In this section, the UV gray-tone photolithography process is verified for 3D fabrication by using a single exposure procedure. If the UV exposure is applicable to proposed LCD gray-tone photolithography system, a commercially available UV photoresist such as SU-8, which is generally utilized in the MEMS field.

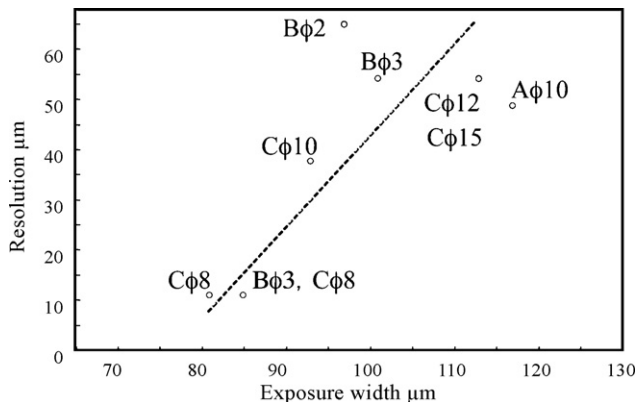


Fig. 8. Resolution of line pattern with different line widths.

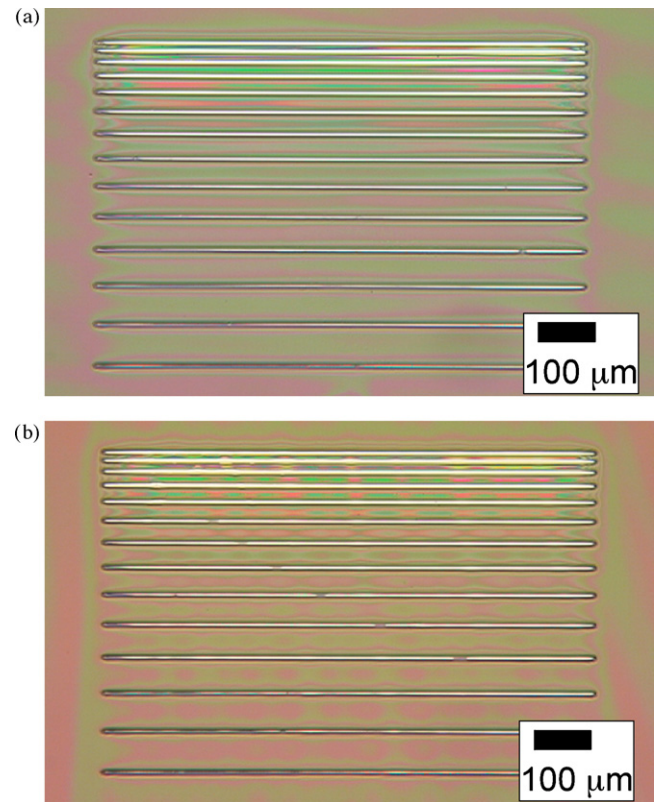


Fig. 9. (a) The fabrication result of the line pattern with a width of 10.8 μm. Aperture C was 8 mm. (b) The exposure result of the line pattern when apertures B of 3 mm and C of 8 mm are added. The exposure lines width was maintained constant despite the addition of B and C.

4.1. Relationship between the beam intensity on exposure plane and gray level of LCD mask

The LCD mask transmittance at the wavelength of 365 nm was measured by varying the gray level of the LCD mask. The relationship between the mask transmittance and the gray level is shown in Fig. 11. A square of the sinusoidal relation was confirmed between the mask transmittance and the gray level ranging from 100 to 230. The exposure energy is corrected based on this relation by control-

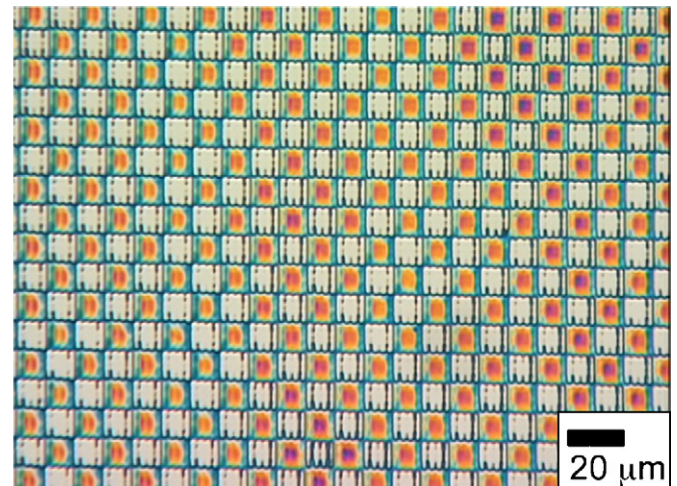


Fig. 10. Checkered pattern with a size of 10.8 μm × 10.8 μm at 12.9 mJ/cm²; aperture C: Ø 8 mm.

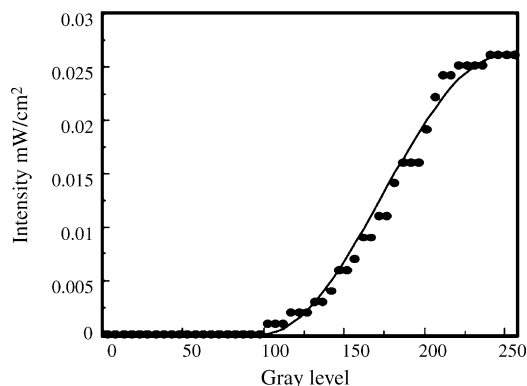


Fig. 11. Mask transmittance measured by varying the gray level of the LCD for 365 nm UV light.

ling the mask transmittance distribution, which is equivalent to the gray level of the LCD.

4.2. Evaluation of photoresist removal rate

First, the removal depth of the photoresist was evaluated with increasing exposure energies using the LCD gray-scale mask. A thick-film positive-type photoresist (PMER) was used for measuring the removal rate. The parts that were irradiated were soluble in the developer. The depth was measured by varying the exposure time in the range of gray levels from 135 to 255, as shown in Fig. 12a. The depth increased linearly with the exposure time; the depth was approximately 9 μm at an exposure time of 30 min.

Second, the relationship between the removal depth and gray level of the LCD was investigated, as shown in Fig. 12b. The exposure time was fixed at either 30 min or 60 min. The relationship is similar to that between the mask transmittance and the gray level, as shown in Figs. 11 and 12b. This implies that the removal depth can be linearly controlled by the gray level of the LCD mask. The removal depth of the photoresist increased rapidly with the gray level from 100 to 230.

A line width of 20 pixels with a gray level of 255 on the LCD mask translated into 54 μm on the exposure plane. In this case, the removal depth was approximately 10 μm for a 30 min exposure. The light intensity corresponding to a gray level of 180 decreased to half in comparison with the intensity at a gray level of 255. In this case, the depth also decreased to 5 μm —half of that of gray level of 255. Therefore, it was confirmed that the removal depth of the photoresist can be controlled by adjusting the gray level of the LCD mask. In addition, the light intensity increased with the line width. The depth for a line pattern of 200 pixels was approximately 16 μm ; this is 1.3 times as deep as that for 20 pixels.

The removal depths at different line width were investigated with increasing exposure energies, as shown in Fig. 13. The line widths of the LCD mask were 20 pixels, 150 pixels, and 200 pixels; the line width reduced to 54, 405, and 540 μm on the exposure plane, respectively. The depth obtained with a line pattern with 150 pixels was similar to that obtained with 200 pixels; this implies that the light intensity does not change when the line width is varied in a range of over 100 pixels.

On the contrary, the depth of the line pattern was decreased from 150 and 200 pixels to that of 20 pixels in width. Therefore, a longer exposure time was required for transferring a narrow line pattern of 20 pixels in width (54 μm on the exposure plane). The exposure should be calibrated in order to transfer gray-scale patterns. The removal depth decreases corresponding to the line width

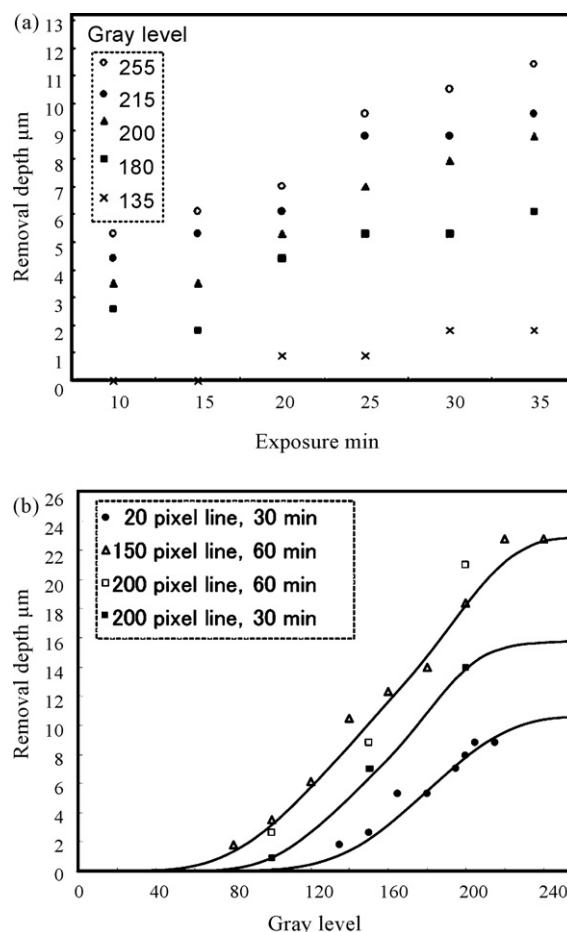


Fig. 12. Evaluation of removal depth of photoresist for different exposure times and gray levels.

as shown in Fig. 13. Thus, the light exposure decreases with the line width. The proposed gray-tone photolithography system can be utilized for the calibration of the exposure distribution in the case of using an intricate mask pattern whose width is greater or less than 50 pixels.

Binary patterns were prepared for exposing the PMER photoresist to line patterns of 20, 50, 100, 150, and 200 pixels in width in order to investigate the relationship between the line width and the removal depth. The line patterns of 20, 100, and 200 pixels in width

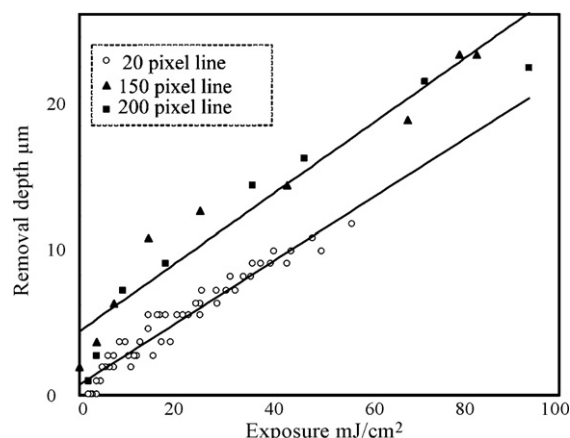


Fig. 13. Plot of the removal depth of photoresist against exposure energy.

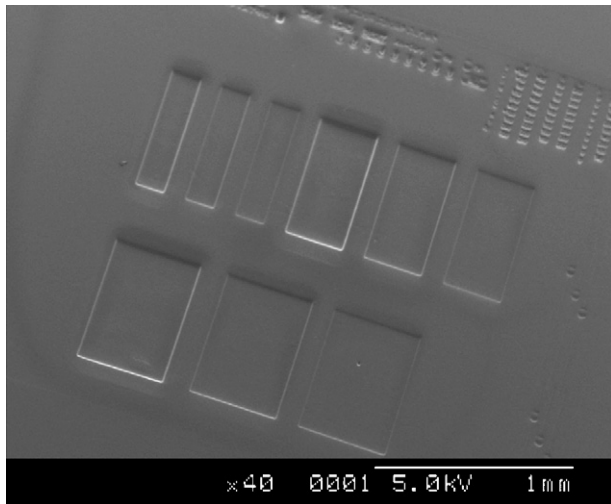


Fig. 14. SEM picture of micropatterns (binary mask and gray-scale mask) (PMER).

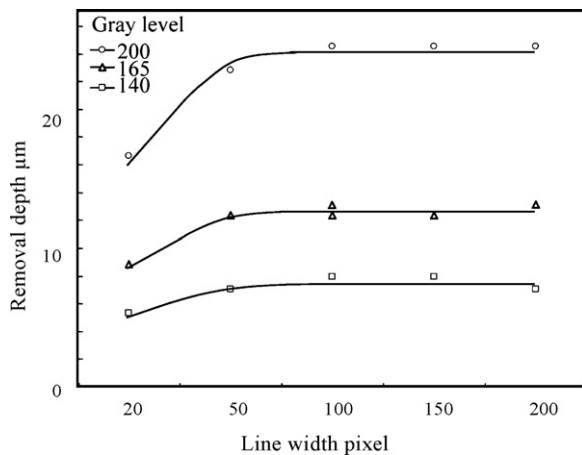


Fig. 15. Characteristics of the line pattern exposure for different line widths (PMER).

were transferred as shown in Fig. 14. Fig. 15 shows the evaluation results of the removal depth. The gray level for the line pattern was changed to 140, 165, and 200, respectively. In this case the light intensity was 1, 1/2, and 1/4, respectively, as compared to a case of the gray level of 200. The removal depths were constant despite an increase in the line width from 50 pixels (135 μm) to 200 pixels (540 μm). On the contrary, the depth decreased to 2/3 with a decrease in the line width from 50 pixels to 20 pixels. Finally, the removal depth was determined by the light intensity depending on the line width and gray level.

4.3. Fabrication of 3D shape by gray-tone photolithography

Fig. 16 shows the fabrication result of the step-shape pattern obtained using PMER. The gray level of the mask pattern for each step depends on the relation shown in Fig. 12b. The gray levels of the mask pattern for each step are 255, 195, and 160, respectively. The profile of the step shape is shown in Fig. 17. It was measured with the help of a confocal scanning microscope (Mitaka Kohki Co. Ltd., NH-3NT) with a 1 nm resolution in the z direction. The optical intensity decreased from the center of the step towards the edge. Therefore, the edge shape becomes circular over the circumference; this is considered to be an effect of the diffracted light from the LCD.

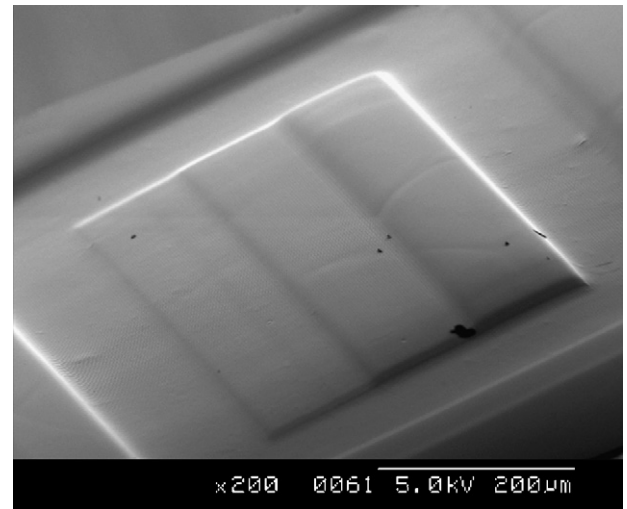


Fig. 16. SEM image of microstep structure.

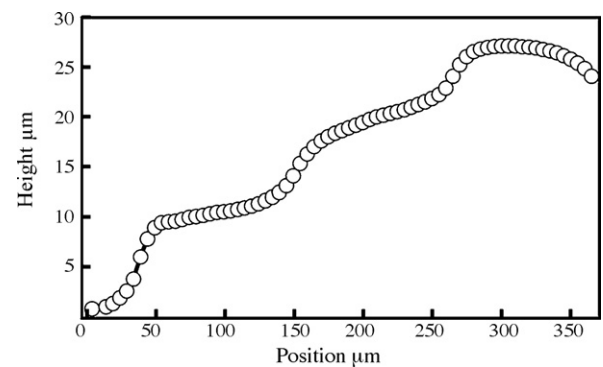


Fig. 17. Cross-sectional profile of 3D step structure of gray-tone exposure measured by using confocal scanning laser microscope.

5. Conclusion

In this study, we designed an LCD-mask exposure system for applying a LCD as a UV photomask. Basic experiments were performed to verify the feasibility of UV gray-tone photolithography using this system. The patterning resolution of the LCD mask was evaluated, and a step-shape was produced with a single exposure procedure. It was experimentally confirmed that both a line pattern of 10 μm in width and a step shape with different heights can be fabricated by using the proposed system.

It is expected that this technique can be applied to the fabrication of μTAS chips such as the flow channel with tapered shapes. 3D MEMS devices may also be fabricated without requiring a repetitive exposure procedure. In addition, this technique is expected to be applied to synthesis technology in DNA chip production because this technique can be applied for controlling the lighting area and exposure distribution in order to control various photochemical reactions.

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