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Simple maskless lithography tool with a desk-top size using a liquid-crystal-display projector

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ABSTRACT

A very simple and low-cost maskless exposure tool with a desk-top size was developed for applying to fabrications of various micro electro mechanical systems (MEMS) and bio-devices. A commercial projector with three liquid crystal display (LCD) panels of red, green, and blue colors was utilized as it was, except attaching a macro-lens for a camera after removing the magnification optics of the original projector. Therefore, the sizes were as small as 300 wide $\times$ 400 deep $\times$ 500 high mm^3, and the system was fabricated at a very small expense (¥500,000 $\approx$ €3500). Pixel pitches on the LCD panel were 8.5 μm, and the 7.4-μm square pixels were projected onto a wafer in a magnification ratio of 1.65. Efficient pixel numbers were 1024 $\times$ 768, and the exposure field sizes were 14.3 $\times$ 10.7 mm^2. Using the system, isolated line patterns with a width corresponding to one pixel size of approximately 14 μm, and 1:1 lines-and-spaces (L&S) patterns with a width of two pixel sizes of 28 μm were stably printed. Not only line patterns in orthogonal directions, but also radial oblique patterns were clearly and smoothly printed, and complicated arbitrary patterns were also printed. These projection ratio and pattern widths were decided considering the present applications to fabrications of micro-fluidic devices and lens arrays. If smaller patterns are required, the minimum pattern size and the projection ratio are conformably changed in principle. Because arbitrary patterns designed on a personal computer are directly printed on a wafer, preparations of expensive reticles are not necessary. Accordingly, besides the system cost and footprint are drastically saved, working expenses are much saved.

1. Introduction

Lithography is often used for printing large patterns with widths of 5–200 μm in various fabrications of micro electro mechanical systems (MEMS), bio-devices, and sensors. For example, patterns with widths of 50–100 μm are required for fabricating micro-fluidic devices and 30–100 μm are required for fabricating lens arrays at hand in the author's group. In the cases of above mentioned devices or articles, production volumes are generally very small comparing with the fabrications of semiconductor devices. On the other hand, various diversities of patterning are required, especially in sizes, shapes, thicknesses, and materials of substrates. In addition, no alignment or only very rough positioning is required in most cases. Therefore, simple, easy, and low-cost lithography tools are strongly required for these usages. However, commercially available lithography systems are too expensive for small companies to possess. In addition, they also need a moderate footprint in a clean room and everyday maintenances. For this reason, it is difficult to apply lithography for small volume productions in small companies. It is required that lithography tools are easy to handle as if they are personal computers, cameras, and televisions in order that lithography is used by engineers in small companies without constraint. In addition, they should be inexpensive even they were generously wasted after being used for the primary purposes.

To reply to these requirements, the authors have been developing maskless matrix exposure systems using liquid crystal display (LCD) panels in place of reticles [1–7]. Similar exposure systems were also proposed by other research groups [8–13]. On the other hand, many researches on exposure systems using digital micro-mirror devices (DMDs) instead of LCD panels were also reported [14–19]. Besides, an exposure system using grating light valves (GLVs) or spatial light modulators (SLMs) was proposed [20].

Although black matrix parts are always opaque for exposure light rays in the case of LCD matrix exposure, smooth patterns without notches are obtained, because parts corresponding to narrow black matrix lines on a wafer are also exposed by light diffracted from the neighbored bright LCD pixels. If the resolvable pattern size for the projection lens is sufficiently larger than the

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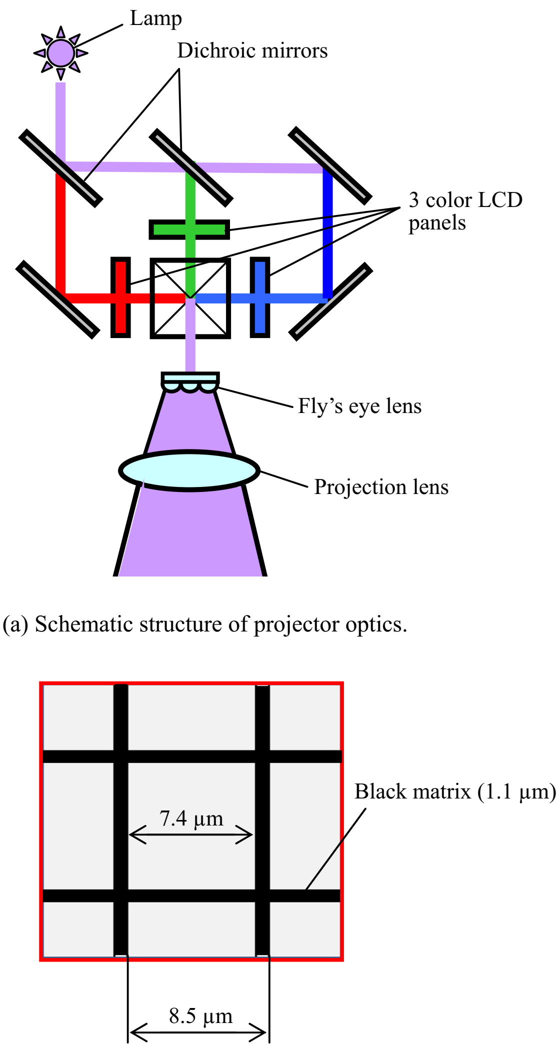
widths of black matrix lines, the black lines are not resolved, and they are not replicated.

In addition, because each transmittance of LCD cells is arbitrarily changed in 256 grades, oblique or curved patterns are also smoothly printed, and they are arbitrarily positioned, if the pattern widths are wider than the twice of pixel pitches [4]. If neighbored pixels of a two-pixel line patterns are assigned in different transmittances, for example, position of the printed line pattern shifts to the side of higher transmittance and brighter pixels depending on the transmittance difference between the neighbored pixels. In contrast, in the case of systems using DMDs or SLMs, laser beams are scanned on element mirrors or GLVs. For this reason, it is difficult to giving different exposure doses arbitrarily on each element mirror or GLV.

On the other hand, the LCD panel can control only visible light with wavelengths between 420 and 750 nm, and efficiency of utilizing light energy is low. These are the disadvantages of LCD matrix exposure. However, an novel multi-layer resist process has already been developed to transform top-layer resist patterns printed by the LCD lithography using visible light to bottom-layer resist patterns sensitive to ultra-violet (UV) light [5–7]. Accordingly, the LCD lithography has also been applicable to UV lithography using resists such as SU-8 (MicroChem). Therefore, it is considered that large inconveniences are not found in effect.

On the basis of these considerations, extremely small and low-cost lithography tool was developed this time [21]. In the past research, an LCD panel with small pixel numbers of 320 × 240 was used. The black and white LCD was a view finder of video camera used approximately 15 years ago. Although it had the smallest pixel pitch of 15 μm in those days, the pixels had rectangular shapes, not square shapes. For these reasons, too small exposure-area size and directional differences of patterning performances prevented the technology from being applied to practical micro-fabrications. In addition, because the hand-made exposure systems developed in the past research were fabricated using a light source at hand and makeshift collective optics, downsizing and cost minimization of the exposure system were not earnestly considered.

In this research, a new advanced commercial LCD projector with pixel numbers of 1024 × 768 and pixel pitch of 8.5 μm was directly used for earnestly downsizing the system and reducing the fabrication cost at minimum. It was the first trial in the world. In addition to reducing the system cost at minimum, pixel numbers and the exposure field size were greatly improved to be applied to various practical applications. Although the target pattern size and exposure field size were different, an exposure system with similar structure was proposed by chance in the same conference [22]. Simple and low-cost exposure tools are impatient.



(a) Schematic structure of projector optics.

(b) Schematic structure of pixels.

Fig. 1. Schematic structure of LCD projector.

2. Concept design and lens selection

In this research, simplification and downsizing of the system, and reduction of the costs required for fabricating the exposure system were strongly considered. For this reason, commercially available video-projectors applicable to the projection exposure lithography were searched at first. To print patterns similarly in both lateral and longitudinal directions, LCD panels with square shapes and same pixel pitches in both directions are expected. In addition, it is preferable that the pixel pitches are as small as possible, and the black matrix lines are as narrow as possible. For this reason, LCD video-projectors with these performances were looked for. As a result, a projector with three-displays of red, green, and blue (RGB) was selected. The schematic projection optics of the selected projector (Mitsubishi Electric, LVP-HC5000) are shown in Fig. 1. LCD pixel pitches in vertical and horizontal directions were 8.5 μm, and the width of black matrix line was 1.1 μm. Therefore, the LCD pixel size was 7.4 μm square. Pixel numbers used for the research were 1024 × 768 depending on the specification of the personal computer used for designing patterns to be printed.

However, at the front of the projector, projection lens optics for making largely magnified images on a screen was attached. In the case of exposure system for lithography, images should be projected onto substrates in a small exposure field compared with large screen sizes, and the resolution appropriate for printing aimed patterns has to be secured. For this reason, it was considered that the initially attached projection lens optics should be removed, and new projection optics should be attached instead. Here, it was also considered that the distance between the projection system and the substrates should be appropriately short for developing a compact exposure system. As a result, a macro-lens of a camera (Sigma, EX DG MACRO) was selected. There was another reason that the lens had been actually used for developing simple exposure system in other researches.

Besides the video-projector and the macro-lens, it was necessary to prepare stages for moving substrates. However, because no alignment or only very rough positioning was required for the live works, it was decided to use very simple manual *XYZ* stages.

3. Fabrication of exposure system

The new exposure system was fabricated using above mentioned LCD video-projector and the macro-lens. The exposure source of the projector was a high pressure mercury lamp with a power of 160 W. It was measured that all the light rays passing through the projection optics included wavelengths of 430–720 nm. However, the light rays passing through the LCD panel with the blue filter included only wavelengths of 430–520 nm. Because the resist was not sensitive to light with longer wavelengths, light rays with these wavelengths were used in this work. Although the intensity peak of the total light was observed at the wavelength of 546 nm, the intensity peak in the blue filter band was observed at the wavelength of 436 nm.

The macro-lens was compactly attached to the projector, as shown in Fig. 2. Optics for largely magnifying the images displayed on the LCD was attached initially to the projector frame using screws. The female screws located in the projector after removing the magnifying optics were reused for fixing the macro-lens. The lens was fixed in advance to a specially designed small frame, and the base plate of the small frame was attached to the projector using above mentioned screws. The lens position was roughly decided at first referring to the lens specification, and the final position was manually adjusted as the image became clear and homogeneous visually. Because the size of exposure field became $14.3 \times 10.7\ \text{mm}^2$, the pattern pixel pitch projected on a substrate was calculated to be $14.3 \times 10^3/1024 = 14.0\ \mu\text{m}$. Accordingly, the projection ratio was calculated to be 14.0/8.5 = 1.65. Above mentioned minimum pattern width and exposure field size were decided by considering present needs for fabricating micro-fluidic devices and lens arrays. Although the lens position has to be shifted down, and the exposure field size is reduced, the minimum pattern size can be reduced by changing the projection ratio and selecting the best *F*-number of the projection lens, if necessary.

A wafer coated with a resist was placed on the top table of *XYZ* stages, and the exact image plane was found out by printing patterns at various *Z* positions, and comparing the patterning performances for various *Z* positions. The image plane came at several tens mm distant from the back end of the lens. Therefore, a very compact projection exposure system with sizes of approximately 300 mm wide, 400 mm deep, and 500 mm high was realized. The frame of the commercial projector was supported using versatile steel angles, and the manual *XYZ* stages were attached on the base of angle frame. Because the schemes were very simple, the total expense for fabricating the exposure system was only approximately ¥500,000 (€3500).

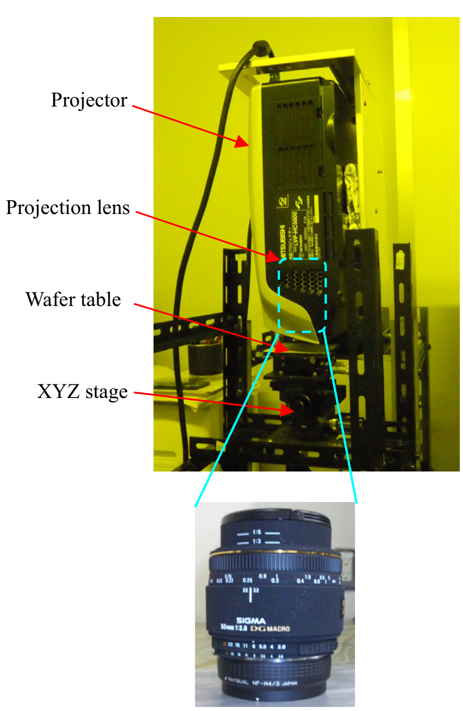


Fig. 2. Outside view of developed exposure system.

4. Patterning performances

Patterning characteristics were investigated using a positive resist of OFPR 800 (Tokyo Ohka Kogyo) with a thickness of approximately 2 μm. Because the main wavelengths of exposure light are 430–520 nm, g-line resists are most suitable. Various g-line resists are usable instead of OFPR 800. However, it was used because it did not need post exposure baking, and patterning processes became simple and easy. Exposed wafers were developed in a commercial developer of NMD-W (Tokyo Ohka Kogyo) that is the water solution of 2.38% tetra-methyl-ammonium-hydroxide (TMAH) for 1 min.

The *F*-number of the macro-lens was set at 16, and 640×480 pixel field was used for the experiments. This is because it was necessary to shot many fields on a wafer and compare patterning performances under the exactly same wafer process conditions. When the exposure field was limited in this region, the field size was $8.9\ \text{mm} \times 6.7\ \text{mm}$. As software to design the patterns, "Photoshop" was used.

At first, relationship between the pattern width and exposure time for 2-pixel lines-and-spaces (L&S) patterns was investigated. The results are shown in Fig. 3. It was clarified that L&S pattern widths changed depending on the exposure time in a relationship almost as same as the one for the normal projection lithography using a reticle. Exposure time when line pattern widths became almost equal to space pattern widths was approximately 130 s. It might be worried that the exposure times were too long. However, the exposure time varies depending on the *F*-number of the lens and the projection ratio. Because the lens was set at *F*-number of 16 in this research, lens aperture area size was reduced to $(2.8/16)^2 = 1/11.4$. In addition, because the projection ratio was 1.65, illumination light density on the wafer was considerably reduced. If the F number was set at 2.8 for printing patterns with widths of around 5 μm, and the projection ratio was reduced to 0.5, for example, it was supposed that the exposure time would be shortened to around $130\ \text{s} \times (1/11.4) \times (0.5/1.65)^2 \approx 1\ \text{s}$.

On the other hand, pattern widths suddenly became narrow at long exposure times. These phenomena are generally observed in

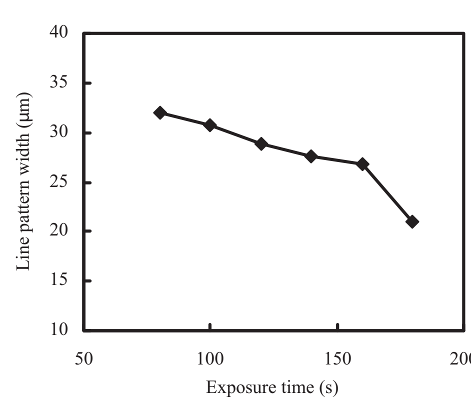


Fig. 3. Pattern width dependence on exposure time.

lithography. The image-intensity distribution of L&S patterns becomes almost similar to a sine curve biased from the base because high-order diffraction light rays cannot pass through the lens aperture. Accordingly, parts corresponding to opaque parts of the reticle are also sensitized by giving a large exposure dose, and all of the sensitized positive resist films are removed during the development.

Next, relationships between the number of LCD element pixels in width direction and a half pitch of L&S patterns were investigated. The results are shown in Fig. 4. It was clarified that the half pitch of printed L&S patterns was proportional to the pixel numbers in the width direction. Examples of printed L&S patterns are shown in Fig. 5. It was verified that L&S patterns with widths equal or more than 2 pixels were clearly printed, as shown in Fig. 5(b) and (c). Patterns in X and Y directions are almost the same. However, 1 pixel L&S patterns were not completely resolved, as shown in Fig. 5(a). It was observed that resolved and unresolved patterns were mixed. For this reason, line width was fixed at 1 pixel, and only space widths were increased between 2–5 pixels. As a result, all the patterns were clearly resolved, as shown in Fig. 6. It was clarified that 1-pixel line patterns were quite easily printed, if the line patterns were separated at least 2 pixels away from neighbored line patterns.

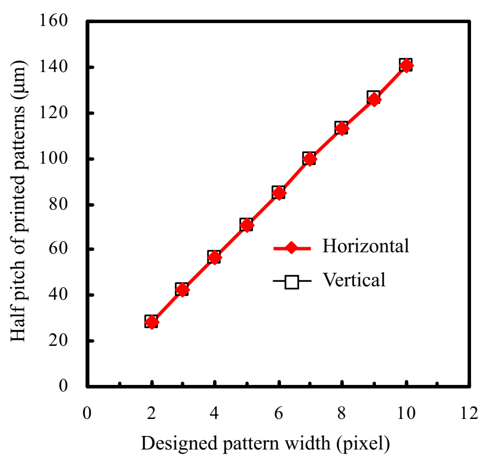
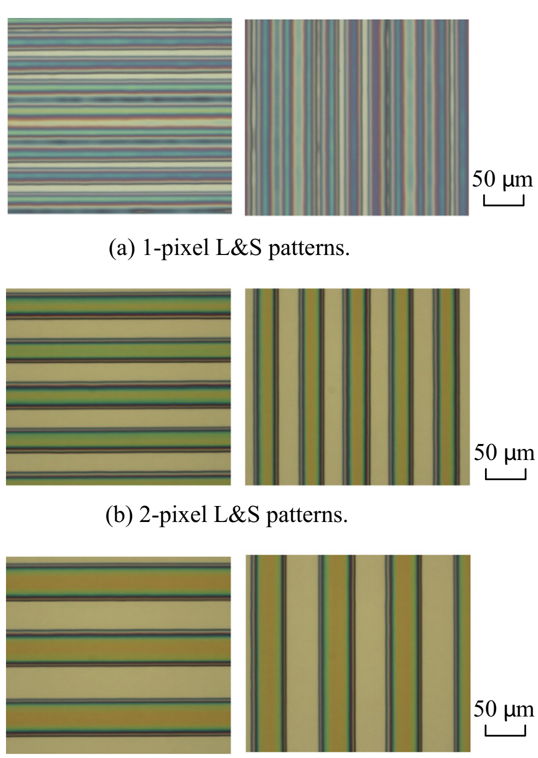


Fig. 4. Relationships between the number of LCD element pixels in width direction and a half pitch of L&S patterns.

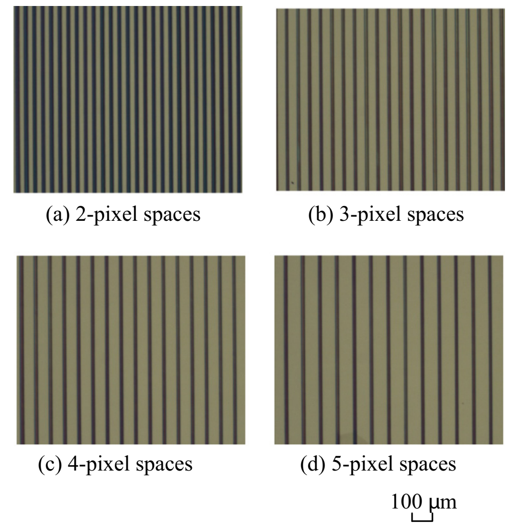


(a) 1-pixel L&S patterns.

(b) 2-pixel L&S patterns.

(c) 3-pixel L&S patterns.

Fig. 5. Patterning results of 1 to 1 L&S patterns.



(a) 2-pixel spaces (b) 3-pixel spaces

(c) 4-pixel spaces (d) 5-pixel spaces

Fig. 6. Patterning results of L&S patterns with 1-pixel line and multi-pixel spaces.

Judging from color changes of printed patterns shown in Fig. 5, it was supposed that sidewalls of patterns were inclined or top corners of side edges were rounded. Cross-sectional profiles of patterns should be investigated in detail, and improved by controlling the focal position more precisely or using a resist with a higher γ value, hereafter.

It was considered that performances of L&S patterning depended on the resolution of the projection lens, and the resolution limit of the lens was decided by the numerical aperture or the F-number of the projection lens. For this reason, appropriate F-number was minutely discussed later, as shown in Section 6.

Based on these results, 2-pixel radial patterns were printed next. Printed patterns are shown in Fig. 7, and the width distribution was measured, as shown in Fig. 8. Mean width and fluctuation were 33 ± 3 μm. Widths were almost homogeneous in all the directions.

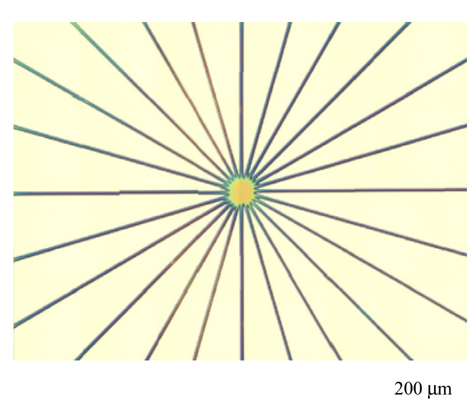


Fig. 7. Printed result of 2-pixel radial patterns.

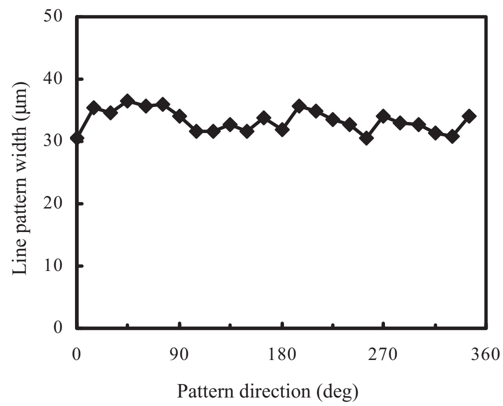


Fig. 8. Pattern width homogeneity of radial patterns.

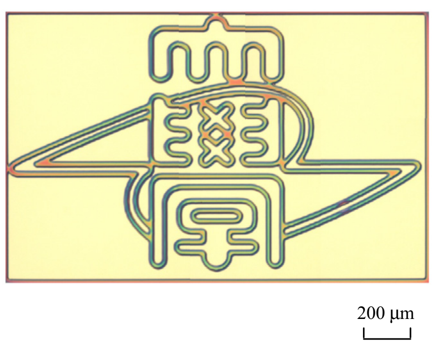


Fig. 9. Example of printed complicated patterns (University mark).

Because fundamental patterns were successfully printed, complicated arbitrary patterns were printed next. Fig. 9 shows the results. The university mark was nicely printed without accompanying any unresolved parts.

5. Homogenization of exposure intensity

Next, light intensity distribution in the 8.9 mm × 6.7 mm field was investigated. The light intensity was measured using a light intensity meter (Ushio INC., UIT-100). The sensor head of the meter was fixed on the wafer stage, and the intensity was measured at many points. As a result, it was clarified that light intensity distributed almost gradually in the diagonal direction, as shown in Fig. 10. Caused by this intensity distribution, printed widths and shapes of 100-µm L&S patterns were different between diagonal apexes, as shown in Fig. 11. For this reason, light intensity compensation using linear gradation in the diagonal direction was applied, as the first step. That is, transmittances of LCD pixels were linearly changed in the diagonal direction. As a result, it was demonstrated that patterns at the upper left corner and the lower right corner became almost same, as shown in Fig. 12. To print such large patterns, image intensity homogenization is almost sufficient by applying this simple transmittance gradation. However, transmittance of each LCD element pixel should be compensated closely for printing finer patterns homogeneously.

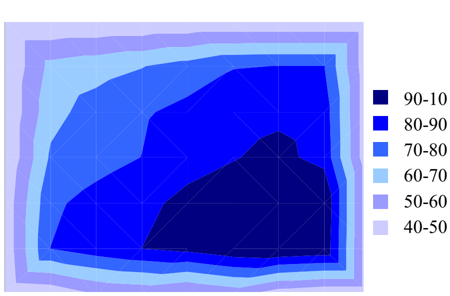


Fig. 10. Distribution of exposure light intensity.

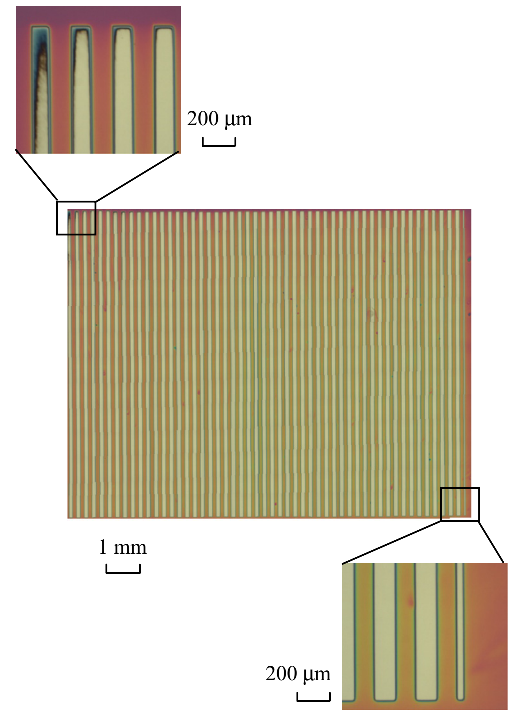
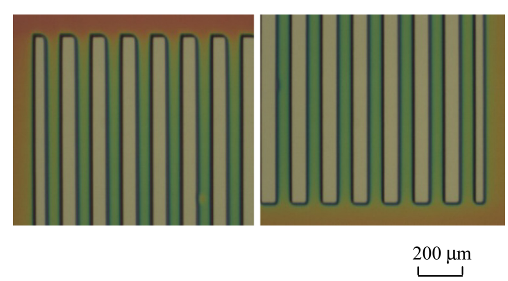


Fig. 11. Difference of pattern shapes between upper left and lower right corners.



(a) Upper left corner. (b) Lower right corner.

Fig. 12. Improved differences of pattern shapes between upper left and lower right corners.

6. Discussion on optimum *F*-number

A key point of this patterning is the *F*-number or the numerical aperture of the projection lens. This time, *F*-number of the camera lens used as the projection lens was changeable between 2.8 and 32. However, it was set at 16. There was a good reason why this *F*-number was selected. It was based on the following discussion and some experiments.

Because the projection ratio m was 1.65, effective *F*-number F_e was calculated by Eq. (1).

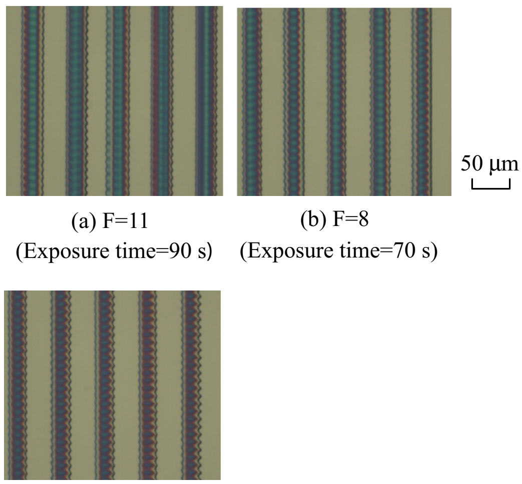


Fig. 13. Comparison of 2-pixel L&S patterns printed under various *F*-number conditions. Because the resolution becomes higher according to use smaller *F*-number, pattern edges become rough influenced by black matrices.

$$F_e = (1 + m)F = 2.65F \quad (1)$$

Using the effective *F*-number F_e, numerical aperture NA is calculated, as shown below.

$$\mathrm{NA} = \frac{1}{2F_e} = \frac{1}{5.3F} \quad (2)$$

Resolution limit *R* of the projection optics is calculated by Eq. (3).

$$R = k_1 \frac{\lambda}{NA} \quad (3)$$

Here, λ is the exposure wavelength, and k_1 is the coefficient called k_1 factor. Substituting typical values of $\lambda = 0.436$ μm and $k_1 = 0.7$, *R* is calculated, as shown below.

$$R = 5.3Fk_1\lambda = (5.3 \times 0.7 \times 0.436)F = 1.62F[\mu\mathrm{m}] \quad (4)$$

Using this equation, it was considered what *F*-number is appropriate for the exposure system developed here. In the case of matrix exposure using an LCD panel in place of a reticle, LCD pixels are arrayed, and each pixel position is regularly fixed. Therefore, positions and widths of patterns are restricted at intermittent ones, or whole number times of a pixel, if only bright or dark of each pixel is assigned. However, it was clarified by the past research that positions and widths of patterns are arbitrarily changeable, if pattern widths are wider than 2 pixels, and the transmittance or the brightness of each pixel is controlled at multiple steps individually [4]. For example, if line patterns with 2-pixel widths were assigned by neighbored weekly and strongly bright pixel lines, line pattern image with a width wider than 1 pixel and narrower than 2 pixels is formed at the position shifted to the side of strongly bright line. Thus, pattern positions and widths can be controlled by adjusting the transmittance or the brightness balance between the neighbored pixels. Therefore, patterns with widths larger than 2 pixels should be mainly used in LCD matrix exposure.

Since the pixel pitch of the LCD panel is 8.5 μm, and the projection ratio is 1.65, the minimum practical pattern width w_m corresponding to 2 pixels becomes

$$w_m = (8.5 \times 1.65) \times 2 = 28.1[\mu\mathrm{m}]. \quad (5)$$

Because the resolution *R* of the projection lens must be smaller than w_m to print patterns with this width, the following equation is obtained from Eqs. (4) and (5),

$$R = 1.62F < 28.1. \quad (6)$$

Therefore,

$$F < 17.3. \quad (7)$$

On the other hand, if *F* is too small or NA is too large, black matrix lines or contours of LCD pixels are sharpened, and there appeared small notches at every boundary between LCD pixels on the side edges of patterns, as shown in Fig. 13. For this reason, the optimum value of *F*-number was decided to be 16. Under the *F*-number condition of 16, no such notches were observed, and very smooth pattern edges were obtained, as already shown in Fig. 4.

If the projection-lens conditions were changed to print finer patterns, and if smaller projection ratios were selected, it is necessary to optimize the *F*-number again.

7. Conclusion

A new simple and low-cost exposure system was developed. The sizes are only 300 W × 400D × 500H mm^3, and the system can be used as a desk-top tool. The sizes include all the accompaniments except a personal computer. The system is operable only connecting to a socket of AC 100 V, and projects patterns arbitrarily designed on a personal computer onto a substrate coated with a resist. The numbers of the used LCD pixels were 1024 × 768, and the field size was 14.3 × 10.7 mm. Pixel size and pitch of the LCD panel were 7.4 μm square and 8.5 μm in *X* and *Y* directions, and the projection ratio was 1.65:1. Accordingly, the minimum pattern width was approximately 14 μm.

It was clarified that 1-pixel isolated patterns and 2-pixel 1:1 L&S patterns were surely printed. All the patterns were very smooth without notches, and pattern widths in all directions were almost homogeneous. Width variations of radial oblique patterns were within ± 3 μm. In addition to fundamental line patterns, complicated patterns such as a university mark were also successfully printed. The fabrication cost of the system was only ¥500,000 (€3500). The system will be sufficiently acceptable to small company engineers.

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