Performances of Fine-Pitch Lenticular Lens Arrays Fabricated Using Semi-Cylindrical Resist Patterns

Toshiyuki Horiuchi*, Maiko Kurata, Satoshi Miyazawa, Akira Yanagida, and Hiroshi Kobayashi

Tokyo Denki University, 5 Senju-Asahi-cho, Adachi-ku, Tokyo 120-8551, Japan
*horiuchi@cck.dendai.ac.jp

Utilizing semi-cylindrical patterns of negative resist SU-8, lenticular lens arrays with a fine lens pitch of 100 µm were fabricated. The patterns were formed on 240-µm thick quartz plates coated with 100-µm thick SU-8 by the defocused projection exposure using a normal reticle with 50-µm line-and-space (L&S) patterns. Because the SU-8 was almost transparent for visible light with wavelengths longer than 400 nm, the patterns were directly used as lenticular lens arrays as they were. Next, a lenticular lens array set was assembled by placing a quartz plate with the lens patterns on an apple picture covered with a film reticle of 50-µm L&S patterns. When the set was observed with great interest, two scenes of an apple and all black were successfully switched alternately. Because the lens pitch of 100 µm was considerably smaller than the conventional one of 254 µm, smoothness of the picture edge was notably improved especially at inclined parts of the pictures. However, the angle for switching the two scenes was as small as approximately 6º. It was discussed that the small angle switching was caused by the substantial thickness of the lens array set including thicknesses of the quartz plate and the reticle film, and the angle might be controllable by decreasing the thickness.

Keywords: Lenticular lens, Two-scene switching, Two-image switching, Projection lithography, Semi-cylindrical pattern, Defocused exposure

1. Introduction

It was clarified in the past research that cross section profiles of patterns printed in a thick resist film using projection lithography are variously changeable by adjusting the defocus and the exposure time. And, on the way to develop a method for fabricating micro-flow path patterns with vertical side walls using a 100-µm thick negative resist of SU-8 (MicroChem) [1,2], it was found that semi-cylindrical patterns closely connected with neighbered ones were formed when line-and-space (L&S) patterns were projected under largely defocused conditions. In addition, the curvature radii of semi-cylindrical surfaces were controllable in a wide range [3]. The semi-cylindrical curves were very similar to the surface profiles of lenticular lenses used for switching two pictures alternately or making three dimensional photographs observable without any special glasses. For this reason, it was thought that the semi-cylindrical patterns would be applicable to molds for fabricating lenticular lenses. The lens pitch of commercial lenticular lenses used as souvenirs, greeting cards, and picture books for children is 1/100 in = 254 µm. For this reason, it was thought if lenticular lenses with finer pitch of 100 µm were applied, the picture qualities such as edge sharpness of inclined lines and shapes, resolution of complicated pictures, and others might be improved. However, such approaches have not been reported yet [4-7].

It is not so easy to fabricate lenses with the same profiles as the resist molds, because the original mold profiles should be replicated to the inverse ones at first, and the inverse second mold profiles have to be transferred once more to the final lens material. For this reason, it was thought important that the fundamental performances of the lens pattern profiles should be evaluated by a simpler and easier method at an early stage. Therefore, the SU-8 patterns were directly used as the lenticular lens...
arrays. Because the main base material of the SU-8 is the epoxy resin, the SU-8 has high transmittance for visible light with wavelengths longer than 400 nm, and it looks almost transparent and colorless. Thus, after semi-cylindrical SU-8 patterns are formed on thin quartz plates, they are used directly as lenticular lens arrays, and characteristics of fine-pitch lenticular lens arrays are investigated.

Various fabrication methods of micro-lens arrays have been developed [8-24]. However, the authors thought that the concerned technology was inventive and most suitable for this application.

2. Fabrication of lenticular lens patterns

The semi-cylindrical patterns were formed by printing 1:1 L&S patterns with a width of 50 µm in thick resist films with a thickness of 100 µm under largely defocused conditions. Being caused by the defocus, pattern images were blurred, and the resist at the line pattern positions was also partially exposed, and the light intensity was distributed as it decreased gradually from the bright space center to the opaque line center. For this reason, when such light intensity distribution was given to the negative resist SU-8, and the exposure light dose was appropriately adjusted, semi-cylindrical patterns were formed, as shown in Fig. 1.

The quartz plates had a thickness of 240 µm and a size of 50 mm square, and the semi-cylindrical patterns were formed using a film reticle with 50-µm L&S patterns. As a lithography tool, a handmade projection exposure system was used [1-3]. The exposure light source was an ultra-high pressure mercury lamp (Inflidge, UV-CURE120). As a projection lens, a camera lens for macro-photography (Sigma AF 50 mm F2.8 EX DG MACRO) was used under the condition of F=2.8. The projection ratio was adjusted approximately 1:1. From these parameters, the numerical aperture (NA) was calculated to be 1/4F=0.089. Although the available exposure size was 15 mm square, the patterning area was limited to 4×5 mm² for printing patterns under various exposure conditions on an identical quartz plate. As a resist, negative SU-8 100 was used. The resist was coated in approximately 100 µm thick by setting the main spin speed at 2,000 rpm. Patterns were printed under the defocus condition of +3,000 µm. The focus origin was defined as the focal position where 5-µm L&S patterns were printed most clearly. The plus defocus means that a quartz plate is moved downward separating from the projection lens.

However, because the quartz plates were not slashed off sharply, pattern profiles were observed at first using patterns printed on a silicon wafer. Cross section profiles of patterns observed by a scanning electron microscope (JEOL, JSM-5510) are shown in Fig. 2. It was confirmed that aimed lenticular lens patterns were formed and the curvature radius was controllable by changing the exposure time.

| Exp. time (s) | Cross section profile |
|---------------|-----------------------|
| 55            | ![Cross section profile](image1) |
| 60            | ![Cross section profile](image2) |
| 65            | ![Cross section profile](image3) |

Fig. 1. Fabrication of semi-cylindrical patterns by adopting the defocused projection exposure.

Fig. 2. Cross section profiles of semi-cylindrical patterns formed on a silicon wafer.
Next, profiles of the lenticular patterns formed on a quartz plate were measured using a laser microscope (Keyence, VK-X100). The results are shown in Fig. 3. Lenticular lens arrays with various curvature radii were successfully formed. Because the curvatures were slightly distorted in some places, each mean radius $R$ was calculated by the lens pitch $p$ and the height $h$ of convex part assuming the profiles were circular. When the angles $\theta$ and $\varphi$ are defined, as shown in Fig. 4,

$$R = \frac{p}{2 \sin \theta}, \quad (1)$$
$$\varphi = \tan^{-1} \frac{2h}{p}. \quad (2)$$

On the other hand, considering the sum of inside angles of $\triangle ABO$ is $\pi$,

$$\varphi = \pi - \frac{1}{2}(\pi - \theta) - \frac{\pi}{2} = \frac{\theta}{2}. \quad (3)$$

Substituting Eqs. (2) and (3) for $\theta$ in Eq. (1),

$$R = \frac{p}{2 \sin 2\varphi} = \frac{p}{2 \sin \left(2 \tan^{-1} \frac{2h}{p}\right)}. \quad (4)$$

When $\theta$ and $\varphi$ are small angles, Eq. (4) is simplified as

$$R = \frac{p^2}{8h}. \quad (5)$$

![Fig. 4. Parameters used for measuring the curvature radius from a semi-cylindrical cross section profile.](image)

From Eq. (5), mean curvature radii of SU-8 lenticular lens arrays were obtained. The curvature radius depended on the exposure time as shown in Fig. 5.

![Fig. 5. Curvature radius dependence on exposure time.](image)

### 3. Performances of a lenticular lens array

Using the SU-8 lenticular lens arrays, optical properties were investigated next. A quartz plate with the lenticular lens arrays were set on a 50-µm L&S film reticle and an apple picture, as shown in Fig. 6. As a result, the scenes were clearly switched between apple and all black ones alternately for the lens array formed by exposing 80 s, as shown in Fig. 7.
When a lenticular lens array is used, each scene is formed by stitching oblong picture elements by the lens pitch, and inclined figures and lines become step-like. However, because the lens pitch was reduced to 100/250 ≈ 1/2.5 of the conventional one, the inclined edges were observed considerably smoother than those of conventional lenticular lenses, as shown in Fig. 8.

Next, inclination angle of the lens set for switching two scenes were measured. The results are shown in Figs. 9 and 10. It was clarified that two figures were alternately switched by changing the inclination angle of the lens set approximately 6°. It was felt that scenes are not steady because they are switched by slightly changing the view angle. This phenomenon is discussed in the next session.

**4. Discussion**

Lenticular lens parameters were discussed for switching two scenes and observing them clearly and distinguishably. At first, the cause why two
scenes were changed so easily by inclining the lenticular lens set only the very small angle of 6º was discussed. The inclination angles for switching two scenes were generally set at 30-45º in conventional lenticular lens sets.

This time, the lenticular lens set was composed of a 180-µm thick film reticle with 50-µm L&S patterns, 240-µm thick quartz plate, and 100-µm thick lens patterns of SU-8. As a result, total thickness of the lenticular lens set was 520 µm. Roughly estimating, all of the refraction coefficients of these materials are 1.65. Therefore, the lenticular lens set was considered almost equivalent to a simple lenticular lens with a lens thickness of 520 µm and an element lens pitch of 100 µm.

Sliced elements of two scenes to be switched by the lenticular lens are arranged under the bottom of the lens in two halves alternately, as shown in Fig. 11. The center light rays to observe each picture element are shown as the lines connecting the element centers at the bottom and the surface center of lenticular lens. The rays from the element centers are inclined each other by the angle of 2α in the figure, and α is calculated by

\[ \alpha = \tan^{-1} \left( \frac{p}{4t} \right). \]  

(6)

Here, p is the lens pitch, and t is the lens thickness. Therefore, α becomes 2.75º when p=100 µm and t=520 µm. Accordingly, it is supposed that two scenes are switched by inclining the lenticular lens set at the angle of 2α=5.5º. The demonstrated results shown in Figs. 9 and 10 were almost consistent with this estimation.

On the other hand, the surface curvature of the lenticular lens should be designed just as all of the light rays come from a point of the scene element would go parallel after refracted at the lens surface between the surface side end and the surface center of the element lens, as shown in Fig. 12. When incident and refraction angles at the surface center and side end of the element lens were defined β₁, β₂, γ₁, and γ₂, respectively, as shown in the figure, and the refractive index of the lens is n₁,

\[ n_1 \sin \beta_1 = \sin \beta_2. \]  

(7)

Because n₁ is assumed to be 1.65, and β₁=α=2.75º, β₂=4.54º.  

(8)

On the other hand, 

\[ n_1 \sin \gamma_1 = \sin \gamma_2. \]  

(9)

Here,

\[ \gamma_1 = \theta - \beta_1, \]  

(10)

\[ \gamma_2 = \theta + \beta_2, \]  

(11)

\[ \therefore n_1 \sin(\theta - \beta_1) = \sin(\theta + \beta_2). \]  

(12)

Because θ, β, and β₂ are small angles,

\[ n_1(\theta - \beta_1) = \theta + \beta_2, \]  

(13)

and,

\[ \theta = \frac{n_1 \beta_1 + \beta_2}{n_1 - 1} = 13.96^\circ. \]  

(14)

Therefore, the best curvature radius R is estimated by Eq. (1).

\[ R = \frac{100}{2 \sin 13.96^\circ} = 207 (\mu m). \]  

(15)
The best performance of two scene switching was obtained under the exposure time condition of 80 s, and the curvature radius of the lenticular lens set was estimated to be approximately 250 µm from Fig. 5. Considering the slight distortions of curvature profiles in Fig. 3, it was thought that the actual radius was near to the calculated ideal value. To enlarge the angle for switching two scenes, it is necessary to reduce the substantial lens thickness and optimize the curvature radius of the lens surface in connection to the lens thickness.

5. Conclusion
A lenticular lens array set for switching two image scenes was fabricated using SU-8 resist patterns with semi-cylindrical cross sections as they were. The patterns were formed on transparent quartz plates with a thickness of 240 µm using a projection exposure system with a projection ratio of approximate 1:1 in fields of 4×5 mm². The patterns were formed under largely defocused conditions, shaded parts by the opaque patterns on the reticle were also sensitized, and patterns with semi-cylindrical cross sections convenient for lenticular lens patterns were obtained. The curvatures of the lens patterns were controlled by changing the exposure time.

When a lenticular lens set was assembled by piling an apple picture, a film reticle with 50-µm L&S patterns, and a lenticular lens array formed on a quartz plate, observed scenes were successfully switched alternately between an apple scene and a black scene. Because the lens array pitch was 100 µm and considerably smaller than 250 µm of conventional ones, picture edges were smoother, especially at inclined parts. However, two scenes were switched by inclining the lenticular lens set only a small angle of approximately 6º. The cause of scene switching in such small angle was discussed, and it was shown that the substantial thickness of the lenticular lens array should be reduced for making the two-scene switching angle larger. It was also considered that the curvature radius of the lens array was too large. This subject will also be improved by reducing the thickness of the lens array.

Acknowledgement
This work was partially supported by JSPS KAKENHI Grant Number 17K05021.

References
1. Y. Morizane and T. Horiuchi, *Proc. Biodevices*, 1 (2016) 209.
2. T. Horiuchi and Y. Morizane, *IEEEJ Trans. Fundam. Mater.*, 138 (2018) 173.
3. H. Kobayashi, Y. Morizane, and T. Horiuchi, *J. Photopolym. Sci. Technol.*, 31 (2018) 45.
4. Q. H. Wang, A. H. Wang, W. X. Zhao, Y. H. Tao, and D. H. Li, *Optik*, 122 (2011) 1326.
5. A. H. Wang, Qi. H. Wang, X. F. Li, and D. H. Li, *Optik*, 123 (2012) 827.
6. H. Kim, J. Kim, J. Kim, B. Lee, and S. D. Lee, *Opt. Commun.*, 357 (2015) 52.
7. S. M. Jung, S. C. Lee, and K. M. Lim, *Current Appl. Phys.*, 13 (2013) 1339.
8. S. Murakami, Y. Yanagida, and T. Hatsuza, *Precision Eng.*, 50 (2017) 372.
9. K. F. Lin, Y. K. Hsiao, C. C. Hsieh, S. C. Hsin, and W. F. Hsieh, *Opt. Commun.*, 367 (2016) 254.
10. Y. Li, Y. Zhang, L. Liu, and C. Yang, *Mater. Today Commun.*, 11 (2017) 119.
11. K. Zhong, Y. Gao, F. Li, N. Luo, and W. Zhang, *Opt. Laser Technol.*, 56 (2014) 367.
12. X. Zhu, L. Zhu, H. Chen, L. Yang, and W. Zhang, *Appl. Surf. Sci.*, 361 (2016) 80.
13. B. Pawlika, A. Riecka, and F. Costache, *Procedia Eng.*, 168 (2016) 1496.
14. M. T. Langridgea, D. C. Cox, R. P. Web, and V. Stolojan, *Micron*, 57 (2014) 56.
15. R. Zhang and L. Lai, *Proc. SPIE*, 9685 (2016) 968502.
16. H. S. Lee, I. Park, K. S. Jeon, and E. H. Lee, *Microelectron. Eng.*, 87 (2010) 1447.
17. J. Y. Kim, N. B. Brauer, V. Fakhfouri, D. L. Boiko, E. Charbon, G. Grutzner, and J. Brugger, *Opt. Mater. Exp.*, 1 (2011) 259.
18. Y. Luo, L. Wang, Y. Ding, H. Wei, X. Hao, D. Wang, Y. Dai, and J. Shi, *Appl. Surf. Sci.*, 279 (2013) 36.
19. F. Chen, H. Liu, Q. Yang, X. Wang, C. Hou, H. Bian, W. Liang, J. Si, and X. Hou, *Opt. Exp.*, 18 (2010) 20334.
20. K. Zhong, Y. Gao, F. Li, N. Luo, and W. Zhang, *Opt. Laser Technol.*, 56 (2014) 367.
21. B. Pawlik, A. Rieck, and F. Costache, *Procedia Eng.*, 168 (2016) 1496.
22. M. T. Langridge, D. C. Cox, R. P. Webb, and V. Stolojan, *Micron*, 57 (2014) 56.
23. C. C. Chiu and Y. C. Lee, *Opt. Lasers Eng.*, 49 (2011) 1232.
24. H. Yang, C. K. Chao, M. K. Wei, and C. P. Lin, *J. Micromech. Microeng.*, 14 (2004) 1197.