A new optical lithography method for fabricating humpbacked pattern arrays was developed. The patterns were printed by adopting intentionally defocused projection exposure under the condition of very low numerical aperture of 0.089. As a resist, approximately 100-μm thick SU-8 (MicroChem) was used, and appropriate defocuses were 1400-2000 μm. When the exposure time and the defocus were changed, curvature radiiuses of lens patterns were controllable in a wide range of 70-300 μm. The curvature radii became large when the exposure time was extended, and the defocus was reduced. The patterns will be usable as original molds of lenticular lens arrays. In addition, the patterns will also be usable as temporal lenticular lens arrays as they are, because the SU-8 is almost transparent for visible light.

Keywords: Humpbacked pattern, Lenticular lens, Projection exposure, Defocus

1. Introduction

Lenticular lens arrays are used for obtaining switchable pictures and three-dimensional photographs [1-4]. At present, they are mainly used as artistic small objects and souvenirs. Spatial frequencies of commercially available typical lenticular lenses are 40-100 lenses per inch (Lpi). These spatial frequencies correspond to lens pitches of 635-254 μm. Most of the lens arrays are fabricated by plastic molding, and the surfaces are not so smooth as polished glass lenses. Therefore, if lens arrays with finer pitches and smoother surfaces are easily obtained, it is expected that the clearness and image edge smoothness of switched pictures and three-dimensional photographs are improved.

For this reason, lithographical fabrication method of lenticular lens arrays is investigated here [5]. Cross section profiles of humpbacked patterns printed by the new method are investigated in detail, and the controllability of curvature radius by changing the defocus and the exposure time is clarified.

To print patterns appropriate for the lenticular lens arrays, a unique projection lithography is applied. A handmade projection exposure system with a low numerical aperture (NA) of 0.089, a projection ratio of approximately 1:1, and a field size of 15 mm square is used, and the patterns are printed under very largely defocused conditions. The system was originally developed for printing large patterns with widths of 30-100 μm in thick resist films with thicknesses of 50-200 μm [6, 7]. The resolution of the exposure system is around 4 μm for a thin resist with a thickness of 1 μm. However, because the NA is small, the depth of focus (DOF) is very large. Therefore, it is possible to print very thick resist patterns with vertical side walls if the patterns are printed under appropriately defocused conditions. Such patterns are applicable to fabricate micro-fluidic devices. In fact, micro-mixers with 50-100 μm wide and 100 μm deep resist flow paths were fabricated using the resist SU-8 (MicroChem) with a thickness of 100 μm, and they were used for investigating diffusive mixing of two liquids [8].

During the research of finding out the best defocus condition for printing patterns with vertical side walls, it was noticed that patterns with gently curved surfaces were obtainable under
1400-2000 µm defocused conditions using a reticle with line and space (L&S) patterns, while the best defocuses to obtain patterns with vertical side walls were 3000-3800 µm [6]. In both cases, the wafer was moved downward separating from the projection lens. Gently curved periodical circular profiles at the surface were surely obtained, and the humpbacked patterns were regularly arrayed without intervals and overlaps.

For this reason, it was thought that the humpbacked patterns might be applied to fabrication of lenticular lens arrays. The fact that the lenticular lens patterns are printable by one and only lithography process is a large merit. Therefore, patterning characteristics are investigated in detail here.

2. Fabrication of lenticular lens patterns

The handmade exposure system used for printing lenticular lens patterns is shown in Fig. 1 [6]. The exposure source was a high-pressure mercury lamp (Infridge, UV-CURE 120), and the nominal light intensity was 4000 mW/cm² at the wavelength of 365 nm. As a projection lens, a commercially available camera lens for macro-photography (Sigma AF 50 mm F2.8 EX DG MACRO) was used. Because the F-number of the lens was set at 2.8, and the projection ratio was almost 1.0, the calculated NA value was 0.089. The sizes of the system were 300(W)×600(D)×900(H). A film reticle with 50-µm L&S patterns was used for printing the patterns. As a resist, 100-µm thick SU-8 was used.

Changes of cross section profiles of patterns printed under the conditions of 1000-2200 µm defocuses and 40-45 s exposure times are shown in Fig. 2. The patterns were observed using a scanning electron microscope (SEM) (JEOL, JSM-...
It was clarified that lenticular lens patterns were obtained under defocus conditions of 1400-2000 μm. It is thought that such lenticular lens patterns are formed because the space parts of the L&S patterns were exposed wider than the space widths by the defocus, and only the central parts of opaque lines were not sensitized sufficiently. For this reason, the central parts of opaque lines are shallowly dissolved when the exposed wafers were developed in the developer after the post exposure bake. Therefore, the pitch of lenticular patterns accords with the pitch of L&S patterns, that is, $2 \times 50 \, \mu m = 100 \, \mu m$.

Next, cross section profile dependence on the exposure time were investigated, as shown in Fig. 3. Here, photographs are the patterns for the defocuses of 1600 and 1800 μm. Pattern profiles were also controllable by changing the exposure time.

So, curvature radii of patterns were measured by pasting the photographs on a screen of mechanical drawing software (Auto CAD 2015, Autodesk). Because the surface profiles turn from convex curves to concave curves near the bottom valley in some cases, circular arcs were drawn by pointing the peak and the both turning points, as shown in Fig. 4. However, roughly speaking, most of the convex arcs were almost sharply connected with the neighbored arcs. The radii of the arcs were measured using a function of the software. When an arcs was clicked by a mouse pointer, the radius was indicated on the screen.

Relationships between the curvature radii and the exposure conditions are shown in Figs. 5 and 6. It was demonstrated that the curvature radius was...
Fig. 6. Relationship between the curvature radius and the exposure time for various defocuses. Controllable between 70 and 300 µm by appropriately adjusting the exposure time and the defocus.

3. Discussion on applicability to actual lenticular lens arrays

Applicability of the lenticular lens patterns was discussed. At first, a commercial lenticular lens array shown in Fig. 7 was prepared, and the profile was measured using a surface roughness measuring system (Kosaka Laboratory, SE1700). The measurement result is shown in Fig. 8. The pitch \( p \) of the element lens was 423 µm and the convex height \( h \) was approximately 40 µm. The circular curves were sharply connected at valleys without roundness, and the curvature radius \( r \) is calculated assuming the profiles were circular.

![Fig. 7. Commercial lenticular lens array used for measuring the lens surface profile.](image)

When the curvature radius is \( r \) and a half angle of the lens patterns is \( \theta \), as shown in Fig. 9,

\[
\sin \theta = \frac{p}{2r} .
\]  
(1)

On the other hand,

\[
r \cos \theta = r - h .
\]  
(2)

From (1) and (2),

\[
\left( \frac{p}{2r} \right)^2 + \left( \frac{r-h}{r} \right)^2 = 1 .
\]  
(3)

\[
p^2 + 4(r-h)^2 = 4r^2 .
\]  
(4)

Accordingly,

\[
r = \frac{p^2 + 4h^2}{8h} .
\]  
(5)

![Fig. 9. Figure drawn for calculating the curvature radius of the lens assuming the lens profile is circular.](image)

When the actually measured \( p \) and \( h \) were substituted in Eq. (5), \( r \) became 579 µm, and the ratio of \( r/p \) became 1.37. In the case of printed lenticular lens patterns, \( p=100 \) µm, and \( r=70-300 \) µm. Therefore, the ratio of \( r/p \) was 0.7-3.0. From this
result, it was confirmed that the profiles of printed lenticular lens patterns were changeable including the profile similar to the commercially used one.

Smoothness of printed lenticular lens patterns were investigated also. Examples of magnified surface profiles are shown in Fig. 10. There remained slight unevenness on the surface. So, it should be improved a little more. However, roughness of the surface was somewhat smaller than the measured roughness of the commercial product shown in Fig. 8.

If the lenticular lens profiles were useful, mainly two methods are thought up for fabricating practical lenticular lens arrays. One is a method using the resist patterns as an original model of a metal mold. If nickel or other metal is electroplated on the resist model, a micro metal mold is obtained after the resist model is removed. Using the metal mold, glass or plastic lenticular lens arrays are replicable by the injection molding.

Another is a method using the resist patterns as a temporal lenticular lens array as they are. The transmittance of resist SU-8 for the visible light with wavelengths longer than 400 nm is higher than 0.95, as shown in Fig. 11. And, the refractive index of SU-8 is supposed to be 1.5-1.55, because the main component is the epoxy resin. Therefore, it is expected that the patterns are directly usable as lenticular lenses, if they were printed on glass or quartz substrates.

Both methods are hopeful, and it is thought that the applicability of the lenticular lens patterns to the fabrication of lenticular lenses is considerably high.

### 4. Conclusion

Patterns suitable for fabricating lenticular lens arrays were printed by one and only lithography process using the projection exposure of 50-µm L&S patterns under large defocus conditions. The surface of the resist SU-8 was gently and smoothly curved periodically in a pitch of 100 µm. The curvature radius was regularly controllable between 70 and 300 µm by adjusting the exposure time and the defocus.
When lens pitch and curvature radius of a commercial lenticular lens array were investigated, it was clarified that ratio between the pitch and the curvature radius of the commercial lens array was in the same range as the fabricated resist lens array. In addition, the surface roughness of the resist lens patterns was smaller than that of the commercial lens array. Therefore, the fabricated patterns will be probably applicable to fabrication of lenticular lens arrays.

Patterns will be usable as the original models for fabricating metal molds of lenticular lenses. Using the metal mold, glass or plastic lenticular lens arrays will be produced by injection molding. On the other hand, the patterns will be directly usable as lenticular lenses, because the SU-8 has a very high transmittance of more than 0.95 for the visible light.

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