Fabrication of Concave Resist Patterns for the Use of Reversal Molds of High-Density Micro-Lens Arrays

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Almost spherical concave resist patterns in a dense array were fabricated to be used as reversal molds of plastic convex micro-lens arrays. In the past research, such micro-lens arrays were replicated using concave metal molds fabricated by replicating original convex resist patterns. However, it was difficult to fabricate the original convex resist patterns densely in a matrix. In addition, because two replication processes from resist to metal and from metal to plastic resin were necessary, procedures were very complicated, and it took long times for obtaining final plastic resin lens arrays. In the new method, original concave mold patterns were obtained by simple 1/19 projection-exposure lithography including only one exposure and one development by applying largely defocused exposure intentionally. Despite the simplicity, very wide-range curvature radiuses of 25-120 μm were obtained by giving various exposure doses even using reticles with same 500-μm transparent square patterns. It was basically checked that epoxy resin lens arrays were obtained by mechanically separating them from the concave resist molds.

Keywords: concave pattern, resist mold, micro-lens array, defocused exposure, epoxy resin

1. Introduction

Convex micro-lens arrays are very important optical components used for making light-spot arrays. They have already been widely applied to cover lenses of image sensors [1,2], illumination homogenizers [3,4], interconnection optics of optical fibers [5,6], and solar cells [7,8]. In addition to making light-spot arrays, they are also used for making image arrays, and various new applications are reported or proposed [9-12]. For this reason, various fabrication methods of micro-lens arrays are also researched and developed very eagerly, and new methods are frequently proposed one after another. Representative methods are thermal reflow of resist or plastic materials [13,14], etching of glass or plastic materials [15,16], ink-jetting of lens materials [17,18], tracking of laser light [19,20], gray scale lithography [21,22], and embossing [23,24]. What fabrication method is appropriate depends on the applications or necessary lens parameters and sizes. In addition, availability and fabrication costs or purchase prices are considered in many cases. It is thought that such wide variety of fabrication methods is mainly caused by the differences of application purpose and cost performance.

The authors also developed a method for fabricating micro-lens arrays using lithography with defocused projection exposure, nickel electroplating, and pour of epoxy resin in the past research [25,26]. In this conventional method, semi-spherical convex resist patterns were quite easily fabricated at first using defocused projection exposure lithography. However, it was difficult to fabricate dense resist pattern arrays in which each convex resist pattern was closely allocated. In addition, the fabrication processes were somewhat complicated, and it took long times for obtaining final lens arrays of plastic resin. Besides, because two replication steps of resist to nickel and nickel to epoxy resin were necessary, it was anticipated that cumulative replication errors arose.
For this reason, a simpler and more inexpensive fabrication method of plastic lens arrays is contrived here. All of simplicity, cost for preparing facilities and instruments, and flexibility for the change of lens parameters are far superior to the conventional method developed in our past research for fabricating similar epoxy lens arrays with diameters of 20-50 μm.

In the new method, almost spherical concave resist patterns are densely printed using similar defocused projection exposure lithography at first, and the resist patterns are used as the original mold. Next, transparent liquid epoxy resin with a hardening agent is poured onto the resist molds. After leaving the resin till it is hardened, the resin lenses are mechanically separated from the resist molds, and it is basically checked that epoxy resin lens arrays are certainly obtained [27,28].

In this paper, details of concave patterning and evaluation results on resist-mold patterns, and controllability of lens parameters are demonstrated.

2. New Fabrication Method of Lens Arrays

The authors developed a method for fabricating micro-lens arrays using projection lithography under the intentionally defocused condition, nickel electroplating, and replication to epoxy resin in the past research [25,26]. However, there were several problems in the method.

To begin with, it was difficult to fabricate dense resist pattern arrays in which each convex resist pattern was closely allocated. Second, the processes composed of patterning, electroplating of nickel, and replication to epoxy resin were complicated and needed long times. In addition, because the electroplated nickel molds should be used many times for replicating resin lenses, hardened lenses had to be removed easily from the nickel molds. However, the removability was not good, and it was difficult to remove the lenses without coating an anti-adhesive material on the nickel molds. For this reason, it was worried that size errors caused by the replication became large.

Considering these problems, it was required that a new fabrication method should be developed for drastically simplifying the fabrication processes, enabling to obtain densely crammed lens arrays, and decreasing size errors caused by the replication. For this reason, a new fabrication method of lens arrays was developed, as shown in Fig. 1.

In the first step, concave patterns in an array are printed using optical projection lithography, as shown in Fig. 1(a). Positive PMER LA-900PM

(Tokyo Ohka Kogyo) with a thickness of 10-12 μm was used as a resist. Under appropriate defocus and exposure dose conditions, concave patterns with almost spherical profile appropriate for the molds were formed. In the second step, a wafer chip with the resist-mold patterns was fixed at the bottom of a small paper cup using a small strip of both-sides adhesive tape, and transparent epoxy resin mixed with a hardening agent in a liquid phase (Nissin Resin, CR-61) is poured onto the wafer chip with the resist-mold patterns, as shown in Fig. 1(b). To remove bubbles in the resin and mix the resin and hardening agent homogeneously, the paper cup was put in a special mixing machine (Thinky, AR-100). The bubbles were removed during the resin and hardening agent were mixed. The resin was left till it was hardened in a solid phase. Next, the solid resin block was taken out from the paper cup, and the adhesive tape was removed, as shown in Fig. 1 (c). Then, the silicon wafer chip with the concave resist-mold patterns was mechanically separated from the hardened resin block, as shown in Fig. 1(d). To separate the
wafer chip from the resin block, fine grooves were dug along the sides of silicon wafer chip using a cutter knife. After that, when forces were given at corners of the silicon chip using a pair of tweezers, air was gradually penetrated between the resin block and the resist mold. Finally, the wafer chip was removed by inserting a tip of tweezers between the wafer chip and the resin block. Thus, transparent plastic lens arrays were obtained.

Figure 2 schematically compares the convex resist patterns used in the conventional method and the concave resist patterns used in the new method. In the case of conventional method, convex resist patterns of positive resist become smaller than the reticle pattern images because the patterns were printed under the intentionally defocused conditions. On the other hand, in the case of the new method, concave resist patterns become larger than the reticle pattern images.

Accordingly, it was enabled to print resist-mold patterns arrayed denser. Moreover, because the resist-mold patterns were directly replicated to the epoxy resin, fabrication processes were drastically simplified. In addition, because it was not necessary to use the anti-adhesive materials, it became unnecessary to care size errors caused by coating them.

### 3. Patterning of Concave Resist Patterns

Concave patterns were printed by defocused projection lithography using binary reticles. Prepared reticle patterns are shown in Fig. 3. Square transparent patterns with a size of 500 μm were uniformly allocated in arrays. The reason why square patterns were used is because it became easy to investigate the cross section profiles of the concave patterns by breaking the wafer in parallel to the square sides.

The concave patterns were printed using a handmade 1/19 projection exposure system [25-28]. Accordingly, the square pattern size was reduced to 26.3 μm on a wafer plane. This size was decided by considering the application to fabricate artificial compound eyes in the next research step. Opaque gaps between transparent square patterns were changed in three steps of 200, 300, and 400 μm for investigating patterning characteristics in detail. If patterns were printed under appropriately large defocus conditions, sensitized areas were enlarged, and semi-spherical concave patterns with cross section profiles suitable for molds of micro-lenses were obtained.

The field size on a wafer was approximately 2-mm square, and lens pitches on a wafer were 700/19=37, 800/19=42, and 900/19=47 μm, respectively according to the opaque gaps. Numbers of lenses in a line and in a column were calculated to be from 2000/47=42 to 2000/37=54.

The concave patterns were printed in exposure fields sufficiently separated each other, and the wafer was broken into chips with several-mm rectangle sizes to fabricate lens arrays individually.

In the exposure system, a special ultra-violet lamp (Sumita Optical Glass, LS-140UV) was used as an exposure source, and a camera lens for macro photography (Canon, New FD/2.8) was used as a projection lens. Because the F-number was set at F=4, and the projection ratio was 1/19, the calculated numerical aperture (NA) was 0.12.

![Fig. 2. Difference of resist-mold pattern intervals between conventional and new methods.](image1)

![Fig. 3. Reticle patterns used for printing concave resist patterns. Unit of the sizes is μm.](image2)
At first, a focal position at which the side walls of patterns became most vertical was searched, and the position was defined as the focal origin where the defocus was 0 µm. Cross section profiles also varied depending on the light absorbance of resist besides the defocus. For this reason, the exposure light was filtered using a band pass filter of 405 nm wavelength (Asahi Spectra, MZ0405). Measured full width half maximum of the filter was 8 nm. The wavelength of 405 nm was selected as the best one among three wavelength candidates of 365, 405, and 436 nm for printing concave patterns appropriate for original molds of micro-lenses using the resist with a thickness of approximately 12 µm. In the case of concave patterning, the resist is sensitized only at the surface. Accordingly, the thickness did not almost influence the resist pattern profiles if it was sufficiently thicker than the concave depth.

When patterns were formed by giving exposure dose of 384 mJ/cm², and using a reticle with an opaque gap of 400 µm, cross sections of resist patterns varied, as shown in Fig. 4, depending on the defocus conditions. This dose corresponded to the exposure time of 10 min. Concave patterns with smooth and circular cross sections were obtained at the defocus of +150 µm. Here, plus means that the wafer was moved downward, and separated from the projection lens.

Figure 5 explains the reason why such round or circular profiles are obtained under the appropriate plus defocus condition. This is because the light rays spread according as the light goes down in the resist, and sensitized area widely spreads at the bottom. If the focal position is shifted in the minus direction by moving the wafer upward, imaging light rays become narrow according as the light rays go down in the resist. Accordingly, the sensitized area at the bottom becomes narrow. For this reason, the sensitized area tends to have a simply inclined side wall profile, and bottom profiles become triangular.

4. Evaluation of Concave resist Patterns

It was very difficult to break silicon wafers at the exact centers of the patterns for observing the cross sections using a scanning electron microscope. For this reason, cross section profiles were evaluated in detail using a laser microscope (Keyence, VK-8510), next. Measured profiles are shown in Fig. 6. It was clarified that the curvature radiiuses and concave depths were very widely changeable by selecting appropriate exposure
doses and opaque pattern widths.

Measured profiles were copied and pasted on a screen of computer aided design software (Autodesk, AutoCAD 2014), and lens-shape parameters and profile errors from real circles were measured, as shown in Fig. 7, using functions of the software. The reference circle was delineated as a circle passing the points of tangency A and C on both sides and the bottom point B. Then, the curvature radius $R$, maximum concave depth $d$, and maximum profile error $\delta$ from the reference circle were measured. Curvature radius variations depending on the exposure dose and opaque gaps between square transparent patterns are shown in Fig. 8. The curvature radius was controllable in a very wide range of 25-120 $\mu$m by changing the exposure dose. On the other hand, curvature radius did not almost depend on the opaque gaps between square transparent patterns.

Next, the concave depth dependence on the opaque gaps between square transparent patterns is shown in Fig. 9. It was clarified that the concave depth of resist mold patterns was controllable between 1 and 10 $\mu$m by changing the exposure dose and the opaque gap.

Accuracy of the curvature profiles compared with the ideal circle was also investigated, as shown in Fig. 10. It was verified that the maximum curvature errors were considerably small, and they

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<th>Exposure dose (mJ/cm²)</th>
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Fig. 6. Variations of curvature profiles. Radiuses and depths of curvature profiles were widely variable by changing the exposure dose and the opaque gap between transparent square patterns.

Fig. 8. Curvature radius dependence on exposure dose and opaque gap between transparent squares.

Fig. 9. Relationship between concave depth and exposure dose. Concave depth depends on opaque gaps between transparent squares also.

Fig. 10. Accuracy of curvature profiles compared with the ideal circle.
were less than the measurable limit of 0.1 µm when the exposure dose was less than or equal to 300 mJ/cm².

Finally, bird’s-eye views of the concave patterns were investigated, as shown in Fig. 11. Although the distributions of the concave profiles should be investigated in detail hereafter, it seems that the patterns are almost homogeneously and densely fabricated judging from the views instinctively.

5. Discussion

Prospects and next-step subjects of this research were discussed. Concave resist patterns were successfully fabricated by the defocused exposure using binary-tone reticles. It was required only one exposure and one development. Accordingly, the patterning processes were very simple and easy. In addition, although square window patterns were completely separated each other by opaque patterns placed between them, quite densely located concave patterns were printable by controlling the exposure dose and the opaque pattern width.

However, such great advantages become insignificant if the concave resist patterns were not easily and faithfully replicated to the resin, and expected plastic lens arrays were not obtained. For this reason, vital possibility for separating the plastic resin from the wafer chip with the concave resist patterns was investigated. In concrete, liquid epoxy resin was actually poured on the concave resist-mold patterns fabricated on wafer chips fixed at the bottom of a paper cup one by one. And, after the resin was hardened, the resin block was taken out by breaking the paper cup. Next, the wafer chip was forcibly removed by making grooves along the chip sides, and inserting a tip of tweezers. As a result, it was clarified that the lens arrays of epoxy resin were certainly separated from the concave resist-mold patterns [27,28]. Therefore, it was verified that the concave patterning is fruitful.

On the other hand, the measure to separate the resin and resist forcibly by a mechanical method was primitive and impractical. On the next stage, an improved effective and practical method should be developed. It is also necessary to develop a
method to make the resin blocks far thinner, and fabricate the lens arrays on the surfaces of the thin base layer of resin.

6. Conclusion
A fabrication method of almost spherical concave resist patterns in a dense array was investigated. The patterns were printed using projection lithography under the intentionally defocused conditions. In concrete, 500-µm square patterns with opaque gaps of 200, 300, and 400 µm were projected in 1/19.

As a result, concave patterns with curvature radiuses of 25-120 µm were obtained under the defocus condition of +150 µm. Because the curvature radius did not almost depend on the opaque gaps between transparent square patterns, it was considered that the curvature radius was easily controllable by changing the exposure dose.

The concave depth was also controllable by adjusting the exposure dose and changing the opaque gaps between transparent square patterns.

Cross section profiles of concave patterns were almost circular, and errors from the real circles were very small. Errors were less than the measurable limit of 0.1 µm except under very large exposure dose conditions.

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References