New Fabrication Method of Plastic Micro-Lens Arrays for Researching on Compound Eyes of Insects

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Abstract: To develop artificial compound eyes, sizes of element lenses of typical insects were actually investigated, and a new simple and low-cost method for fabricating plastic micro-lens arrays was developed. It was thought essential to research on artificial compound eyes that lens parameters were freely controllable by our minds. For this reason, a new easy and low-cost fabrication method had to be developed. In the new method, original molds of micro-lens arrays with concave profiles were formed lithographically in a thick resist film. The concave resist patterns were printed using a handmade 1/19 reduction projection exposure system by only one exposure. Using intentionally defocused exposure, curvature radiuses were controllable in a very wide range of 21-85 μm for the same transparent hexagon patterns with an inscribed circle diameter of 26.3 μm. It was also verified that the resist-mold patterns were faithfully replicated to epoxy resin. After pouring the liquid resin onto the silicon wafer chip with resist-mold patterns, hardened solid resin with micro-lens arrays was separated from the wafer chip by peeling off the wafer chip mechanically. It is promising to fabricate micro-lens arrays with aimed lens parameters although some more subjects should be cared from now on.

1 INTRODUCTION

Human beings have been imitating distinguished functions of other living things, and invented various apparatuses exercising performances superior to the original ones. Recently, biomimetic technologies utilizing exquisite functions or special organs of small insects or protozoa are drawing attension for improving our lives or curing some diseases of our organs. For example, structures of morpho-butterfly are utilized for obtaining highly reflective surfaces with beautiful blue colors in wide view angles (Neu et al., 2015) (Saito et al., 2004). Hydrophobic surfaces are researched by getting hints from wrinkles of living things (Bowden et al., 1998) (Genzer and Groenewold, 2006). Flapping flight technology reffering to insects are also researched for developing light and small flying robots (Maet al., 2013).

Organs that the authors are especially interested are compound eyes of insects. They are excellent optical systems that humans are not equipped, and a lot of very interesting papers were published (Chen et al., 2011) (Ogata et al., 1994) (Sanders and Halford, 1995) (Cao et al., 2015) (Li et al., 2013) (Tanida et al., 2001) (Duparré et al., 2006) (Jeong et al., 2006) (Jiang et al., 2015). Compound eyes are highly precise optics using micro-lens arrays, and new applications will probably be found in the future besides ordinary usage as eyes.

To start researches on compound eyes, it was thought preferable to possess technology for fabricating micro-lens arrays with various lens parameters such as diameters and curvature radiuses by ourselves easily. For this reason, a new fabrication method of plastic micro-lens arrays is investigated here.

2 SURVEYS ON SIZES OF LENS ARRAYS

Compound eyes have been eagerly researched in the world, and artificial compound eyes have also been reported (Ogata et al., 1994) (Tanida et al., 2001) (Duparré et al., 2006) (Li et al., 2013). Accordingly, typical sizes of micro-lens arrays are known. However, in the first step, it is preferable that actual examples are easily obtained, and they are easily observed for imitating them. For this reason, compound eyes of cicada, dragonfly and goldbug were in fact investigated. Outlooks of insects and magnified photographs of their compound eyes are shown in Figures 1-3.

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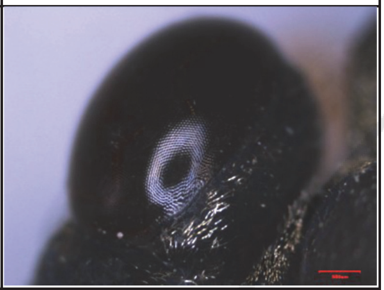
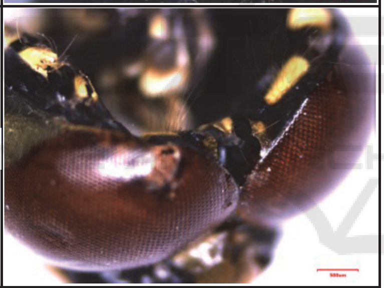
(a) Cicada (b) Dragonfly (c) Goldbug

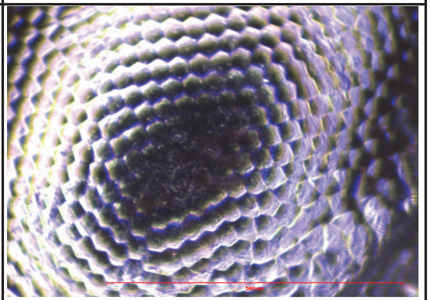
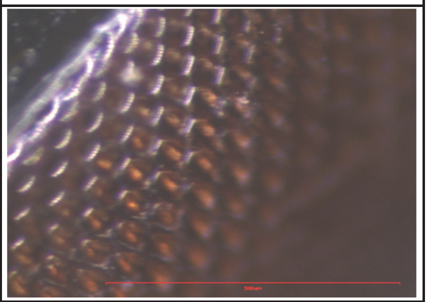
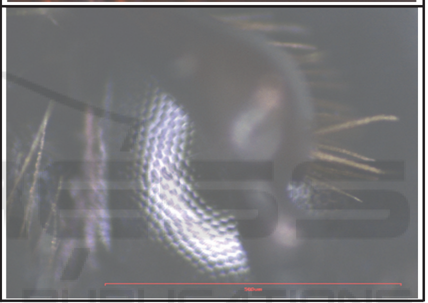
Figure 1: Insects whose compound eyes were investigated.

Insect	Outlook of compound eye
Cicada	
Dragonfly	
Goldbug	

500 µm

Figure 2: Photographs of compound eyes of insects.

All of investigated compound eyes were composed of micro-lenses arrayed in dense hexagonal arrangement like a honeycomb. Typical widths of the element hexagons or the inscribed circle diameters of element lenses were 33, 53, and 16 µm, respectively. For, this reason, sizes of fabricating micro-lenses were

Insect	Magnified view of compound eye
Cicada	
Dragonfly	
Goldbug	

50 µm

Figure 3: Magnified view of compound eyes of insects.

tentatively fixed to around above diameters, and a new simple and easy method for fabricating plastic lens arrays was investigated. It was considered that the lens parameters such as diameters, pitches, and curvature radiuses should be widely controllable to increase the facility of optical designs. In addition, lens arrays should be fabricated by researcher ourselves according to necessary specifications. Regrettably, roundness or curvature radiuses of the micro-lenses were not detectable. However, lens characteristics are defined by both side curvatures of the lens. In addition, the medium behind the lens is not air but organic materials. Accordingly, refraction characteristics of the lens are not decided only by the curvature radius of the lens surface. For this reason, it was thought that measurement of the lens surface curvature was not necessarily required on this stage.

3 NEW FABRICATION METHOD OF MICRO-LENS ARRAYS

Various fabrication methods of micro-lens arrays have already been developed in the world. Representative methods are ink-jetting (Zhu et al., 2015) (Luoa et al., 2013) (Voigt et al., 2011) (Kim et al., 2011), etching (Chen et al., 2010) (Deng et al., 2012), grey scale lithography (Wu et al., 2002) (Kuang et al., 2009) (Yang et al., 2007), laser tracking (Wang, 2005) (Chiu and Lee, 2011), heat reflow (Cheng et al., 2010) (Liu et al., 2010) (Pan and Su, 2007), and others.

However, It was thought that fundamental lens parameters such as sizes and curvature radiuses should be in suit with those of actual compound eyes in the first step. In addition, it was considered that it was preferable that various lenses were easily purveyed for the research with a low cost. For this reason, simple and low-cost fabrication method of plastic lens arrays was reseached here.

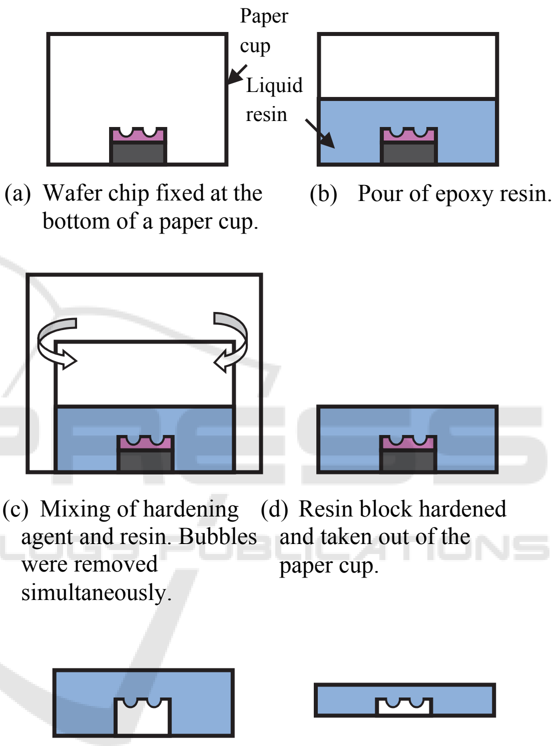
The new method investigated in this research is shown in Figure 4. At first, original resist-mold patterns were lithographically formed on silicon wafers using a handmade 1/19 reduction projection exposure system (Hirota et al., 2003). Concave resist patterns were printed by intentionally exposing the resist under large defocus conditions. By applying such defocused exposure, smoothly distributed light intensity profiles were given to the resist films even using binary reticles with only transparent and opaque parts and without gray tone parts. After forming the resist-mold patterns, the wafer was cut in small chips, and each silicon wafer chip with resist patterns was fixed at the bottom of a paper cup using a piece of both-side adhesive tape, as shown in Figure 4(a).

In the next step, a plastic resin was poured on the resist-mold patterns, as shown in Figure 4(b). Epoxy resin (Nissin Resin, Crystal Resin NEO) was used here. After adding a material for hardening the resin to the main epoxy resin, they were mixed using a mixing machine with a function of removing air bubbles (Thinky, AR100), as shown in Figure 4(c). This time, thicknesses and sizes of the resin blocks were roughly controlled by the cup diameter and the poured resin volume. Because the lens characteristics are influenced by the lens block thickness, however, the thickness should be strictly controlled in the next research step.

After the resin block was sufficiently hardened, it was taken out from the cup, as shown in Figure 4(d), and the wafer chip with resist patterns was forcibly peeled off. In concrete, grooves were dug along the wafer chip edges using a cutter knife, and the wafer chip was lifted up by climbing a tip of tweezer under it. As a result, the resin block with profiles inverting the resist-mold profiles was obtained, as shown in Figure 4(e).

Convex plastic lens patterns obtained by peeling the wafer chip off had defects of remained resist fragments. For this reason, the resist fragments were removed by dipping the resin block in acetone for a short while.

Finally, the resin block was thinned by polishing it. As a result, finished resin plate with micro-lens arrays were obtained, as shown in Figure 4(f).



(a) Wafer chip fixed at the bottom of a paper cup.
(b) Pour of epoxy resin.
(c) Mixing of hardening agent and resin. Bubbles were removed simultaneously.
(d) Resin block hardened and taken out of the paper cup.
(e) Resin block after removing the wafer chip.
(f) Finished micro-lens array plate.

Figure 4: New fabrication method of micro-lens arrays.

Because lens sizes and profiles are decided by the reticle pattern size and the exposure conditions for forming the original resist patterns, it is expected that lens parameters are variously and widely changeable suiting to optical designs.

4 EVALUATION OF RESIST MOLDS AND RESIN LENSES

4.1 Conditions for Printing Concave Resist-mold Patterns

Micro-lens arrays were actually fabricated, and cross sections and bird's view profiles were evaluated. As a resist, positive PMER P-LA900PM (Tokyo Ohka Kogyo) was used, and the resist was coated on silicon wafers in a thickness of approximately 10 µm. Because actual compound eyes were hexagonally arrayed, reticles shown in Figure 5 were used. The width of transparent hexagon was fixed to 500 µm. Because the reduction ratio was 1/19, the hexagon width corresponds to the width of 26.3 µm on the wafer plane, and this width almost corresponds to the element lens diameter of cicada's compound eye. On the other hand, opaque boundary widths between transparent hexagons were changed to 400, 300, and 200 µm.

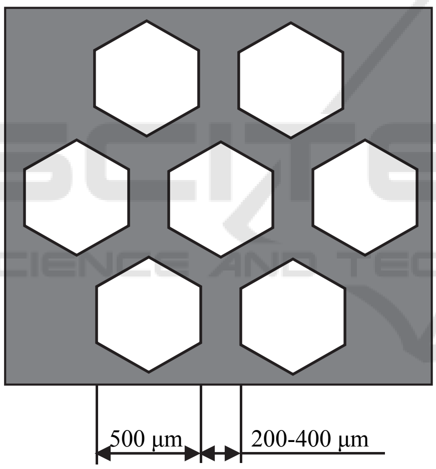


Figure 5: Reticle patterns used for printing resist-mold patterns of micro-lens arrays.

4.2 Evaluation of Resist-mold Patterns

At first, the best focal position or the focal origin was decided as the stage position at which the sidewall profiles of resist patterns became most perpendicular to the wafer surface. Concave patterns with favorite circular cross section profiles were obtained at the defocus of +150 µm, as shown in Figure 6. Here, "+" means that the exposed wafer was lowered down from the projection lens. Concave patterns became rounder and more circular in "+" direction than "-" direction. Numerical aperture (NA) of the projection lens was set at 0.12. Photographs of cross sections were taken using a scanning electron microscope (JEOL, JSM-5510).

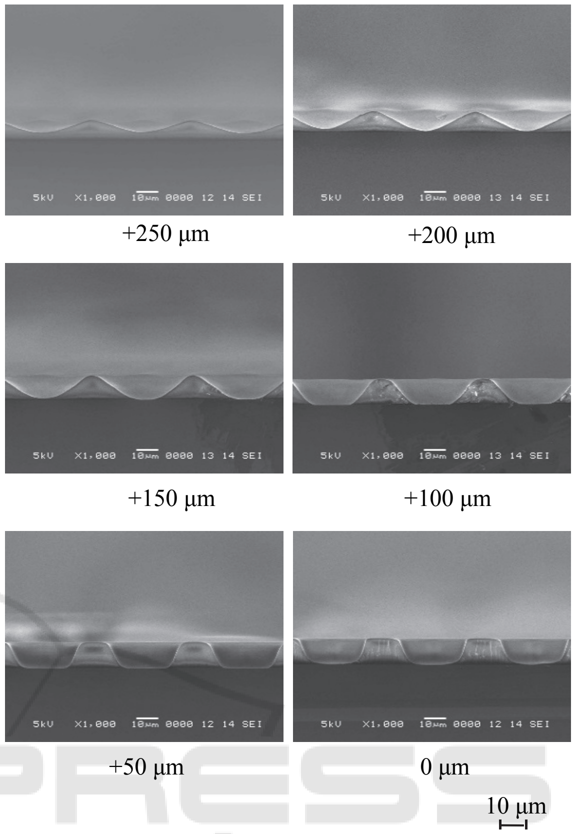


Figure 6: Cross section variations of resist-mold patterns under various defocus conditions.

Next, exposure time was varied to investigate the relationship between the element lens profiles and the exposure dose. In the experiments to decide the focal origin by observing cross sections, it was very difficult to break wafer chips at the exact center of the concave resist patterns. For this reason, cross section profiles under various exposure conditions were evaluated using a laser microscope (Keyence, VK-8510). Using the laser microscope, bird's-eye views were also obtained in addition to cross section profiles.

At first, cross section profiles of resist-mold patterns were measured. To evaluate cross section profiles, they were pasted on screens of CAD (Computer Aided Design) program (Autodesk, AutoCAD 2014), and circles were delineated superimposing on the cross section profiles by defining the circles as they pass the concave bottoms and both ends of the circular parts, as shown in Figure 7. By these manipulations, curvature radius R, maximum profile error from the delineated CAD circle δ, and concave depth d defined in the figure were investigated.

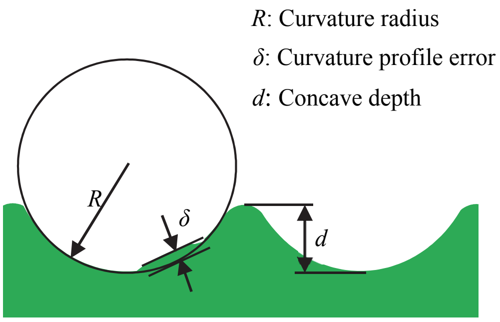


Figure 7: Evaluated lens parameters of resist-mold patterns.

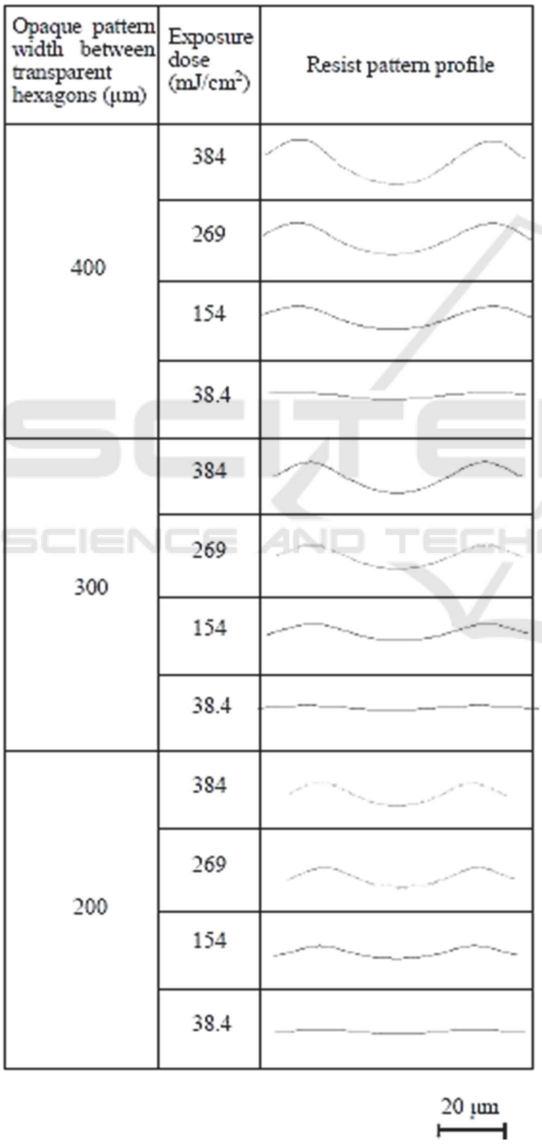


Figure 8: Wide variety of concave resist-mold patterns when opaque pattern widths between transparent hexagonal patterns and exposure doses are changed.

Dependence of circular radius R on exposure dose is shown in Figures 8 and 9. Exposure dose of 384 mW/cm^2 corresponds to exposure time of 10 min. It was clarified that the curvature radius was not almost influenced by the opaque pattern width. This characteristic is very convenient for designing reticles to be prepared for fabricating micro-lenses with aimed curvature radius. It was clarified that profiles of resist-mold patterns were widely controllable by changing exposure dose and opaque boundary width between transparent hexagons, as shown in Figures 8 and 9.

Next, dependence of concave depth d is shown in Fig. 10. In contrast to circular radius R, the concave depth d varied depending on both exposure dose and opaque pattern width between transparent hexagons. The reason why the concave depths decreased for reticles with narrow opaque parts is probably because the resist at the opaque positions are exposed doubly by light rays through transparent hexagons on both sides, and slightly sensitized by the defocused exposure. Therefore, the resist thicknesses of opaque parts are also decreased during the development.

On the other hand, maximum profile error δ from circular profiles are shown in Fig. 11. Although errors became somewhat large under relatively large exposure dose conditions, they were small, and it was clarified that almost circular resist profiles were obtained. Errors of 0.1 μm was the read out limit of the used microscope.

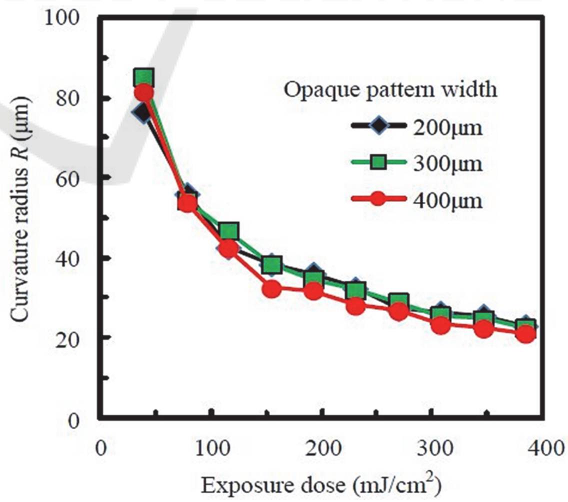


Figure 9: Curvature radius dependence on exposure dose. Curvature radiuses are not almost influenced by opaque pattern widths between transparent hexagonal patterns.

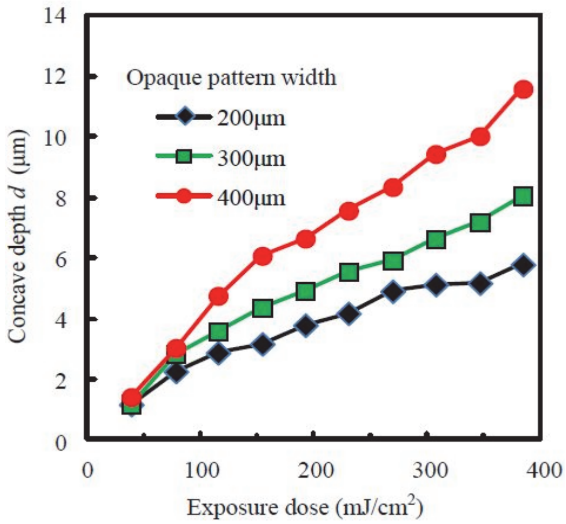


Figure 10: Concave depth dependence on exposure time and opaque pattern width between transparent hexagonal patterns.

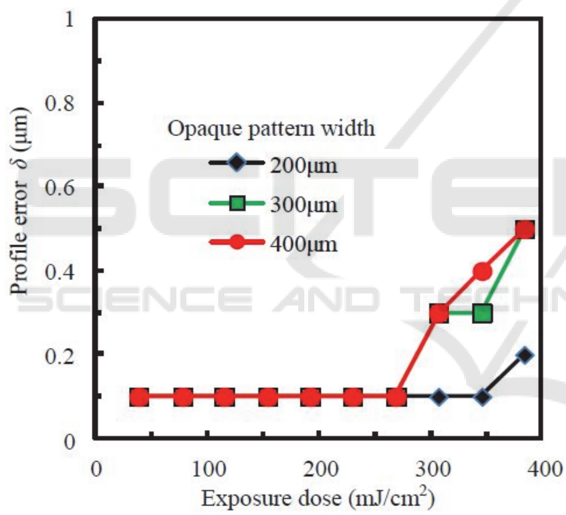


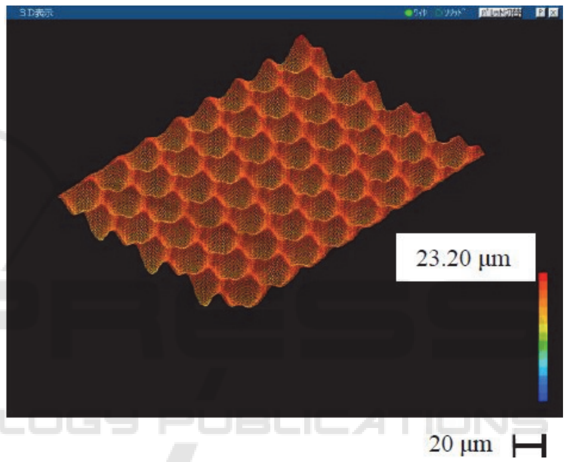
Figure 11: Profile error dependence on exposure time and opaque pattern width between transparent hexagonal patterns. Detection limit of profile error was approximately 0.1 μm.

4.3 Replication to Plastic Resin

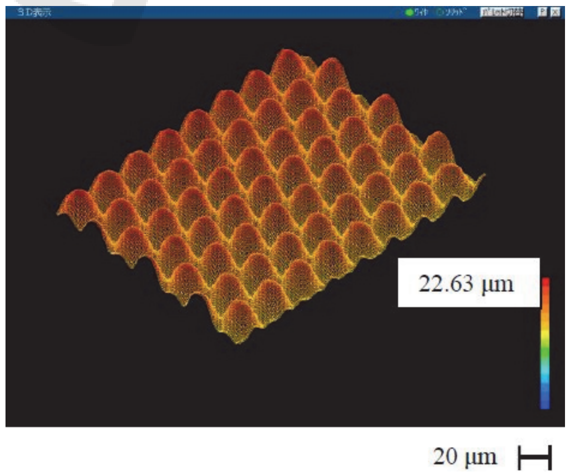
Because technologies for fabricating resist mold patterns were almost fixed, replication to plastic resin was investigated next. That is, feasibility of separating a wafer chip with resist patterns and a resin block was investigated, and replicated plastic lens profiles were compared with the original resist-mold patterns.

Resist-mold patterns were formed by adding exposure dose of 230 mJ/cm^2 (exposure time of 6 min). Bird's-eye views of resist-mold patterns and replicated plastic lens profiles are shown in Figure 12(a) and Figure 12(b). It was clarified that resist-mold profiles were almost faithfully replicated to the resin. In Figure 13, cross sections of resist-mold patterns and resin lens patterns are compared. It is known that both cross section profiles are almost the same though they are symmetrically formed. Measured curvature radiuses, depths and profile errors were compared, as shown in Table 1.

Finally, because the hardened resin blocks were too thick, they were thinned down by polishing. However, it took very long times to thin the blocks, and it was very difficult to control the final thicknesses. It is necessary to develop a better method to thin the lens plate precisely without spending long times from now.



(a) Resist-mold patterns replicated by an exposure dose of 230 mJ/cm2 using opaque patterns with a width of 200 μm. The scale mark of 20 μm is effective only in horizontal direction. Concave depths are displayed by colors.



(b) Micro-lens pattern finally replicated to epoxy resin.

Figure 12: Comparison of resist mold patterns and faithfully replicated epoxy micro-lens patterns.

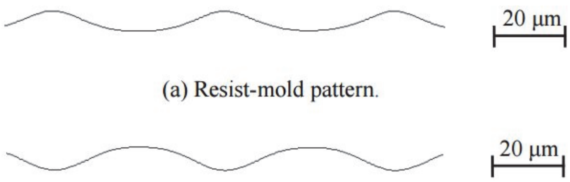


Figure 13: Comparison of profile curves between resist-mold patterns and faithfully replicated epoxy micro-lens patterns.

Table 1: Size differences between resist mold pattern and resin lens pattern.

	Radius (µm)	Depth (µm)	Error (µm)
Resist-mold pattern	32.4	4.2	0.1
Epoxy resin pattern	31.3	4.1	0.1

5 RATIONALITY OF CONCAVE PATTERNING

Good balance of simplicity and accuracy of the new method depend on the lithography process for printing concave resist patterns. The key technology is projection exposure under intentional large defocus conditions.

In the past research, a similar method was used for printing SU-8 patterns with vertical side walls and very high aspect ratios (Hirota et al., 2003). In that case, the negative resist SU-8 was a highly transparent material, and the defocus was given for making the widths of light intensity distribution curves at the resist bottom equal to those at the resist surface. However, in this paper, positive resist of PMER P-LA900PM with large absorption was used, and the pattern images were made vague even at the surface. Using such translucent resist materials and vague and gentle light intensity distributions, smooth concave patterns with favourable quasi-spherical profiles were obtained.

6 CONCLUSION

After investigating the typical compound eyes of insects, plastic micro-lens arrays with similar lens parameters were actually fabricated by developing a new method. The aim is to prepare for developing artificial compound eyes in the future. Because actual element lens sizes of typical insects were in a range of 16-53 µm, how to obtain micro-lens arrays with such sizes simply and easily were investigated. Various methods for fabricating micro-lens arrays have already been proposed in the world. However, a method that was simpler and more inexpensive was necessary. In addition, it was preferable to make possible to fabricate lens arrays by ourselves, and change lens parameters such as diameters, curvature radiuses and shapes freely.

In the new method, plastic micro-lens arrays were fabricated by lithographically printing resist-mold patterns, and faithfully replicating them to epoxy resin. It was demonstrated that original concave resist patterns were simply formed by only one lithography process using intentionally defocused projection exposure. In spite of the simplicity, curvature radiuses of resist-mold patterns were widely controllable by changing exposure dose. In addition, it was also demonstrated that the resist-mold patterns were faithfully replicable to epoxy resin by pouring the resin onto the resist molds, and peeling a wafer chip with the resist-mold patterns off mechanically after the epoxy resin was hardened. Thus, convex lens arrays of epoxy resin arranged in honeycomb styles, and with an element shape of hexagon were successfully fabricated.

There are still some subjects. The main subject is the development of a better method for fabricating lens arrays with precisely controlled thickness and designed outline shapes. It is necessary to get down to work hereafter.

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