Shape-controlled, high fill-factor microlens arrays fabricated by a 3D diffuser lithography and plastic replication method

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Abstract: This paper describes a simple and effective method to fabricate a plastic microlens array with controllable shape and high fill-factor, which utilizes the conventional lithography and plastic replication. The only difference from conventional lithography is the insertion of a diffuser that randomizes paths of the incident ultraviolet (UV) light to form lens-like 3D latent image in a thick positive photoresist. After replication of the developed concave microlens mold onto the polydimethylsiloxane (PDMS), the focal length of the fabricated hemispherical microlens was observed to be 13-88 μm depending on the UV exposure dose. Two PDMS curing conditions were tested, where the elevated temperature of 85 °C resulted in smoother surface roughness of 2.6 nm in RMS value in the microlens mold. The proposed method can be extensively applied for microlens fabrication with other plastic materials due to its simplicity and versatility.

OCIS codes: (220) Optical design and fabrication. (220.4000) Microstructure fabrication. (230) Optical devices. (230.3990) Microstructure devices.

References and links

1. D. Daly, "Applications and Fabrication Technologies" in *Microlens Array* (Talyer and Francis, London, 2001).
2. M. V. Kunnavakkam, F. M. Houlihan, M. Schlax, J. A. Liddle, P. Kolodner, O. Nalamasu, and J. A. Rodgers, "Low-cost, low-loss microlens arrays fabricated by soft-lithography replication process," Appl. Phys. Lett. **82**, 1152-1154 (2003).
3. C. R. King, L. Y. Lin, and M. C. Wu, "Out-of-Plane Refractive Microlens Fabricated by Surface Micromachining," IEEE Photonics Technol. Lett. **8**, 1349-1351 (1996).
4. M.-H. Wu and G. M. Whitesides, "Fabrication of two-dimensional arrays of microlenses and their applications in photolithography," J. Micromech. Microeng. **12**, 747-758 (2002).
5. M.-K. Wei and I -L. Su, "Method to evaluate the enhancement of luminance efficiency in planar OLED light emitting devices for microlens array," Opt. Express **12**, 5777-5782 (2004).
6. J. Chen, W. Wang, J. Fang, and K. Varahramyan, "Variable-focusing microlens with microfluidic chip," J. Micromech. Microeng. **14**, 675-680 (2004).
7. H. Yang, C.-K. Chao, M.-K. Wei and C.-P. Lin, "High fill-factor microlens array mold insert fabrication using a thermal reflow process," J. Micromech. Microeng. **14**, 1197-1204 (2004).
8. Z. L. Liau, V. Diaduik, J. N. Walpole and D. E. Mull, "Gallium phosphide microlenses by mass transport," Appl. Phys. Lett. **55**, 97-99 (1989).
9. Z. L. Liau, D. E. Mull, C. L. Dennis, R. C. Williamson and R. G. Waarts, "Large-numerical-aperture microlens fabrication by one-step etching and mass-transport smoothing," Appl. Phys. Lett. **64**, 1484-1486 (1994).
10. A. W. Lohmann and S. Singzinger, "Array of doublet lenslets," Optik **93**, 84-86 (1993).
11. R. Yang and W. Wang, "Out-of-plane polymer refractive microlens fabricated based on direct lithography of SU-8," Sensor. Actuat. A-Phys. **113**, 71-77 (2004).
12. N. Chronis, G. L. Liu, K.-H. Jeong, and L. P. Lee, "Tunable liquid-filled microlens array integrated with microfluidic network," Opt. Express **11**, 2370-2378 (2003).

#5799 - $15.00 US Received 23 November 2004; revised 4 December 2004; accepted 6 December 2004

13. J.-B. Yoon, B.-I. Kim, Y.-S. Choi, and E. Yoon, "3-D Construction of Monolithic Passive Components for RF and Microwave ICs Using Thick-Metal Surface Micromachining Technology," IEEE T. Microw. Theory **51**, 279-288 (2003).
14. B. D. Gates and G. M. Whitesides, "Replication of Vertical Features Smaller than 2 nm by Soft Lithography," J. Am. Chem. Soc. **125**, 14986-14987 (2003).
15. P. Nussbaum, R. Völkel, H. P. Herszig, M. Eisner, and S. Haselbeck, "Design, fabrication and testing of microlens arrays for sensors and microsystems," Pure Appl. Opt. **6**, 617-636 (1997)

1. Introduction

Microlens arrays have a variety of applications in optical interconnection and optical communication [1]. Accordingly, various microlens array fabrication methods have been extensively investigated, including photoresist thermal reflow method [2-7], mass transport technique [8,9], droplet method [10], and direct lithography method [11]. Also, microlens arrays with variable focal lengths were developed by liquid-filling in a cavity [6,12]. Among them, the photoresist reflow method has been most widely used. Nevertheless, due to the thermal and chemical instability of the photoresist, it is not yet accepted as a practical solution suitable for commercial optical systems. And reflow conditions must be delicately controlled to create a high fill-factor microlens array [7], which increases the process uniformity and reproducibility requirements. Finally, the microlens material should be photosensitive to be patterned. Other microlens fabrication methods mentioned above had the relatively complex process steps and were restricted to narrow application range.

From this perspective, 3D diffuser lithography (simply adding a diffuser into conventional lithography) followed by plastic replication is proposed here to provide a simple method of fabricating versatile microlens arrays with high fill-factor and pre-defined shape.

2. Microlens fabrication

Figure 1 shows the proposed microlens fabrication processes. Contrary to conventional lithography in which only a collimated light source is used to obtain photoresist patterns with a rectangular cross-section, the proposed 3D diffuser lithography utilizes randomized light to form various cross-sections (circular or elliptical) in the photoresist. After thick AZ9260 photoresist spin-coating (1500 rpm, 1.5 sec for 45 μm thickness) on the substrate and soft-baking (85 °C, 1 hour), the thick photoresist film was ultraviolet (UV)-exposed through a diffuser and a mask (Fig. 1(a)). Since the diffuser on the mask randomized the direction of the UV light, the exposed region formed a circular or an elliptical cross-section after development (Fig. 1(b)). A liquid polydimethylsiloxane (PDMS) was cast on the photoresist pattern (Fig. 1(c)) and peeled off from the photoresist mold after it was cured (Fig. 1(d)). The curing condition is described later.

Various cross-sectional photoresist profiles were obtained by using different diffusers. The type-I diffuser (F43-719, Edmund Optics Ltd.) is a 10 cm × 10 cm square soda-lime 5 mm-thick glass-sheet, of which a 450 μm-thick opaque opal layer is coated on the single-side. The type-II diffuser (F45-656, Edmund Optics Ltd.) is a 1.6 mm-thick single-side sandblasted sheet (peak-to-peak roughness=8.7 μm) of the same size. In all experiments, the diffuser was placed with the opal-coated or sandblasted side up, as indicated in Fig. 1(a). The photoresist pattern cross-section obtained using the type-I diffuser is shown in Fig. 2(a). The exposure dose was 300 mJ/cm^2 and it had a circular cross-section. The cross-sectional profiles of the photoresist patterns are overlapped in Fig. 2(b). The photoresist pattern without a diffuser had a very steep profile on the pattern edges [13], while those with the type-I and II diffusers had rounded cross-sections.

The exposure dose is another important parameter affecting cross-sectional photoresist profiles. Figure 2(c) shows the cross-sectional photoresist profiles obtained using the type-I diffuser (the same diffuser as Fig. 2(a)) and an exposure dose of 1200 mJ/cm^2. The photoresist pattern cross-sectional profiles shown in Fig. 2(d) indicate that the depth of the photoresist

#5799 - $15.00 US Received 23 November 2004; revised 4 December 2004; accepted 6 December 2004

patterns increased in proportion to the exposure dose. The maximum incident angle of the UV light into the photoresist was maintained at about 36° regardless of the exposure dose, as shown in Fig. 2(d). This is in accordance with the calculation result based on the well-known Snell's law when the total internal reflection condition of the light and the refractive indices of the glass diffuser ($n_{diffuser}$=1.53), mask (n_{mask}=1.53), and the photoresist ($n_{photoresist}$ =1.67) were considered.

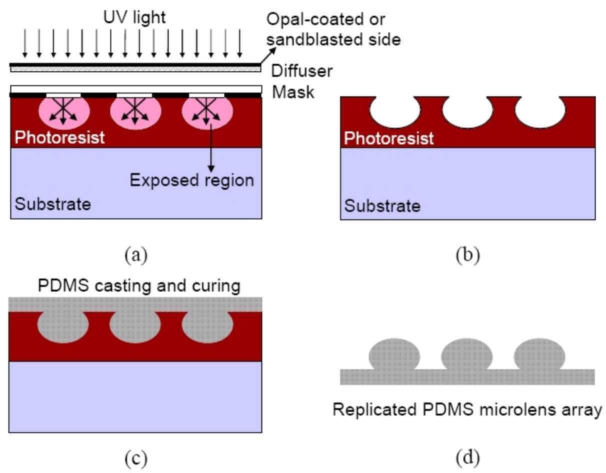


Fig. 1. Process flow of the proposed plastic microlens fabrication. (a) UV exposure through a diffuser and a mask. (b) Development. (c) Liquid PDMS casting and curing. (d) Replicated PDMS microlens peel-off.

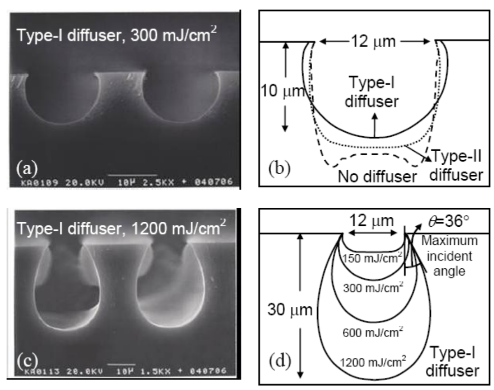


Fig. 2. SEM photographs and schematic cross-sections of the photoresist patterns. (a) Photoresist pattern cross-section with type-I diffuser and an exposure dose of 300 mJ/cm^2. (b) Cross-sectional photoresist profiles (solid line: type-I diffuser, dotted line: type-II diffuser, dashed line: no diffuser). (c) Photoresist pattern cross-section with type-I diffuser and an exposure dose of 1200 mJ/cm^2. (d) Cross-sectional photoresist profiles with different exposure doses.

3. Results and discussion

Figure 3 shows SEM photographs of the photoresist patterns with various cross-sections obtained by an appropriate combination of the pattern width and the exposure dose. Various diameters of circular cross-sections from 1.5 μm to 80 μm for this experiment were obtained. All the circular cross-sections in Figs. 3(a) and 3(b) were formed with the type-I diffuser. The cross-section in Fig. 3(c) was obtained with a wide mask pattern (30 μm), low exposure dose (300 mJ/cm^2), and the type-I diffuser, while the elliptical cross-section shown in Fig. 3(d) was

Received 23 November 2004; revised 4 December 2004; accepted 6 December 2004

formed by applying a narrow mask pattern (10 μm), high exposure dose (1200 mJ/cm^2), and the type-II diffuser. Furthermore, we could obtain photoresist patterns with a high density by using type-II diffuser and quite large exposure dose of 1800 mJ/cm^2. Due to the excess exposure dose, the adjacent patterns were merged together and such patterns could act as an excellent photoresist mold for the microlens with a fill-factor of about 100%.

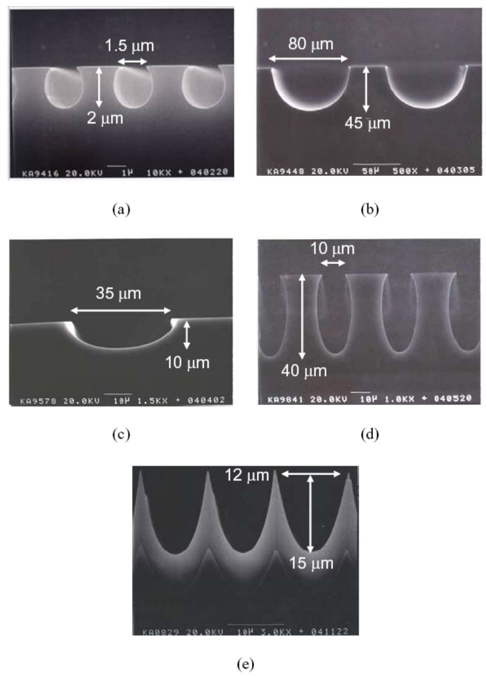


Fig. 3. SEM photographs of the photoresist pattern cross-sections. (a) A circular cross-section with a 1.5 μm diameter and (b) with an 80 μm diameter. (c) A concave cross-section. (d) An elliptical cross-section. (e) A cross-section with a very high density.

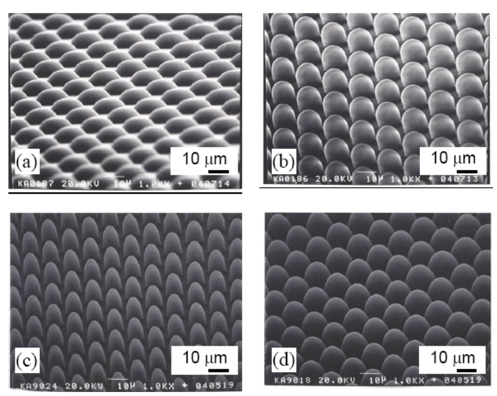


Fig. 4. SEM photographs of the fabricated plastic microlens array. (a) Conventional convex microlens. (b) Hemispherical microlens. (c) Ellipsoidal microlens. (d) Microlens array with a high fill-factor (~100 %).

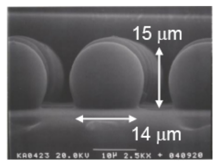
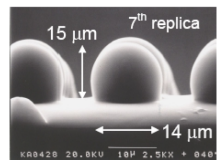
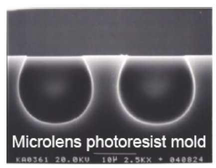
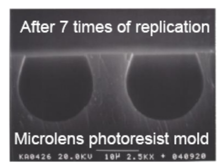
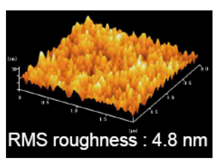
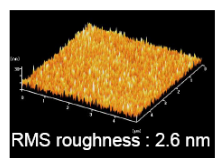
Based upon extensive photoresist patterning experiments, diverse plastic microlens arrays were fabricated and their SEM photographs are shown in Fig. 4. The fabricated convex, hemispherical, and ellipsoidal microlens arrays can be used in appropriate applications. Especially, the hemispherical microlens array shown in Fig. 4(b) may have a very large

#5799 - $15.00 US Received 23 November 2004; revised 4 December 2004; accepted 6 December 2004

numerical aperture. The focal length of the fabricated hemispherical microlens was observed from 88 μm to 13 μm as the exposure dose was increased from 150 to 600 mJ/cm^2. It was obtained by the radius of curvature measured from the SEM photograph of the individual microlens, using the conventional formula for a focal length (focal length = radius of curvature/(refractive index of the lens – 1)).

The microlens array with an extremely high fill-factor was also realized as shown in Fig. 4(d). The fill-factor of the microlens array was almost 100%. And the light energy passing through the microlens array is expected to be collected with high efficiency if scattering of the incident light at the sharp borders between two adjacent microlenses is negligible. Thus, the efficiency of optical systems can be improved.

Table I. Characteristic comparison of the fabricated PDMS microlenses and photoresist molds cured at two different conditions.

Curing temperature	Room temperature	85 °C
Curing time	24 hours	1 hour
SEM photograph of the fabricated PDMS microlens		
SEM photograph of the photoresist mold after PDMS peel-off		
AFM measurement result of the photoresist mold after PDMS peel-off		
PDMS shrinkage after peel-off	None	2.2 % shrinkage

During microlens fabrication, the PDMS was cured at room temperature. However, the curing temperature must be adjusted depending on the process time and microlens materials. Table I compares characteristics of the fabricated PDMS microlenses and photoresist molds cured at two different conditions of room temperature for 24 hours and 85 °C for 1 hour. As we can see in Table I, no shape change was observed between the two curing conditions. When the photoresist mold was treated at 85 °C solely without PDMS casting, it became severely distorted from its original lens shape. On the other hand, with PDMS, the shapes of the photoresist mold and PDMS microlens were not deformed at all in spite of the high curing temperature even after 7 times of PDMS replication at 85 °C. We speculated that the highly viscous liquid PDMS (viscosity: 3100 cP) suppressed the reflow of the photoresist mold effectively. Also, the narrow inlet of the photoresist mold cured at 85 °C was not deformed during the 7 times of PDMS peel-off process as shown in Table I. This is believed to be due to the elastic property of the PDMS. AFM measurement results showed that the surface roughness of the photoresist mold after PDMS peel-off was improved from 4.8 nm to 2.6 nm by elevating the curing temperature. The PDMS microlens is expected to have almost the same surface roughness as the photoresist mold since the PDMS replicates the photoresist mold surface roughness at the sub-nanometer scale [14]. As a result, the total integrated scattering (TIS) of the fabricated microlens surface is expected to be below 1% for visible light [15], which is small enough to be used in most optical applications. The various polymers which need a high curing temperature can be used as microlens materials as well to achieve satisfactory microlens characteristics in varying applications. Only the PDMS shrinkage (about 2.2 %) due to its relatively large thermal coefficient of expansion (310 ppm/°C)[2] needs to be considered at the microlens design step to obtain a precise microlens array.

Finally, the array of the circular gold pattern with a diameter of 20 μm on a glass was observed through the fabricated microlens array with a width and a space of 50 μm. Figure 5 shows the microscope photographs of the gold patterns seen through the fabricated microlens array, clearly showing magnification done by the microlens array.

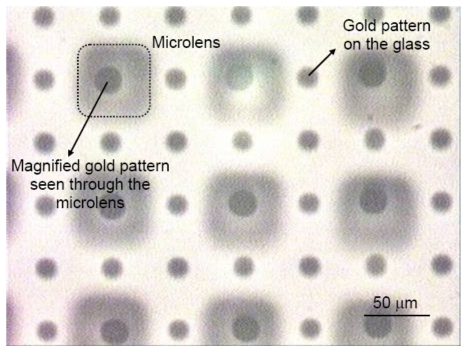


Fig. 5. Optical photograph of the magnified gold patterns on a glass through the fabricated microlens array.

4. Summary

To summarize, a simple plastic microlens array fabrication method was proposed and investigated. In order to form various 3D photoresist molds for the microlens array, a 3D diffuser lithography technology was developed, based on conventional lithography technology with novel usage of a diffuser. The proposed method has three major advantages over conventional methods. First, the process is very simple. Second, the microlens shape can be controlled precisely and reproducibly by changing the diffuser and lithography process parameters. Finally, the microlens array with a fill-factor of almost 100% can be fabricated in a lithographical way, which is difficult to achieve with conventional technologies. The fabricated versatile microlens array can be used for diverse optical systems with maximized efficiency due to its various and controllable shapes and high fill-factor.

Acknowledgments

This work was supported by Brain Korea 21 program of the Ministry of Science and Technology in Korea. The authors would like to thank Prof. Y.-K. Choi and Prof. Y.-H. Lee at KAIST for their helpful comments.