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Organic selective-area patterning method for microlens array fabrication

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Abstract

Refractive microlens arrays (MLAs) are widely used in many electro-optical devices due to their high performance and low optical loss. To fabricate a microlens array effectively, we have proposed a novel fabrication method based on a selective-area patterning method. The surface properties of glass substrates were defined as either hydrophilic or hydrophobic regions by microcontact printing of self-assembled monolayers (SAMs). Consequently, the microlens arrays were self-organized on the hydrophilic regions after the lens materials were nozzle-spread followed by UV curing. As a result, we have demonstrated microlenses with 50, 75, and 100 μm footprints, and *f* numbers as low as 5.4. The focused spot size of the 50 μm lens was 9.82 μm, which is near the diffraction limit. The optical measurement shows excellent light collecting efficiency of a microlens array, which is suitable for many electro-optical applications. Furthermore, all fabrication steps can be accomplished in ambient environment and at room temperature. It is anticipated that the present proposed method has great potential for mass production.
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1. Introduction

Due to their excellent light collecting efficiency, refractive microlens arrays (MLAs) are used in many optical systems extensively, such as flat panel displays (FPDs), photodetectors, and photovoltaic devices. For example, a microlens array can enhance the light out-coupling efficiency of light emitting diodes [1], improve the responsivity and *S/N* ratio of photodetectors [2], and enlarge the light absorption efficiency of solar cells [3]. Conventionally, several methods have been demonstrated successfully to fabricate high performance microlens arrays, such as ink-jet printing [4], hot embossing [5], and laser direct writing [6]. However, these methods require either complicated instrumentation or high energy consumption. In this paper, we demonstrate a novel, simple, and energy-saving process

to make microlens arrays by a selective-area patterning method. Glass substrates are patterned as either hydrophobic or hydrophilic regions by soft lithography processes. The hydrophobic area is defined by micro-contact printing (μCP) of self-assembled monolayers (SAMs). Because of the poor adhesion of the lens material with the hydrophobic area, the lenses only form on the hydrophilic area. Additionally, because the SAMs can also control the surface tension between the interfaces, it might be possible to alter features of the microlenses by using different materials (Fig. 1). Consequently, unlike the previous self-assembly pre-patterning methods [7], which can only orient the lens position or control the patterns, our approach is also capable of altering the interfacial tension to precisely control the profile and optical properties of the microlenses.

2. Experimental

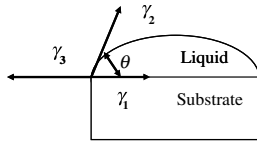The fabrication processes of mold and microcontact printing (μCP) are illustrated in Fig. 2. The photoresist

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Fig. 1. The shape of a microlens is determined by three interfacial tensions. γ_1: the tension at liquid/substrate interface, γ_2: the tension at the liquid/air interface, γ_3: the tension at air/substrate interface, θ: contact angle.
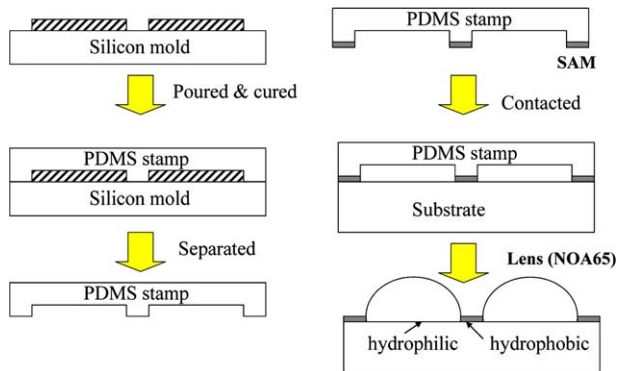

Fig. 2. Fabrication processes of PDMS mold and microcontact printing. The pattern of the hydrophobic regions was defined by microcontact printing of SAMs. After spin coating of the prepolymer (NOA65) on the substrate, the microlenses were self-organized on the hydrophilic regions. Finally, the microlenses were completed by UV curing.

was spin-coated on a silicon wafer with 2 μm film thickness and then developed by 2.5% TMAH. The patterns of photoresist were circles of 50, 75, and 100 μm diameter and 5, 10, and 15 μm spacing. Stamps used in μCP were made of poly (dimethylsiloxane) (PDMS) and replicated from the silicon mold. In a typical selective surface treatment experiment, the PDMS stamp was immersed in a solution of 1H,1H,2H,2H-perfluorodecyltrichlorosilane (FOTS) dissolved in heptane (1 mM) for 30 s. After being removed from the solution and dried under a stream of nitrogen, the stamp was brought into contact with a UV-ozone treated glass substrate for several seconds and the force applied during the contact was 0.2 N. The UV-ozone treated glass substrate showed high wettability such that the contact angle (CA) was smaller than 5° and the FOTS formed SAMs with extremely low surface energy such that the CA was greater than 110°. As a result, the surface properties of the substrate were divided into a hydrophilic region on the bare glass and a hydrophobic region on the SAMs treated surface. The substrate was then spin coated with a prepolymer solution NOA65 (Norland Optical Adhesive 65, THORLABS INC.), an index matching material. Consequently, the NOA65 was swept away on the SAMs modified surface because of poor adhesion on the hydrophobic regions and then self-organized as microlenses with hemisphere structures by the surface-tension effects. Finally, the microlenses were completed by UV curing.

Static CAs of water, diiodomethane and hexadecane were measured by drop shape analysis system DSA100

(KRUSS) and calculated by OSS and Good method [8]. Atomic force microscopy (AFM) images of SAMs morphology was obtained with the Dimension 3100 from Digital Instruments (DI) in tapping mode. Images of the MLA were acquired by a scanning electron microscope (SEM). Optical properties of the MLA were estimated by an experimental setup of a collimated light source and image forming system. The system includes a He–Ne laser (wavelength $\lambda = 632.8$ nm) light source, a spatial filter, beam focusing and expanding lenses, and an optical power measurement and analysis system.

3. Results and discussion

To prepare the substrate with different wetting ability, the glass substrates either were dipped into two different SAMs, OTS and FOTS, or underwent UV-ozone treatment. Table 1 lists the surface energy obtained with the three different surface treatments. It clearly shows that the surface energy of the glass substrates decreases to 27.31 and 12.47 (mJ/m^2) after OTS and FOTS treatment, respectively. The lower surface energy means that the surface is more hydrophobic and, therefore, that the hydrophilic liquid will not easy condense on it. On the other hand, the surface energy increases to 47.68 mJ/m^2 after UV-ozone treatment. The CA reduces to less than 5°, which means the glass substrates become more hydrophilic.

Fig. 3 shows side views of the CA of water drops on the three differently treated surfaces. The CA values of FOTS- and OTS-treated surfaces are higher than that of UV-ozone-treated surface. The glass substrates treated with both FOTS and OTS clearly demonstrate their unique dewetting ability with respect to NOA65. Furthermore, FOTS shows the better dewetting ability owing to the fluorine contained molecule. In fact, the film with molecules with fluorine atoms have been used to serve as the anti-adhesion layer for hot embossing system [9,10] or UV-curing system [11]. To reduce the adhesion of the prepolymer, NOA65, we chose FOTS as our alignment layer to confine the prepolymer (NOA65) after spin coating processes.

Fig. 4 reveals the as-fabricated MLAs with different sizes from 50 to 100 μm after NOA65 coating and UV-curing on the glass substrate. The lens size and shape corresponds well to the pattern of the mold used in the micro contact printing. In addition, the well-defined pattern of

Table 1
Contact angles and surface energies of glass substrates treated with UV-ozone, OTS[a], and FOTS[b]

Surface treatment of substrates	Contact angle (°)			Surface energy (mJ/m2)
	Water	Diiodomethane	Ethylene glycol	
UV-ozone	5.0	39.9	6.6	47.68
OTS[a]	87.4	50.8	75.3	27.31
FOTS[b]	105.1	91.5	92.5	12.47

[a] Octadecyl-trimethoxysilane.
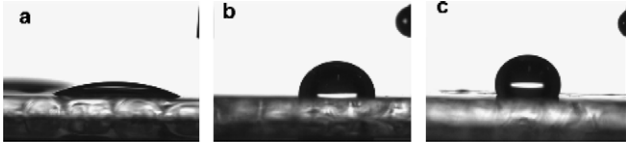[b] 1H,1H,2H,2H-perfluorooctyl-trichlorosilane.

Fig. 3. Drop images of water on glass substrates with different surface treatments: (a) UV ozone treatment; (b) OTS treatment; (c) FOTS treatment.
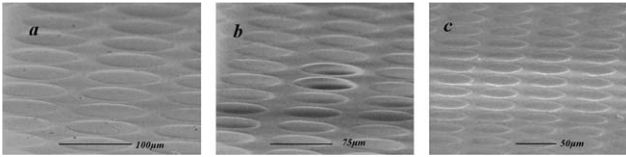

Fig. 4. Vertical view images of microlens arrays obtained on a scanning electron microscope (SEM). The diameters of the microlenses are: (a) 100 μm; (b) 75 μm; and (c) 50 μm.

lenses also shows the priming layers (SAMs) are printed on the surfaces without any mold deformation during imprint process. Finally, the surface around the lenses is nearly flat and without any residual materials (NOA65) due to the poor adhesion force. The residual NOA65 might introduce the light scattering, which would degrade the performance of the MLA, while light passes through the glass substrates.

The *f*-number ($f_\#$), which indicates the light-gathering power of the lens, is calculated from the following formulas:

$$R = \frac{h^2 + r^2}{2h}, \quad f = \frac{R}{n-1}, \quad f_\# = \frac{f}{2r},$$

where h is the sag height, r is the radius of the circular lenses, R is the radius of curvature of the lenses, n is the refractive index, and f is the focal length. In these calculations, the refractive index is set to be 1.5 for the NOA65 microlenses. Following the above equation, for example,
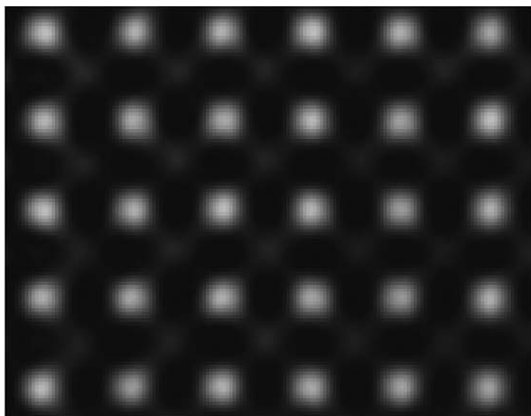

Fig. 5. Focused light spot image of a MLA obtained with an experimental setup of a collimated light source and image forming system. The image shows a portion of the focal plane produced by one MLA (100×100) with lens diameter of 50 μm and spacing of 10 μm. From the measurement, the focused spots have a size of 9.82 μm, which is very close to the theoretical diffraction limit.

the *f*-number of the 50 μm lens with 15 μm spacing is 5.4, which is the lowest one obtained in this work.

In contrast to the previous reports, in which the lenses were made on a semitransparent Au surface [12], the resulting MLA in our work has high transparency (>95%) which can suppress the optical loses, because of the usage of transparent glass substrates. The only losses seem to be due to the reflection between the lenses and air.

Fig. 5 shows a portion of the focal plane produced by one MLA (100×100) with lens diameter of 50 μm and spacing of 10 μm. The image reveals a strong focusing ability and good uniformity of the MLA as well. From the measurement, the focused spot size is 9.82 μm, which is very close to the theoretical diffraction-limited spot size (9.26 μm) of the microlens.

4. Conclusion

In summary, we have demonstrated a novel method to fabricate a polymer microlens array. The surfaces of glass substrates were defined as either hydrophilic or hydrophobic regions by microcontact printing of self-assembled monolayers (SAMs). As a result, we have made microlenses with 50, 75, and 100 μm footprints, and *f* numbers as low as 5.4. The focused spot size was 9.82 μm, which is near the diffraction limit. The SEM images also show that the microlenses have excellent surface quality as well as good uniformity. The smooth surface ensures the absence of unlikely optical aberrations. Besides, optical measurement also reveals an excellent light collecting efficiency. Finally, all fabrication steps were done in ambient environment and at room temperature; the proposed fabrication method is ideal for mass production and could be realized on a flexible substrate.

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