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Microlenses fabricated by discontinuous dewetting and soft lithography

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ABSTRACT

This letter describes an approach to fabricating microlens arrays with low cost and large area through the combination of discontinuous dewetting and reversible water–ice transition via a soft lithography replica process. Microlenses with different curvature can be tuned by the modulation of the wettability of the substrates. The microlenses fabricated can project clear miniaturized images.

1. Introduction

The microlens array has been a focus of research because of their wide applications in optical imaging systems [1,2], image sensors [3], optical communications [4], photolithography [5,6], and so on. In addition to a huge reduction in space, the use of an array of microlenses can help to provide sharper images, more accurate detectors and more precisely controlled laser beams. Many approaches have been developed for fabricating microlenses by using various materials and processes [7–11]. Some of these methods are based on photolithography [7,8], which is expensive, requires the use of clean-room facilities and suitable materials are also limited. Another conventional approach to fabricating microlenses is ink-jet printing [9], which is technically sophisticated and also requires expensive apparatus. For these reasons, several alternative techniques that could provide simpler and cheaper routes to their fabrication have been developed. For example, Xia et al. proposed self-assembly of polystyrene particles based on physical confinement and templating to fabricate arrayed microlenses [10]. Peng et al. proposed a soft-lithography-enabled fabrication process to fabricate microlens arrays in hybrid SiO_2–TiO_2 sol–gel [11]. However, in their fabrication process, the photoresist template also plays a key role, and can not be used repeatedly. It also requires a high temperature in the fabrication processes.

Here we propose a method for the fabrication of large area micolens arrays by the use of the discontinuous dewetting proposed by Whitesides [12], and a reversible water–ice transition via a soft lithography replica process [13–15]. The technique we present is simple, requires little technical expertise and its cost is low due to the reusability of the elastic template. The mechanisms of the process are discussed in detail. Microlenses with different curvature can be tuned via the modulation of the wettability of the substrates. The microlenses fabricated can project clear miniaturized images.

2. Experimental

Poly (methyl methacrylate) (PMMA, $M_w = 15\ \mathrm{kg\ mol^{-1}}$) was purchased from Aldrich. PDMS (Sylgard 184) and its kit (curing agent) were purchased from Dow Corning. Chloroform was chosen as the solvent. The concentration of the PMMA chloroform solution was around 8 wt%. Prior to use, the solution was kept in a refrigerator.

The untreated glass substrate after cleaning exhibited a water contact angle of ~60°. In order to achieve a more hydrophilic substrate, the glass substrate was treated in a piranha solution (7/3 (v/v) of 98% H_2SO_4 and 30% H_2O_2) at 80 °C for 1 h and as for a more hydrophobic substrate, the glass substrate was treated with H_2SO_4/H_2O_2 and rinsed repeatedly with DI water and dried under nitrogen gas. Then the glass substrate was immersed in the solution of 1 H, 1 H, 2 H, 2 H-perfluorooctyltrichlorosilane (FOTS)/hexane (1/1000 (v/v)) for 30 s. Subsequently, the substrates were rinsed repeatedly with DI water and dried under nitrogen gas. The water contact angles of the treated substrate were ~5° and ~110°, respectively.

By casting the prepolymer Sylgard 184 and its kit in a ratio of 10:1 on the photoresist thin films patterned by photolithography and curing at 65 °C for 4 h, a PDMS stamp with relief structures forming negative replicas of the structures in the photoresist master was formed [13]. The PDMS stamp used here composed of concave squares with sides of length 50 μm.

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When the patterned PDMS stamp was pulled from water (Fig. 1), discontinuous dewetting occurred and left the concave wells filled with an equal volume of water. Such a PDMS stamp was then placed on the three different glass substrates, respectively, and put into a refrigerator (temperature −20 °C) quickly. After a few minutes, the water turned into ice. Then the PDMS stamp was lifted off. A PMMA chloroform solution was dip coated onto the ice mold. After being taken out and kept at room temperature for a while, the ice thawed into water while the solvent in the polymer solution evaporated. Then, the system was put into water to separate the polymer film from the glass substrate. The polymer film then acts as the template in the fabrication of microlenses through a replica molding process. The fabrication process is the same as the fabrication of the PDMS stamp described above but the curing temperature is reduced to 50 °C and the curing time increased to 6 h.

Here we chose PDMS as the material to fabricate microlenses for several reasons: PDMS prepolymer does not dissolve the template; The reflective index of PDMS is ∼1.43, which is high enough for the lens material; PDMS is almost transparent to visible light (wave length from 400 to 800 nm); and PDMS has a very low surface energy and its elasticity is sufficient to allow its separation from the polymeric structure.

The microlenses fabricated were characterized by Leica optical microscopy (in reflection mode with a CCD camera attachment), scanning electron microscopy (SEM) (a JOEL JXA-840 microscope and a Philips XL-30-ESEM-FEG instrument operating at 20 kV) and atomic force microscopy (AFM) (SPI3800N Probe Station, Seiko Instruments Inc., Japan) in tapping mode (Silicon tips on silicon cantilevers with spring constant 2 N/m). Drop shape analysis (DSA, DSA 10 control unit, Krüss GmbH, Germany) was used to estimate the contact angle of water on the substrate.

3. Results and discussion

It is well known that the liquids have a tendency to dewet both heterogeneities on planar surfaces and geometrical heterogeneities. Discontinuous dewetting is a method that takes advantage of the difference in the interfacial free energies of the substrate and the liquid used and the controlled topography of the stamp surface. This phenomenon occurs when a drop of liquid is allowed to drain from a surface bearing discrete depressions and having surface free energy lower than that of the liquid. As the liquid dewets the surface of the stamp, equal volumes of solution will remain in pre-existing the microwells. The discontinuous dewetting of water with a receding contact angle of 81° ± 5° from poly (dimethysiloxane) (PDMS) stamp has been demonstrated [12]. In the present paper, this phenomenon was used to fabricate microlenses.

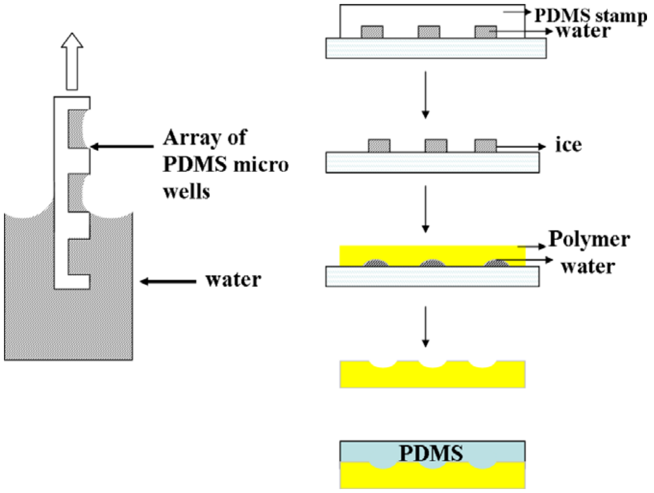

Fig. 1. Scheme for microlens fabrication: (a) PDMS stamp with microwells on its surface was pulled from water and the microwells filled with water via discontinuous dewetting. Such a PDMS stamp was put on a glass substrate. Then, the system was put into a refrigerator at −20 °C. (b) After the water droplets froze into ice, the PDMS stamp was peeled off. (c) After the polymer solution was dip coated onto the ice mold, the system was taken out to room temperature. Ice thaws into water while the solvent evaporates. (d) Microcaves were left on the polymer film surface after it was separated from the substrate. (e) PDMS microlens was fabricated with replica molding.

Fig. 1 outlines the schematic procedure of the microlens fabrication process, which consists of several fairly straightforward and simple stages. The first stage involves pulling a patterned PDMS stamp from water, thus the concave wells were filled with an equal volume of water as the result of the discontinuous dewetting. After placing such a stamp in contact with the substrate, a cooling process was performed. The water turns into ice. When the PDMS stamp is lifted up, the ice remained on the substrate. Dip coating the polymer solution on the ice mold, and increasing temperature to thaw the ice into water, a spherical surface was formed for each water droplet due to surface tension. The morphology of the water droplet can be faithfully reproduced by the polymer film after solvent evaporation. Then, the system was put into water to realize the separation of the polymer film from the glass substrate. The craters on the polymer film may serve as templates for another polymer, so that the complementary form of the crater, a convex lens, is formed.

Fig. 2 displays a microlens array fabricated with our method. The PDMS stamp used here consisted of concave squares with an optimized side length of 50 μm (Fig. 2a), Fig. 2b shows the water droplet pattern formed under the polymer film. As we can see, the arrangement and the size (diameter) of the fabricated microlens array are consistent with the original PDMS stamp except for the morphology transformation from cube to sphere. The polymer template can be further used to fabricate microlenses through the replica molding process, and such fabricated microlens are shown in Fig. 2c and d. The polymer template can be used to fabricate microlens more than once without any noticeable degradation of the pattern quality. The smallest lens size we have fabricated is ∼10 μm in diameters. The packing density via this technique has not been explored, but we believe that it should be possible to fabricate lens separated by ∼1 μm when referred to the approach described by Whitesides [12].

The radius of curvature of the microlens R and the focal length f are two important parameters, which can be expressed as:

$$R = \frac{(h^2 + r^2)}{2h} \tag{1}$$

$$f = \frac{R}{n - 1} \tag{2}$$

where h is the sag height, r is the radius of the circular lenses, n is the refractive index of the elastomer. The plano-convex lens in Fig. 2d has a radius of curvature $R = 137$ μm and a focal length $f = 318$ μm.

The curvature and the focal length of the microlens can be further tuned through the modulation of the wetting property of the substrate. The contact angle further determines the behavior of the droplet on the substrate when ice thaws into water under the polymer film. When substrates with different wetting properties were used, the morphologies of the resulting microlens changed accordingly. As we can see from Fig. 2e, the height of the profile fell to ∼800 nm on the hydrophilic substrate compared with the ∼2.3 μm on the untreated glass substrate. The radius of curvature and the focal length changed to 562 μm and 1306 μm, respectively. In the case of a hydrophobic substrate, the roof became flat (Fig. 2e-c′). This is because the hydrophobicity drives the water droplet to dewet the substrate and exhibit a large contact angle. But the