Fabrication of Hydrophobic Micro-lens Arrays by Capillary Force Lithography

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Abstract. This paper presents a method based on the capillary force lithography technology to fabricate the micro-lens arrays. The micro-lens arrays characterized with hydrophobic were obtained by combining this capillary force lithography and photolithography. In the method, the PDMS is used as an elastomeric mold that has a planar surface with the negative concave micro-lens structures by casting PDMS against a complementary relief structure prepared by photolithography. The imaging and the hydrophobic performances of the micro-lens array are achieved during the experiments, and the maximum contact angle reaches 124° approximately. This technology is suitable for applications required a self-cleaning surface such as image sensors and detectors operating under the natural conditions.

Introduction

Micro-lens array is a function device composed of numerous small lenses with the matching feature [1]. It usually is used as the essential components to integrate with some optical systems for special applications, including optical wave-front sensors, backlight modules, confocal microscopy, fluorescence detection and imaging system [2, 3]. In the current study, micro-lens array is playing the more and more important role in other areas such as biochemical analysis, OLED package and so on [4, 5]. In order to obtain the structures of the micro-lens array, there are various methods used to propose and demonstrate for the processing [7, 8]. The thermal reflow technology was the general method for many years. It provides a way for low cost volume production of micro-lens arrays. However, due to the fluctuations of the exposure energy, the temperature and the solvent concentration, the repeatability and stability of the processing were reduced during the lithography and heating. Electron beam lithography (EBL) and ion beam lithography (IBL) can obtain the arbitrary patterns, but the high cost and the low production efficiency restrict the industrial applications of the technologies [9, 10]. Laser interference lithography can also be used to produce the periodic micro structures, but the intensity distributions of the interference patterns restricts the aspect ratio of the microstructures, and it is not suitable for micro-lens arrays [11-13].

Capillary force lithography provides an emerging technology for the fabrication of micro-lens arrays with large areas, low cost and high efficiency [14, 15]. Capillarity is a useful concept to pattern on the material surface [16, 17]. When the capillary tubes are wet with some liquid, the wetting will results in the capillary rise of the liquid because of the the free energy lower by the wetting [18-20]. This phenomenon has been used as a method called micromolding in capillaries [21-25]. Using the capillary molding process with the curing, the molds of the different sizes, the desired surface structures are created by the heating or UV radiation [26, 27].

In our work, a simple, rapid capillary force lithography technology is presented to fabricate the micro-lens arrays by using a single PDMS mold with the thermoplastic. The morphology of micro-lens arrays are characterized by observing the surface using the scanning electron microscopy.
(SEM) and the imaging and the hydrophobic properties of the micro-lens arrays are investigated using the optical microscope and the contact angle meter.

**Method and Experiments**

The essential feature of the capillary force lithography used for the micro-lens arrays is combined with photolithography. A schematic of the capillary force lithography processing is shown in Fig. 1 (a). It uses the PDMS as an elastomeric mold and fabricate the PDMS master that has a planar surface with the negative concave micro-lens structures by casting PDMS against a complementary relief structure prepared by photolithography. When the photoresist film is thick enough to fill the cavity of the PDMS mold, the residual resist structures are remained on the substrate as shown in Fig. 1 (a). If the resist film is so thin that the interaction between the film and the substrate is much weak, no residual film remains and the substrate surface is exposed as shown in Fig. 1 (b). In this case, a meniscus will emerge at the protruding top of the resist film.

![Figure 1](image)

Figure 1. Schematic diagram of capillary force lithography for the hydrophobic micro-lens arrays: (a) the photoresist film is thick enough to fill the cavity of the mold; (b) the resist film is thin. In the process, the elastomeric mold is placed on the photoresist film spin-coated on a substrate, and then the sample is heated. The capillary force allows the resist melt to fill up the negative concave micro-lens structures. After cooling to the ambient temperature, the mold is removed to obtain the remained micro-lens array structures.

In the capillary force lithography, the most important concept is that the wetting of the mold wall by the photoresist lowers the total free energy. Because the interaction at the surface between the photoresist and the substrate can be negligible and the photoresist melt is liquid-like during the heating process, the height that the photoresist melt can rise to through a channel of the width \( L \) by the capillary action can be achieved by equating the capillary force to the resistant gravitational force, that is expressed as [28]

\[
h = \frac{2 \gamma \cos \theta}{\rho G L}
\]  

(1)

Where \( h \) is the height, \( \gamma \) is the surface tension between the photoresist and the air, \( \theta \) is the contact angle at the surface between the resist and the mold, \( \rho \) is the density of the resist and the \( G \) is the gravitational constant. Analogously, if the effect of the gravity is neglect, the time took for filling up the void space of the mold with the resist is determined by the surface tension and viscosity of the resist melt and the capillary, and it can be expressed as [29, 30]

\[
t = \frac{2 \gamma z^2}{\eta R \gamma \cos \theta}
\]  

(2)

Where \( z \) is the length to be filled, \( t \) is the time for filling, \( \eta \) is the viscosity of the resist melt and the \( R \) is the hydraulic radius.
In the experiments, AZ9260 was used for the positive photoresist. Typically, the quartz glass was used as the substrate that is planar enough to allow conformal contact with the PDMS mold. The substrate was cleaned by the ultrasonic treatment in the acetone and absolute alcohol for 5 min each and dried on the hot plate. The photoresist film was spin-coated onto the substrate to 17 um thickness and the PDMS mold was placed on the photoresist surface. In spite of the spontaneous wetting property of the PDMS mold, the sample was stood for 50 min to avoid the small gaps and bubbles between the mold and the photoresist. The photoresist film was then annealed at a temperature above the glass transition temperature. Due to the difference of the thermal expansion coefficient, the PDMS mold should be soft to avoid the separation between the resist surface and the mold at high temperature. At the same time, the process of the heating was carried out gradually from room temperature to the setting temperature.

**Results and Discussion**

Each sample was heating at 90°C, 100°C, 110°C and 120°C separately for 10 min to make the resist sufficiently mobile. After the heating process and cooling to the ambient temperature, the PDMS mold was easily removed from the micro-lens array structures of the resist, due to the elasticity and low reactivity toward the resist. The remained micro-lens array structures was observed by the SEM. Fig. 2(a)-(c) shows the SEM images of the micro-lens array structures with different distributions and feature sizes, 40um and 20um of diameter, . The images of the words “We”, “us”, and “of” are obtained through the various micro-lens arrays, as shown in Fig. 2(d)-(f).

![Image](image-url)

**Figure 2.** SEM photographs and the imaging performance of the micro-lens arrays with the different diameters and distributions: (a) diameter with 40 um and the honeycomb distribution; (b) diameter with 20 um and the rectangular distribution; (c) diameter with 20um and the honeycomb distribution; (d)-(f) the word images correspond to the different micro-lens arrays of (a)-(c).

For the applications of sensors, detectors and imaging system, the devices of the micro-lens arrays are usually used under the natural condition [31-33]. The efficiency of the devices are reduced because of the dust on the surface of the micro-lens arrays. In generally, this problem can be solved by the self-cleaning structures with the hydrophobic.

![Image](image-url)

**Figure 3.** Schematic diagram showing the water droplets on the sample, surface, Wenzel model and Cassie model.

In the theory of hydrophobic effect, the wettability of a sample surface is generally evaluated by measuring the contact angle (CA) of a water droplet. When CA is greater than 90°, the surface
characterizes hydrophobic interaction at the interface. As shown in Fig. 3, the Wenzel model and Cassie model are usually used as the basic guidelines to express the CA on the structural surface. The effective CA \( \theta_w \) in the Wenzel model is expressed as

\[
\cos \theta_w = r \cos \theta_0
\]

\[
r = 1 + \frac{2h}{w+d}
\]

Where \( \theta_0 \) is the CA on a flat surface and \( r \) is the roughness factor. In the Cassie model, it assumes that the water droplet is suspended on the top of the surface structures, then the effective surface area in the Cassie model is much smaller than in the Wenzel. The effective CA \( \theta_c \) in the Cassie model is expressed as

\[
\cos \theta_c = f(1+\cos \theta_0) - 1
\]

\[
f = \frac{w}{w+d}
\]

Where \( f \) represents the solid on the top of asperities which is wet by the liquid.

Figure 4. Droplet shapes on the micro-lens arrays for the different contact angles of 92°, 113° and 124°.

In our experiments, the micro-lens arrays produced by the capillary force lithography are used to test the surface hydrophobic. CAs were measuring using a contact angle meter (CA systemJGW-360A). Fig. 4(a)-(c) show the photographs of the water droplet shapes for the different micro-lens array. It can be seen that all the results show the hydrophobic states, and the different contact angles of 92°, 113° and 124° were achieved respectively.

<table>
<thead>
<tr>
<th>Figure</th>
<th>( \theta_m (\degree) )</th>
<th>( \theta_w (\degree) )</th>
<th>( \theta_c (\degree) )</th>
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<tbody>
<tr>
<td>4(a)</td>
<td>92 ± 2.15</td>
<td>95.5</td>
<td>94.8</td>
</tr>
<tr>
<td>4(b)</td>
<td>113 ± 3.55</td>
<td>133</td>
<td>114.3</td>
</tr>
<tr>
<td>4(c)</td>
<td>124 ± 3.87</td>
<td>168</td>
<td>125.5</td>
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Table 1. The resulting CAs for the different micro-lens arrays.

Table 1. compares the measured CA values \( \theta_m \) with the calculated values \( \theta_w \) and \( \theta_c \). The CAs were measured three times for each sample at the same location, and the relevant mean values \( \theta_m \) were compared with their deviation ranges. It can be seen that the \( \theta_m \) values were much closer to \( \theta_c \) than \( \theta_w \), denoting that the micro-lens arrays show the characteristics of the Cassie state. As shown in Fig. 4(b) and (c), the measured CAs \( \theta_m \) show slightly different trends: the maximum CA value was obtained in Fig. 4(c) (124°) while the much lower CA value was measured in Fig. 4(b) (113°). This difference can be explained by the contact status with different densities of the micro-lens arrays. In
the Cassie regime, when there are lots of micro-lens in contact with the droplet, a water droplet advances along the convex region of micro-lens arrays because the surface energy on the convex solid region is much higher than that on the concave air region. However, in Fig. 4(b), it was found that the surface-structure density is lower compared with Fig. 4(c). The water droplet then tends to drop down to the concave region, which results in partial wetting on the surface. According to this principle, the CA will increase further with the density of the micro-lens arrays if the period of the micro-lens structure is decreased.

Conclusions
In this work, the capillary force lithography technology is used to provides an emerging patterning technique for the fabrication of the hydrophobic micro-lens array with large areas, low cost and high efficiency. In the experiment processing, the PDMS is used as an elastomeric mold that has a planar surface with the negative concave microlens structures by casting PDMS against a complementary relief structure prepared by the photolithography. The imaging and hydrophobic of the micro-lens array are achieved, and the maximum contact angle reached 124°approximately. Consequently, it is suitable for the potential applications required a self-cleaning to improve the efficiency of the device.

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References

174


