Free-Form Micro-Lens Array Fabrication via Laser Micro-Lens Array Lithography

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Micro-lens array (MLA) is widely used in various applications, such as imaging systems, light sources, optical sensors, and laser modulation. The traditional lithography method is a way to fabricate a micro-lens array while suffering from unavoidable drawbacks such as fixed-period patterns, high surface roughness, and small areas. Laser MLA lithography is a method that can direct write ~500, 000 micro-lenses in an area of 0.5 cm^2 within 70 s. The period and pitch size could be arbitrarily changed with multiple lens structures including square, rectangle, and ring. With thermal reflow, the surface roughness of photo-resist could achieve lower than 5 nm. By reactive ion-etching (RIE), the patterns on photo-resist are successfully transferred onto a quartz substrate with a high depth-to-width ratio. This method paves a flexible new way to make multiple kinds of micro-lens arrays, used for photolithography, optical imaging, and focusing.

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1. Introduction

In recent years, research interest in micro-lens array fabrication has increased dramatically due to their wide applications in imaging systems, light sources, optical sensors, and laser modulation[1]. There are several methods to fabricate MLAs, such as ink-jet printing[2], lithographic patterning by electron beam[3], proton beam[4], ion beam[5], and thermal reflow [6-11]. Due to its ease of operation, the thermal reflow of photo-resist has been used to make the micro-lenses. It was first described by Popovic et al. in 1988 and used a standard photolithographic process to create photo-resist cylinders in desired dimensions[8]. Cherng et al. combined thermal reflow of photo-resist and multiple replications to obtain a curved MLA[12]. Lian et al. prepared semi-ellipsoidal micro-lenses by thermally reflowing two different photo-resists into elliptical photo-resist columns[13].

As a lithographic patterning method, laser interference lithography (LIL) can fabricate the periodic patterns for micro-lens array (MLA) manufacturing over a large area uniformly[14]. However, it only makes fixed-period and regular patterns. The digital micro-mirror device (DMD) is a three-dimensional (3D) lithography technology that digitizes the position and intensity of the illumination by accurately switching one million micro-mirrors at a high speed[15]. However, the MLA fabricated by DMD has a relatively high surface roughness beyond 1 μm[16]. Recently, the laser-induced direct separation is a good way to obtain lower roughness[17].

Microsphere femtosecond laser irradiation, which can achieve nano-structuring with feature size <50 nm on Sb_2S_3 thin films, is a potential method to make a 3D micro-lens array [18]. Femtosecond-laser two-photon polymerization (TPP) is a 3D technology with a nanometer precision through the two-photon absorption to make a small array of micro-lens by a layer-by-layer process. However, they both suffer from unavoidable drawbacks in large-area fabrication due to only one focus [19, 20]. Digital holography combined with two-photon lithography (TPL) is a kind of parallel lithography method with 1-2000 foci to address this problem, while its device is more complicated and expensive [21]. Convex grid-patterned microstructures on silicon can be produced by femtosecond laser irradiation assisted with KOH etching, while the edge of microstructures' surface is rough even if it could achieve large area fabrication at a high speed[22].

Laser micro-lens array lithography is a good means to solve these problems. The characteristics of micro-lens array lithography are a non-contact process, cost-effective, and high throughput. Micro-lens array, which could transform a laser beam into tens of thousands of tiny light beams, acts like an array of light "pens" that can directly write patterns over a large area in a fast and uniform way.

Laser MLA lithography together with thermal reflow and RIE etching not only makes arbitrary designs of micro-lenses arrays but also achieves low roughness and large-area fabrication.

In this paper, a laser micro-lens array lithography system is built. The optimal parameters of direct writing are obtained to realize ~5 μm line width. Combined with a three-axis platform, it can directly write 500,000 micro-lenses in 0.5 cm^2 within 70 s. The period and pitch size can be arbitrarily changed with multiple lens patterning in square, rectangle, and ring. After thermal reflow, a photo-resist of the MLAs exhibits an average surface roughness lower than 5 nm. By reactive ion etching, the patterns on photo-resist are successfully transferred onto quartz substrate at a high depth-to-width ratio. MLAs fabricated are further used for photolithography, optical imaging, and focusing. This method provides a flexible new way to make multiple kinds of micro-lens arrays.

2. Experimental

Laser micro-lens array lithography is shown in Fig. 1 (a). A fiber flat-top laser (405 nm, Changchun New Industry Photoelectric Technology Co., Ltd, China) beam is coupled into the MLA. The sample surface is adjusted parallel to the MLA surface by a 5-axis platform, while its distance from the MLA is controlled by the Z axis along the optical axis. The MLA lithography is equipped with a commercial MLA (ML-S100-F1.0, Highlight Optics Co., Ltd, Shenzhen, China) with 100 μm pitch and 1 mm focus distance. The three-axis stage is used to focus and pattern the sample surface. Various patterns can be realized by the synchronous motion of the x and y-axis stages and the laser operation. The whole system also can work as a stepper, which steps the substrate back and forth, left to right under the MLA and can cover an area of 150 cm × 150 cm. By using this setup, this lithography method is capable of achieving high throughput.

The schematic of MLA fabrication is shown in Fig. 1 (b). For better adhesion of photo-resist (PR), hexamethyldisilazane (HMDS) is spin-coated on a clean surface of glass with a size of 1.5 cm×1.5 cm, and the PR (AZ5214E, Merck, USA) is then spin-coated for 40 s at 4000 rpm and annealed on a hot plate at the temperature of 95°C for 4 min to remove the moisture and harden the photoresist. Then, the sample is exposed at the focal plane of the MLA and the patterns of different micro-lens arrays are formed by the direct writing MLA lithography. The laser power is about 130 mW. The laser spot is magnified by a factor of ~40 by increasing the distance between the MLA and the sample surface. The speed of patterning ranges from 25 to 30 μm/s for 10-sec development and 20-sec cleaning. The sample is then heated on a hot plate at a temperature of 160 ~ 180 ºC for 46 min. The heating causes the resist to melt. Due to the surface tension among the melted resist, sample surface, and surrounding air, the resist pillar changes its shape into hemispherical to minimize surface energy. By the proper control of the processing parameters, such as time and temperature, the large area resist pillars become micro-lens arrays on the quartz surface [5, 23, 24]. Then patterns are transferred into the quartz substrate by RIE in CHF_3 gas. The etch rate is around ~71 nm/min at a CHF_3 flow rate of 20 standard cubic centimeters per minute (SCCM) with 17 min processing time. Samples are finally put into the alcohol solution for 5 min ultrasonic cleaning.

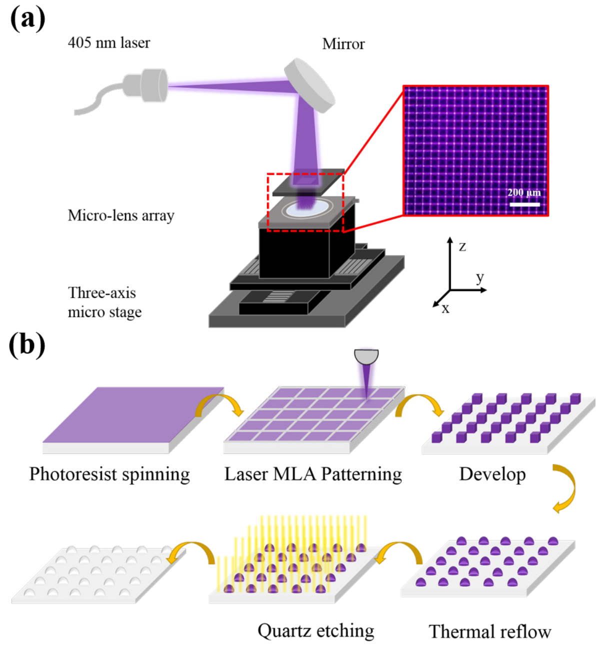

Fig. 1 (a) Schematic of laser micro-lens array lithography and (b) fabrication.

Optical microscope (KX4R, Kwong Kuk, China), field emission scanning electron microscope (GeminiSEM 500, Zeiss, Germany), and Atomic Force Microscope (AFM) (Dimension FastScan, Bruker Nano Inc., USA) are applied to characterize the MLAs. Due to the conductivity requirement, the quartz substrate is coated with a layer of Au film. A measurement system with a beam analyzer and charge-coupled device (CCD) camera (DC500, Mshiwi, China) is used to characterize the focusing performance of MLAs. The cross-section of an exposure spot is detected by a proper profiler (DEKTAK-XT, Bruker, USA).

3. Results and discussion

3.1 Direct write fabrication of micro-lens arrays

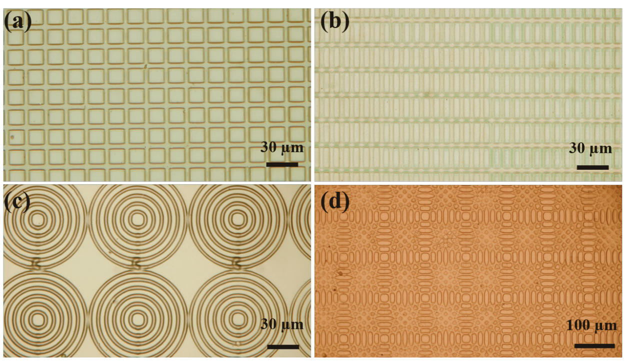

Fig. 2 Optical microscope images of various patterns array on photo-resist (a) square; (b) rectangle; (c) circle and circular ring; (d) circle and ellipse.

AZ5214E is a widely used positive photo-resist, usually applied in the spectral range of 310 to 420 nm. When it is exposed, the photosensitive component of the exposure area is transformed into a carboxylic acid, which is hydrophilic and soluble in alkaline developer. The photo-resist patterning via the laser MLA lithography is used in producing large arrays of complex structures [25]. The optimal exposure of AZ5214E photo-resist is 2~5 mJ/cm^2. During the photo-resist exposure, z-axis movement, laser power, exposure time, and development time play important roles in pattern quality. The focus depth of MLA ML-S100-F1.0 is about 100 μm. To find the focus plane of MLA, the high-resolution Z-axis stage is applied. The higher the laser power, the longer exposure and the longer development time are applied, the larger width of the exposure pattern is formed. The uniformity of the array pattern is affected by the incident light distribution and the parallelism between the MLA and the sample surface[25]. A fiber flat-top laser with <5% deviation of power distribution is applied. It also needs to know the position of MLA, referred to as the exposure results at the beginning. Then adjust the 5-axis platform to parallel MLA to the sample surface. The uniformity of spots or lines in the array can reach more than 95%.

After the parameters optimization, ~5 μm of line width and uniform large area patterns array are obtained on the quartz surface. The direct writing of various patterns can be realized as shown in Fig. 2. Fig. 2 (a) is a square pattern array with ~13 μm of side width. By controlling the distances and passes of line direct writing in x and y directions, it proves that 500, 000 micro-lenses can be produced in a 0.5 cm^2 within 70 s. Rectangle pattern which becomes half cylindrical micro-lens after thermal reflow is shown in Fig.2 (b), with ~20 μm length and ~6 μm width. The cell pattern in Fig. 2(c) shows an array similar to Newton's ring design, comprising circle and circular rings, after 6 circular trajectories writing at a distance of 7.5 μm. When the shutter opens at the starting point, the stage speed is accelerated from zero. It is similar to the endpoint for the deceleration. The line width changes slightly around the bottom corners in Fig. 2 (c). This corner rounding is attributed to the repeated exposure of the start position and end position at the bottom regions. As the distance of rings increases to 20 μm, it is like a water drop array joining into the water surface. Finally, a complex pattern consisting of circle and ellipse pattern arrays is produced in Fig. 2 (d).

3.2 Shape and morphology of micro-lens arrays after thermal reflow and RIE etching

Thermal reflow is used to fabricate polymer micro-lens arrays after patterning by lithography [11]. It is defined as the material relocation or displacement above a certain threshold temperature driven by surface tension. Once the reflow material becomes viscous enough, it loses its constraints: polymer chains can move freely within geometrical boundaries and are governed by cohesion; surfaces can be adjusted to geometrical boundaries defined by surface energy and material properties such as adhesion and wettability at interfaces. After cooling, the polymer is solidified in a shape that is either at the equilibrium of total systems energy or in an intermediate state[26]. As a result, a curved surface is formed on the patterns in Fig. 3. The characteristic parameters of micro-lens include fill factor, surface roughness, and array uniformity. Fill factor η can be defined as follows:

$$\eta = \frac{Se}{St}, \qquad (1)$$

where *Se* is the effective light receiving area and *St* is the total array area. The fill factors of square MLA are ~42% and ~48% for Figs. 3 (a) and (b). Roughness of root mean square (RMS) at the center is ~0.55 nm and ~3.63 nm, respectively, within 1 μm×1 μm. The diameters of micro-lenses are 12.89 μm and 5.88 μm with 93.19 nm and 158.67 nm height, respectively.

$$R = \frac{h^2+r^2}{2h}, \qquad (2)$$

$$f = \frac{R}{n-1}, \qquad (3)$$

$$NA = n \times \sin\theta = n \times \frac{r}{\sqrt{f^2+r^2}}. \qquad (4)$$

Sag height *h* and the radius of the lens *r* co-determine the radius of curvature *R* given by expression (2). In formula (3), the focal length *f* depends on the radius of curvature *R*. The deviation of focal length or intercept position for each micro-lens element is about 2%. It shows that polymer MLAs have good uniformity. Under the 405 nm laser exposure, the refractive index n of quartz is 1.47. Numerical aperture (NA) for two MLAs could be calculated as 0.018 and 0.065, respectively. Longer heating time and higher heating temperature cause more resistance to being vaporized, thus reducing the height or sag of the lenses[27].

Multiple patterns micro-lens arrays can also be produced at the same temperature and time, such as half cylinder and circle and circular ring as shown in Figs. 3 (c) and (d). In Fig. 3 (c), the half cylinder has 25 μm length and 10 μm width with 116.03 nm height. The RMS of its center is about 0.71 nm. In Figs. 3 (d), the micro-lens is like Newton's ring, which consists of a circle center and circular rings. The circle pattern in the center has been transferred into a dome after thermal reflow, which has a 20 μm diameter with 197.56 nm height. The RMS of its center is ~0.50 nm. The circular rings surrounding the dome have a 10 μm diameter with 123.27 nm height. RMS at its center is ~2.48 nm. The surface roughness of polymer MLAs satisfies the requirements of the MLA-based optical element[28, 29]. When the thermal temperature becomes higher, photo-resist has a lower viscosity. Under the surface tension, the prepared micro-lenses have a low NA[30].

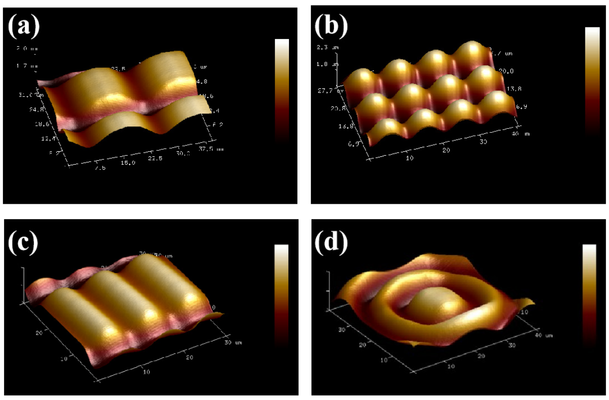

Fig. 3 AFM images of square MLA with side length (a) ~13 μm; (b) ~6 μm after thermal reflow; (c) half cylinder, (d) circle and circular ring after thermal reflow.

To have a higher NA value, polymer micro-lenses can act as a mask to transfer the spherical profile to the quartz substrate by etching[31]. The polymer MLA patterns are fully transferred onto the quartz after the reactive ion etching

(RIE). RIE uses gases, such as CHF_3, CF_4, SF_6, etc. as the etchants. The type and amount of gas effectively affect the etching ratio between photo-resist and quartz and the etching power controls the etching speed. The results are displayed in Fig. 4. It shows that large-area, uniform, and high-quality micro-lens arrays are produced on quartz through etching.

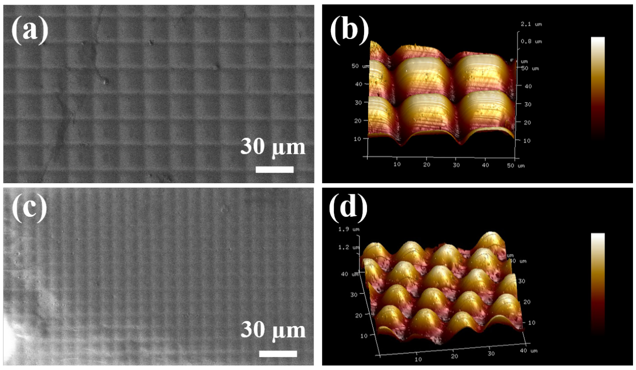

Fig. 4 SEM and AFM images of square MLA with side length (a-b) 20 μm, (c-d) 10 μm.

Through further investigation, the diameter of micro-lens of Figs. 4 (a) and (c) are 20 μm and 10 μm with 1.23 um and 481.41 nm height, respectively. The fill factors of micro-lens arrays after etching in Figs. 4 (b) and (d) are both nearly 100%. RMS values at the centers are ~8.38 nm and ~5.77 nm, respectively. The height of the micro-lens after RIE etching is about 7 times of the micro-lens after thermal reflow. It proves that etching parameters make the speed of quartz etching much faster than photo-resist, which overcomes the drawbacks of thermal reflow. However, the surface roughness of the micro-lens array increases significantly after the etching, due to the sticking of polymer-forming species produced in the CHF_3 discharge which could increase the polymer-induced micro-masking[32]. However, the surface roughness is much smaller than its operating wavelength, so the requirement of an optically smooth surface is achieved. Optical devices with large surface roughness may experience scattering problems, which reduces the contrast and light concentration efficiency of the formed image.

3.3 Photolithography, imaging, and focusing applications

After calculation, the NA of micro-lenses from Figs. 4 (b) and (d) are 0.13 and 0.09, respectively. The higher the NA is, the smaller spot can be formed on the photo-resist. Considering the uniformity and repeatability, micro-lens with 20 μm side width are chosen for further investigations. The micro-lens array is also used to perform surface microlithography by recording the focused light beams onto a photopolymer layer coated on a Si substrate using the fiber flat-top laser. The spots array is achieved and the average dot-size is ~2.2 μm as shown in Fig. 5 (a). The period of the dots array is ~10 μm through 4-times exposure. The size deviation of the spots is less than 10%. In Fig. 5 (b), a diffuse light source goes through the microscope and the MLA to image the micro "XMU" pattern array, enlarged through a 10× objective lens. This demonstrates that our method achieves the large-area fabrication of MLA with high quality.

To examine the ability of the fabricated micro-lens array to focus a light beam, the micro-lens array is illuminated by laser from the top, and a CCD is placed under the micro-lens array. Focal spot arrays are formed by the parallel light with wavelengths of 405 nm. It is seen that the micro-lens array can effectively focus the incoming laser beam into a series of identical tiny light spots as shown in Fig. 5 (c). After 1 sec exposure, 90 sec development, and 90 sec cleaning, the spot size is about ~5 μm, while its full width at half maximum is ~3 μm as shown in Fig. 5 (d). The image depicts the intensity distribution of the focal spots in the focal plane going through MLA. The distribution of the pattern array is the same as that of micro-lenses. The laser MLA focusing can also generate more complicated patterns when the sample is exposed at other positions, due to the Talbot effect[33]. This proves that MLA fabricated by laser MLA lithography processing method has high value.

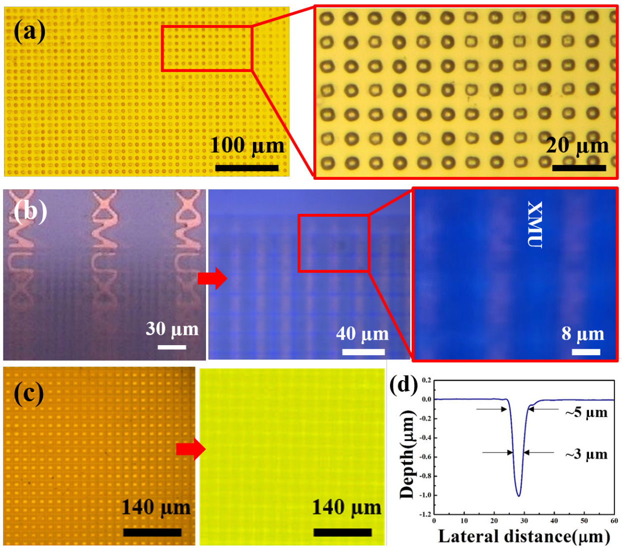

Fig. 5 (a) Lithography; (b) "XMU" imaging; (c) the microscope image of the micro-lens array and its light distribution on the focal plane with the sharpest focus spots; (d) the cross-section of an exposure spot on the photoresist.

4. Conclusion

Laser MLA lithography combined with thermal reflow and RIE makes multiple lens structures such as square, rectangle, circle, and ring. It can directly write ~500, 000 micro-lenses in a 0.5 cm^2 within 70 s. Through thermal reflow, the surface roughness of photo-resist MLAs is lower than 5 nm. The height of the micro-lens after RIE etching is about 7 times of the micro-lens after thermal reflow. Such MLAs fabricated could achieve ~2.2 μm average dot-size exposing and the imaging of the micro "XMU" pattern array. Focal spot arrays are also formed through the MLAs fabricated, using parallel light with the wavelengths of 405 nm. Multiple patterns of MLAs made by laser MLA lithography lead to a new way for large-area direct writing, imaging systems, and light sources.

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