An ultra-long-focal-length microlens array fabricated based on SU-8 photoresist

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In this paper, a novel method to fabricate ultra-long-focal-length microlens arrays (MLA) has been proposed. The microlens arrays were fabricated based on surface tension when heating temperature is over glass transition temperature of SU-8 photoresist. An ultra-long focal length was achieved by the large radius of curvature of photoresist surface. Microlenses of widths from 30 μm to 210 μm were successfully fabricated. The longest focal length was up to 4.4 mm from the microlens of 210 μm width. The formation mechanism was also studied and validated by simulation based on finite element method (FEM).

OCIS codes: *(220.0220) Optical design and fabrication; (220.4000) Microstructure fabrication (160.5470) Polymers.*

Introduction

Microlens and microlens arrays (MLA) are widely used in the fields of imaging, integral photography and atmospheric wavefront sensors known as Shack-Hartmann wavefront sensors (SHWS) [1]. Long-focal-length MLA is a vital optical element, which decides the performance of SHWS [2, 3]. In recent years, many fabrication methods were proposed to make long-focal-length microlens or extend the focal length of MLA [4-7]. The thermal reflow method has been proposed for many years [8, 9]. The photoresist reflow method involves melting photoresist structures to fabricate microlens shaped by the liquid resist's surface tension. This fabrication process is facile and cost-effective. However there were some potential drawbacks of positive photoresist reflow method. It is difficult to achieve large focal length in millimeter range for microlenses by positive photoresist thermal reflow process [10]. Besides, the profiles formed by this method could be much more complex than the simple surface energy minimization, which resulted in a huge aberration of the microlenses for certain fabrication parameters [8, 9, 11]. Hsin-Ta Hsieh has presented a method to extend focal length of reflowed microlens arrays based on two materials. By decreasing the refractive index difference between two layers of materials, the light rays could be less bended when passing through MLA and could be focused on a further distance[6]. Nevertheless, this process is complicated and the quality of microlens array is relying on two materials. Difference of thermal expansion between the materials could cause the thermal stresses, which could limit the application temperature range of the microlens arrays.

In order to achieve ultra-long focal length with small diameters of MLA, we proposed a novel method to fabricate the ultra-long-focal-length MLA by a single kind of material. This is a facile and cost-effective fabrication approach. The ultra long focal length is determined by the large radius of curvature of lens profile achieved due to surface tension. The longest focal length of MLA, which was fabricated and measured in experiment, could be up to 4.4 mm. To understand the formation mechanism of microlens arrays, a finite element method (FEM) was studied by Surface Evolver to simulate the forming process.

Principle and Design

The schematic diagram of microlens array and light propagation path is shown in Fig. 1. Negative photoresist was used to fabricate microlens arrays. MLA structure was fabricated by the exposure process and then a concave MLA was formed by heating reflow procedure. Negative photoresist is typically low molecular weight polymer and exposed photoresist cross-linked and formed high molecular weight polymer by chemical reaction[12]. In the following post-bake and reflow section, the exposed cross-linked polymer will not reflow and the shape will stay unchanged. Meanwhile, unexposed resist will reflow to form a lens profile due to surface tension. Based on the negative photoresist microlens, a replication method was applied to translate the photoresist structure into the convex microlens. This microlens array is easy to test the optical performance. The focal length, f, of the convex microlens could be described as Eq-(1) and Fig. 1(e).

$$f=\frac{r_c}{n-1} \quad (1)$$

where n is the refractive index of replicated microlens material, r_c is radius of curvature. According to Eq. (1), the focal length is directly proportional to radius of curvature instead of the thickness of photoresist. Long radius of curvature can be attained though rheological status during exposure and baking.

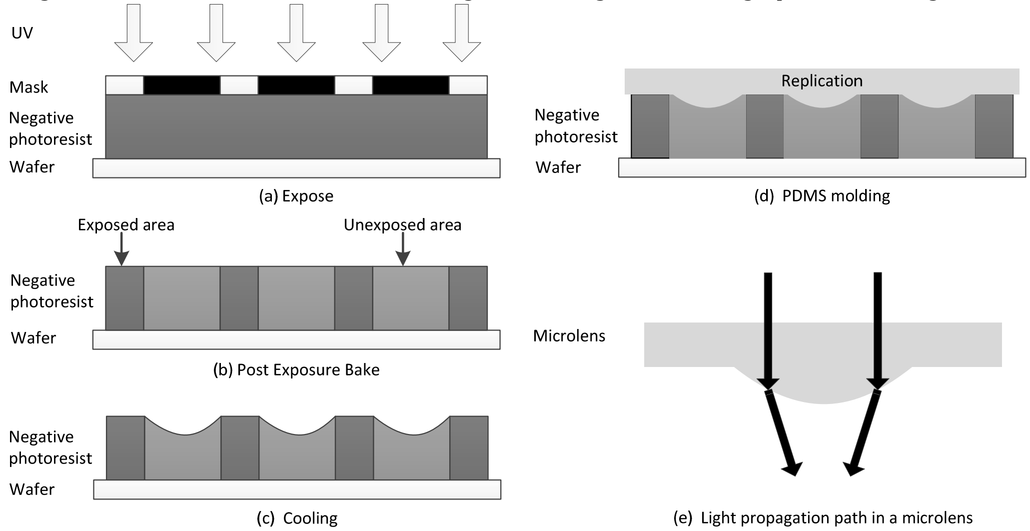

Fig.1 The schematic diagram of microlens array. The black arrows shows the light propagation in a microlens

Fabrication process and experiment

SU-8 photoresist was selected to fabricate ultra-long-focal-length microlens arrays and PDMS was chosen as replication material. The fabrication process is described and illustrated in Fig. 1. The Si wafer (127 mm × 127 mm × 0.5 mm) was rinsed with acetone, and dried at 200 °C for 30 min. The silicon wafer was then spin-coated with a layer of SU-8 photoresist (SU-8 2050, MicroChem) at 1700 rpm for 30 s and a two-step soft bake (65 °C for 5 min and 95 °C for 20 min) was performed on a level hot plate. The photoresist was then patterned by UV exposure (i-line, 220 mJ/cm^2). A level hot plate was used for the post exposure bake (PEB) (65°C for 5 min and 95°C for 10 min). After baking SU-8 photoresist, the substrate was allowed to cool down to ambient temperature on the hot plate to release stress. The appropriate PDMS was poured on photoresist. Placing the PDMS and photoresist in an oven at 50 °C for 24 hours cures the PDMS. After cooling to the ambient temperature, the PDMS mold can be easily detached from SU-8 microlens arrays without anti-stiction because of material property. A convex microlens arrays with large focal length were fabricated.

In order to obtain the morphology of varied kinds of MLA, the diameters and widths of microlens arrays fabricated were from 30 μm to 390 μm and the step length is 30 μm. The profiles of MLA were measured by surface profiler (XP-1 stylus Profiler, Ambios Technology), optical microscope and scanning electron microscope (SEM).

Results and discussion

Microlenses with widths from 30 μm to 210 μm were successfully fabricated. The microscope image of microlens arrays and the scanning electron microscope (SEM) image of cross section of MLA are shown in Fig. 2. The width and contact angle of microlens are shown in this picture. In Fig.2 (a), the focused beam spots are in the center of each microlens. The spot profiles are symmetrical and have little variation, so the MLAs have high uniformity. In Fig.2 (b), the surface profile of microlens is smooth and symmetrical, which means the microlens has good quality. In the widths from 30μm to 390μm, the 210 μm microlens was the biggest microlens demonstrated by this fabrication method and it showed the longest focal length. For comparison, two sizes of MLA, 210 μm and 240 μm were fabricated to illustrate the width effect. The surface profiles of microlenses with two widths measured by surface profiler are shown in Fig. 3. The dash line is the profile of microlens with 210 μm width. The dot line shows the profile of non-fully formed microlens with 240μm width. The convex top profile is mainly caused by the large width, instead of insufficient bake time. In the large width, the viscosity of photoresist plays a big role in formation process, so the effect of surface tension cannot reach to the center of microlens to form a complete arc.

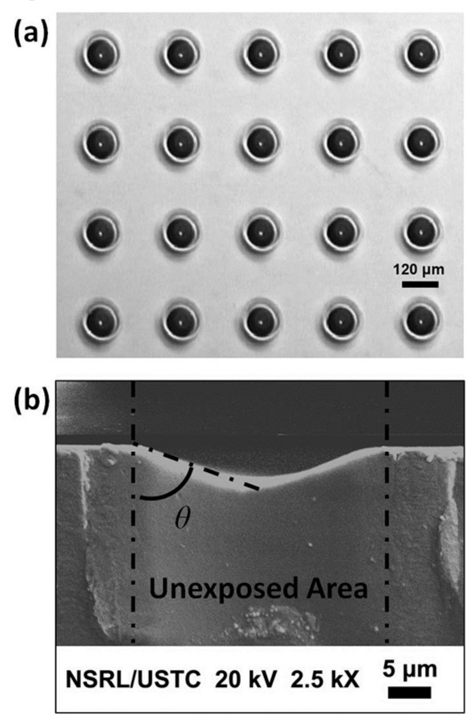

Fig.2 (a): The microscope image of MLA. The focused beam spots are in the center of each microlens; (b) SEM image of cross section of a SU-8 microlens. The unexposed area is between the dash lines and the contact angle is indicated.

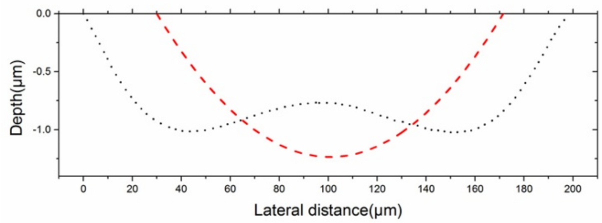

Fig.3 Microlenses profiles by a surface profile. The dash line is the profile of microlens with 210 μm width. The dot line shows the profile of non-fully formed microlens with 240 μm width.

1. Radiuses of curvature and contact angles of MLA

The surface profile of microlens is decided by the width and contact angle. The focal length of microlens is determined by radius of curvature. To achieve the surface profiles and to calculate the focal length of MLA, the morphology of MLA were measured by surface profiler and scanning electron microscope.

Based on the data of morphology of microlens, nonlinear curve fitting was applied to fit the surface profiles. The radiuses of curvature were achieved from the fitting results. Fig. 4 shows the radiuses of curvature of microlens arrays and the relational fitted curves of different widths. Based on the fitting result, the relation between radius of curvature and width is determined from the Eq. (2)

$$r_c = 52.60 \times e^{\frac{w}{55.63}} - 115.68 \qquad \textbf{(2)}$$

where r_c is the radius of curvature and w is the width of microlens. The Adj. R-Square (COD) shows the quality of a fit. The Adj. R-Square of radius fitting is 0.99, so the curve of microlens is well fitted which means the result of the fitted radius is reliable. The results of radius could be used to calculate the focal length in following section.

In the ideal condition, the contact angle is decided by the solid, liquid and vapor at a given temperature and pressure, instead of the width of microlens. In this condition that the contact angle is not affected by the width, the radius is proportional to the width of microlens. The radius could be described as Eq. (3)

$$r_c = \frac{w}{2 sin\theta} \qquad \textbf{(3)}$$

Compared with Eq. (2), Eq. (3) shows the exponential relationship between the radius and width. Based on the difference, it is expected that the contact angle of microlens changes with the width.

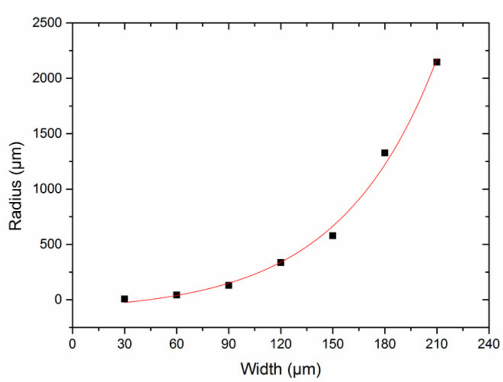

Fig. 4 Radiuses of microlenses and the curve fitting line. The square dots are the radiuses of curvature of microlenses and the widths of microlens are from 30μm to 210μm. The solid line is the curve fitting line.

The contact angles of microlens arrays and the relational fitted curve of different widths are shown in Fig. 5. It shows the logarithmic relationship between the contact angles and width. According to the fitting result, the relation between contact angle and width is determined from the Eq. (4)

$$\theta = 44.34 + 8.15 \times ln(w - 29.37) \qquad \textbf{(4)}$$

where θ is the contact angle and w is the width of microlens.

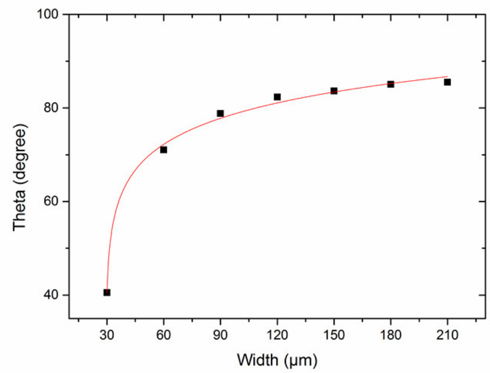

Fig. 5 Contact angles of microlenses and the curve fitting line. The square dots are the contact angles of microlenses and the widths of microlens are from 30 μm to 210 μm. The solid line is the curve fitting line.

When the widths of microlens are below 90 μm, the contact angles increase significantly from 40 degree to 80 degree. It results in the radius of curvature enlarge slowly when the widths are below 90 μm. When the widths are above 90 μm, the contact angles increase slowly and approach 90 degree finally and the radius of curvature of MLA enlarges quickly. Therefore, the radius shows an exponential relationship with the width. The photoresist is polymer and its viscosity is significant during reflow process. The viscosity has a big effect on formation of microlens, so the contact angle will change with the width of microlens which results in the nonlinear increase of radius.

2. The focal length of MLA

The focal length is relative directly to radius of curvature of microlens arrays based on Eq. (1). According to Eq. (1) and Eq. (2), the relation between the focal length and the width of microlens is determined by the Eq. (5)

$$f = \frac{52.60 \times e^{\frac{w}{55.63}} - 115.67}{n-1} \qquad \textbf{(5)}$$

where f is the focal length of MLA, w is width of microlens and n is refractive index of replicated microlens material. The equation could be used to calculate the focal length based on the data of morphology of microlens measured in experiment.

A professional setup was implemented to measure the focal length of the microlens arrays and observe the optical quality. The setup [7] was composed of a 633 nm wavelength laser light source, a lens system, a CCD camera, a guide and a computer, as shown in Fig. 6.

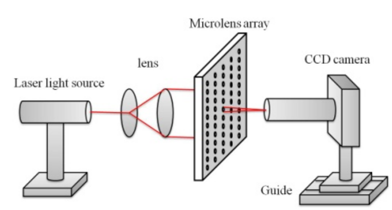

Fig. 6 Schematic diagram of the setup to measure the focal length of the MLA

The result of the focal length based on the data of morphology of microlens and measured by the optics setup is shown in Fig. 7. The square line is the focal length calculated based on the data of radius in experiment and Eq. (5) .The dot line is the focal length measured by the optics setup. The differences between the two kinds of values are slight in small widths. There are some differences in large widths which could be caused by measurement error, fitting error and spherical aberration. Based on the results of Fig.7, the largest focal length is 4465 μm, which is much larger than that of microlens fabricated by other methods[4-7]. The ultra long focal length is an advantage of this fabrication method.

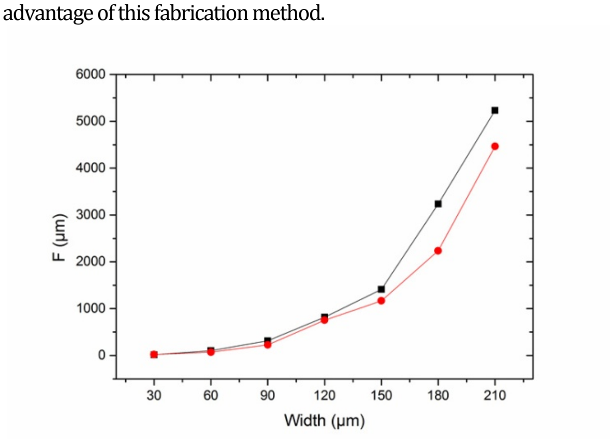

Fig. 7 Focal length of microlens arrays based on measurement of the morphology and optics performance. The square line is the focal length calculated based on the data of radius in experiment .The dot line is the focal length measured by the optics setup.

In our experiment, the refractive index is n = 1.41 (PDMS). Based on the calculation of the previous section, the focal length is expected to 2.43 times long as radius of curvature. A longer focal length could be achieved by replacing the PDMS by other material with less refractive index.

3. Simulation of microlens arrays by FEM software

To understand the formation mechanism of microlens arrays, a finite element method (FEM) was applied by software Surface Evolver. When the unexposed photoresist was melted, the photoresist surfaces were pulled into a shape which minimizes the energy of the system. If gravitational effects are presumed to be negligible, which for very small lenses will generally be the case, and assuming ideal conditions, one would expect the shape of these microlens to be well approximated by a spherical surface[8, 9]. Surface Evolver is an interactive software for the modeling of liquid surfaces shaped by various of forces and constraints[13]. Given the widths and contact angle, the software model could form the curved surface. The model of simulation by Surface evolver and the results of radius of lens curvature simulated by Surface Evolver and measured by optics setup are shown in Fig. 8. The square line is the radius measured by the optics setup. The dot line is the radiuses of curvature simulated by Surface Evolver. The experimental result agrees well with the result of simulation, which proves that the surface tension is the most crucial impact element of MLA's formation procedure. There were slight differences between the measured and simulated values. The reason is that the reflowed SU-8 photoresist is rheological state and there is other elements such as shrinkage of photoresist and viscosity to impact the formation process.

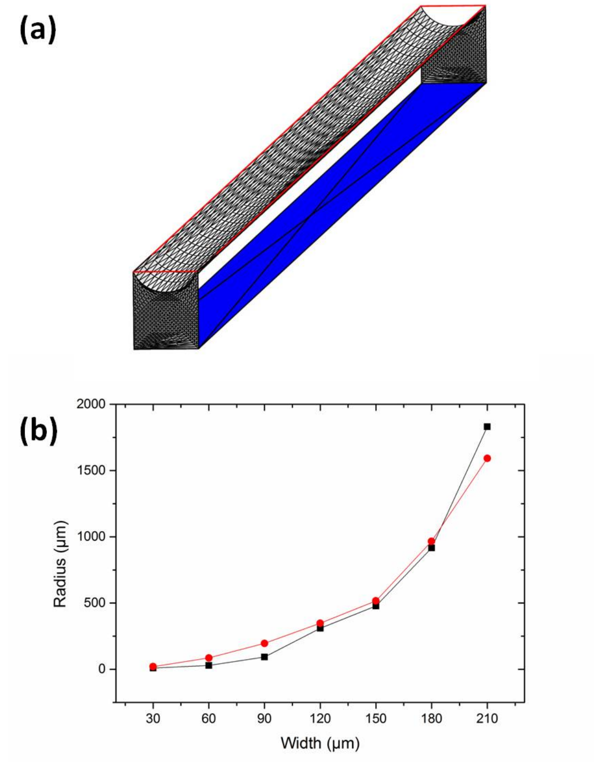

Fig. 8 (a): The model of simulation by Surface evolver. (b): Radiuses of measured data and Surface Evolver simulations. The square line is the radius measured by the optics setup. The dot line is the radiuses of curvature simulated by Surface Evolver.

Conclusion

A new method to fabricate ultra-long-focal-length microlens has been proposed. Surface tension during postbaking was used to form the profile of microlens. This fabrication approach is facile, cost-effective, highly reproducible and easily controllable, offering a great opportunity of large-scale production of ultra-long-focal-length microlens arrays. Various focal lengths have been achieved by regulating widths of the mask, in spite of the thickness of photoresist. The ultra long focal length as long as 4.4 mm was achieved in the experiment, which was much longer than that made by other methods. It is applicable in situations required a long focal length such as wavefront detecting in Shack-Hartmann wavefront sensors. Ultra Long focal length also provides large depth of focus (DOF), which can adopt position variance of image sensor. Besides, it is useful for future photolithography technology.

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