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Fabrication of microlens arrays with varied focal lengths on curved surfaces using an electrostatic deformed template

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Abstract

A microlens array (MLA) with varied focal length was fabricated on a curved surface for the application of compound-eye imaging. Electrostatic deformed concave membrane was used as the initial molding template, and the deformation was determined by different applied voltage. By transferring the pattern to another polymeric template and deforming it by negative pressure, MLAs on a curved surface were fabricated successfully by using this molding process and polymeric template. The fabricated MLAs were optically characterized and the result demonstrated a larger field-of-view than that of flat MLAs and better imaging performance than that of MLAs with uniform focal length on curved surfaces.

Keywords: microlens array, varied focal length, electrostatic deformed template, curved surfaces

(Some figures may appear in colour only in the online journal)

Introduction

The microlens array (MLA) has attracted a great deal of research interest for various imaging systems, including thin wafer-level cameras [1, 2], three-dimensional (3D) imaging [3], micro-optical telescopes [4], confocal microscopy [5], endoscope systems [6–8], machine vision [9, 10], etc, because it allows for reduced optical components and minimized volume compared to traditional optical lenses.

Most currently available MLAs are built on a planar surface [11], which makes them have a narrow field-of-view and thus limits their medical, industrial, and military applications. Thus, MLAs on curved surfaces, like the compound eyes of insects, are in demand for achieving a large field-of-view and better imaging performance.

However, in a compound-eye imaging system on a curved surface, photo detectors have to be located in the curved focal plane of the MLA to obtain a clear image, but the commercially available imaging sensors such as CCD or CMOS are restricted to planar chips at present. Several approaches had been proposed to address this issue. For example, deformable arrays of thin silicon photo detectors had been prepared on hemispherical surfaces to realize an apposition compound-eye camera [12, 13], or guiding the light from curved MLAs to planar imaging sensors by polymer cones [14]. Another easier solution was to make the focal lengths of the microlenses varied at different locations and to be equal to the corresponding distances between the center of the microlenses and the planar photo detectors [15]. However, the only design algorithm was given in [15] due to the current lack of effective fabrication technologies to prepare MLAs with varied focal length (v-MLA) on a curved surface.

Thermal photoresist reflow is widely used to prepare MLAs [16–19], and the pattern is usually transferred to a polydimethysiloxane (PDMS) membrane for further deformation by negative pressure or punching to realize MLAs on curved surfaces [20]. In addition, several unique technologies have also been reported to prepare MLAs on

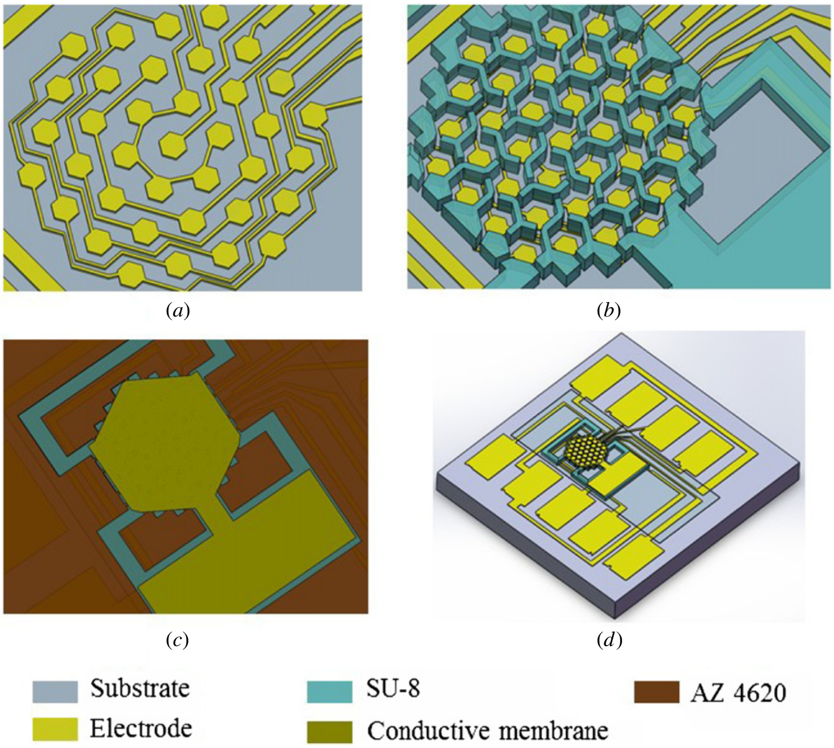


Figure 1. Fabrication of the electrostatic deformed template: (*a*) patterning and deposition of metal driving electrode; (*b*) patterning of the SU-8 15 micron-thick layer; (*c*) part filling of the SU-8 cavity with AZ 4620 and polishing, followed by conductive membrane deposition and patterning; (*d*) stripping AZ 4620 completely.

curved surfaces. For example: laser lithographic fabrication of a spherical artificial compound eye [21]; a femtosecond-laser-based process to create close-packed MLAs on flat polymer substrate, followed by a thermo-mechanical bending process to turn the planer MLAs into a curvilinear shape [22, 23]; and self-assembly of polystyrene microspheres on the spherical surface of a reflowed photoresist [24, 25]. However, most of the previous developed technologies are suitable for fabricating uniform MLAs, and it is still difficult to fabricate chirped MLAs on curved surfaces.

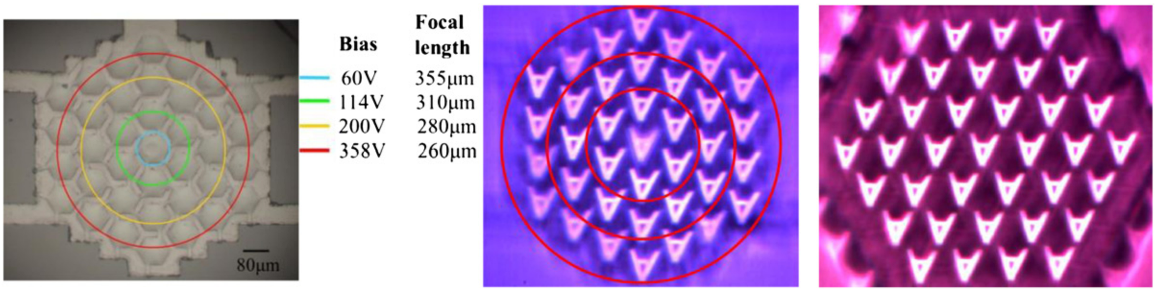
On the other hand, the merits of chirped MLAs, such as extended depth-of-field and field-of-view [26, 27], aberration correction [28], and improved system integration [29], are obvious in various optical imaging systems. Accordingly, it is desirable to develop some simple fabrication methods for preparing v-MLAs on curved surfaces, and making the focal length of each microlens as well as the curvature of the curved surface controllable.

An electrostatic deformed concave membrane had been used as a molding template to realize freeform MLAs in our previous publication [30, 31], and their focal length is controllable by applying different driving voltage. In this paper, a series of variable voltages were applied to each pixel of the template, and the v-MLAs on curved surfaces were prepared successfully through the molding process. In the following sections, this technology is demonstrated experimentally and the fabricated MLAs are optically characterized. Generally, this proposed method is promising for realizing compound-eye imaging systems on a curved surface using conventional planar imaging sensors.

Fabrication

The driving electrode with a chromium (20 nm) and gold (200 nm) bilayer was patterned on a silicon/silicon dioxide substrate by sputtering and a lift-off process (figure 1(*a*)). The driving electrodes were divided into several groups, and the electrodes in the same group located on a circular ring and electrically connected. Next, 15 micron-thick SU8-2015 (MicroChem Corp., USA) was spin coated and developed after exposure with a dose of 120 mJ cm^{-2} (figure 1(*b*)). After that, a kind of photoresist (AZ 4620, Futurrex, USA) was spin coated to partly fill the trench. The photoresist on top of the SU-8 was then polished away (POLI 400, G&P technology Inc., Korea) after baking in a 135 °C vacuum oven for 2 h. Here, the top surface of the AZ 4620 layer is curved and the altitude of its center is lower than the edge of the SU-8 cavity by adjusting the spinning rate carefully. The second bilayer of chromium (5 nm) and gold (50 nm) was deposited and patterned (figure 1(*c*)). Last, the wafer was diced into chips, and the AZ 4620 photoresist was stripped by acetone and ethanol ultrasonic bathing (figure 1(*d*)). The bilayer metal membrane was relaxed after releasing due to its curved shape and exhibited a large deflection with electrostatic force applied.

The chip was glued to a printed circuit board with an embedded series-resistive voltage assignment circuit, and different voltages were applied on the different groups of driving electrode, respectively, while the membrane was grounded. The largest voltage was applied on the electrodes on the edge, and dropped step by step from the edge to the center. A kind of ultraviolet optical resin (NOA61, Norland



(*a*) (*b*) (*c*)

Figure 2. The focal length of the lenses in the array varied with applied voltages: (*a*) optical image of the resin template with bias voltages of 358, 200, 114 and 60 V applied from the edge to the center of the conductive template, (*b*) the measured focal length of the lenses in the array is 260, 280, 310 and 355 μm from the edge to the center, (*c*) the image obtained by using a uniform resin template when applying a constant driving voltage on each pixel.

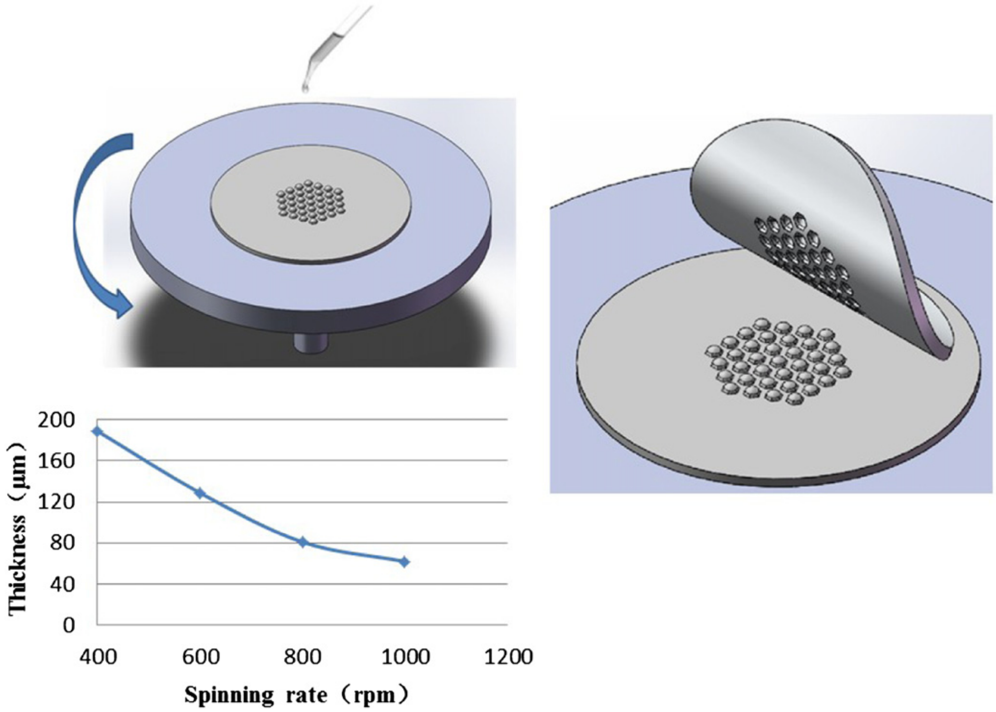


Figure 3. The preparation of PDMS template: UV resin template was placed on a spin-coater and PDMS was spin-coated (left top), the thickness of the membrane is controlled by spinning rate (left bottom), and the PDMS template was peeled off after curing (right).

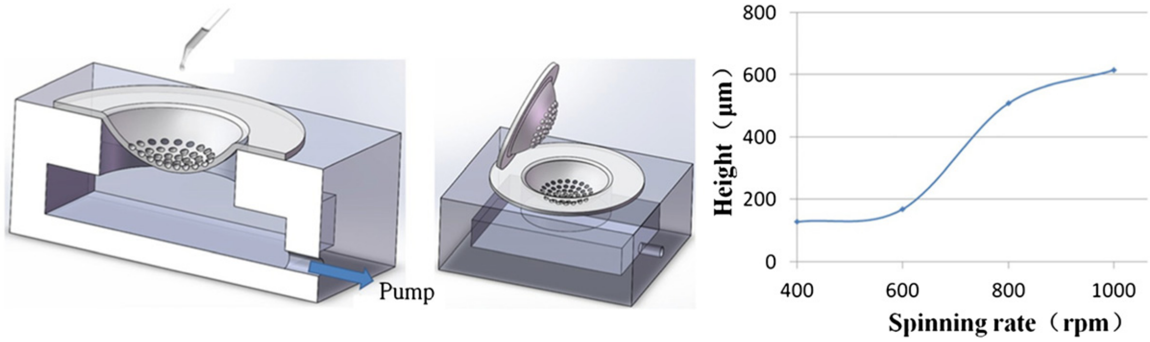
Products, Inc.) was then poured on the concave template while the voltage was kept on. In such a configuration, the lenses on the edge have bigger sag height and smaller focal length because they are closer to the underneath planar CCD in a curved imaging system.

An optical microscopy picture of the peeled ultraviolet resin template after ultraviolet curing is shown in figure 2(*a*), here bias voltages of 358, 200, 114 and 60 V were applied on different groups of electrodes, respectively, according to the design algorithm presented in [15] to correlate the focal length of these microlenses to their distances from the photodetectors underneath. In this algorithm, the radius and the sag height of the curve surface was set to be 560 and 380 μm according to the process parameters shown in figure 4. The specific driving voltage to obtain a certain focal length was predetermined by finite element analysis [31].

The sag height of different lenses in the MLA were measured by using a 3D laser confocal microscope (OLS1200-FAR2, Olympus), and they ranged from 3.6 to 6.9 μm. The fabricated MLA had a larger sag height than that reported in [30] because a larger deflection of the conductive membrane was achieved by replacing the planar conductive membrane with a curved one.

The resin template was placed between the objective lenses and a light source shielded by a pattern ‘A’. The image was captured by using a CCD camera through the objective lenses (figure 2(*b*)). By adjusting the distance between the objective lenses and the resin template to focus the pattern ‘A’ on the CCD, the focal length of different groups of lenses was measured to be 260, 280, 310 and 355 μm from the edge to the center. As a control, another resin template was prepared by applying a uniform driving voltage of 200 V on each electrode, and the focal length of each lens was uniform, too (figure 2(*c*)).

As shown in figure 3, the resin template was placed on a spin-coater, and PDMS primer was spin-coated on the resin and peeled off after curing. The thickness of the PDMS



(*a*) (*b*) (*c*)

Figure 4. Preparation of v-MLAs on curved surface: (*a*) PDMS template deformed by negative pressure; (*b*) ultraviolet optical resin is poured on the concave membrane and peeled off after curing; (*c*) the relation between the sag height of the curved surface and the spinning rate to form the PDMS membrane.

membrane was controlled by the spinning rate and ranged from 60 to 200 microns in this experiment.

As shown in figure 4, the PDMS template was placed on an aluminum platform and covered a vacuum hole of 1.0 micrometer in diameter completely. After the PDMS template was deformed by negative pressure, ultraviolet optical resin was poured on the concave template. Last, the v-MLA was peeled up after curing. Since the maximum deformation of the PDMS membrane was almost the sag height of the molded curve surface in the molding process, and was decided by the thickness of the membrane, the sag height of the molded curve surface can be determined by the spin coating speed to form the PDMS membrane. The relation between the sag height of the curved surface and the spinning rate of the PDMS membrane is shown in figure 4(*c*).

Several other samples were prepared as contrast samples in the following optical characterization. One kind of sample was molded by using a PDMS template which was not deformed by negative pressure, the so-called 'flat MLA'. Another kind of MLA was on a curved surface but with uniform lenses because the same bias voltage was applied on the conductive template, the so-called 'uniform MLA'.

Optical characterization

The optical performance of the MLAs was characterized using the testing apparatus as illustrated in figure 5. A lamp shielded by a pattern 'A' is utilized as the light source, and the light passing through the MLA is collected by an objective lens ahead of a CCD camera. The light source is placed in different positions while the corresponding images are recorded by the CCD, and the inclined angle of a certain position is also recorded. The critical positions where the pattern 'A' becomes unidentifiable are recorded as positions I and III, and the field-of-view of the MLA is determined as the vertex angle of the triangle formed by the location of MLA, position I and position III (figure 5).

The testing results of the flat, uniform and v-MLA are shown in figure 6. The optical microscope image of the test sample, the images recorded by the CCD at positions I, II, III, respectively, are shown, and the inclined angle of each image is given on top of the image.

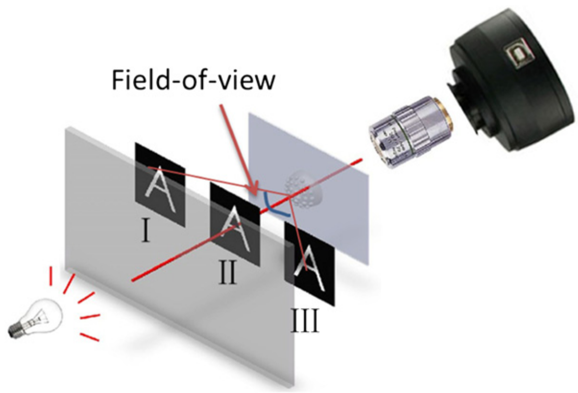


Figure 5. Illustration of the testing apparatus for optical characterization.

The field-of-view of the flat MLA was about 14.4° in the experiment, while the uniform and the v-MLA had an extended field-of-view about 24.8° and 36.6°, respectively, because they were built on curved surfaces. Compared to uniform MLA, more lenses in v-MLA can be focalized on the CCD focal plane and output more of the legible 'A's due to the chirped configuration. For example, in the images shown in figure 7, which were captured by the CCD through the uniform MLA (figure 7(*a*)) or the v-MLA (figure 7(*b*)) at the same inclined angle of −12°, there were more clear-cut 'A's in figure 7(*b*) than in figure 7(*a*).

Discussions and conclusions

The dimensions of a single microlens in the v-MLA were determined by the size of the SU-8 cavity in the proposed fabrication technology, and they ranged from hundreds of nanometers to hundreds of microns according to what kind of SU-8 was used. Such a wide range of dimensions is able to match either the size of single-mode, multi-mode or imaging optic fiber, or the pixel size of a CCD or CMOS imaging sensor, etc.

Hexagon-shape lenses with a 45 μm side length and 15 μm space were prepared in this experiment, so the filling factor of the MLAs was about 73%. This gap was decided by the width of the SU-8 bank in the conductive template.

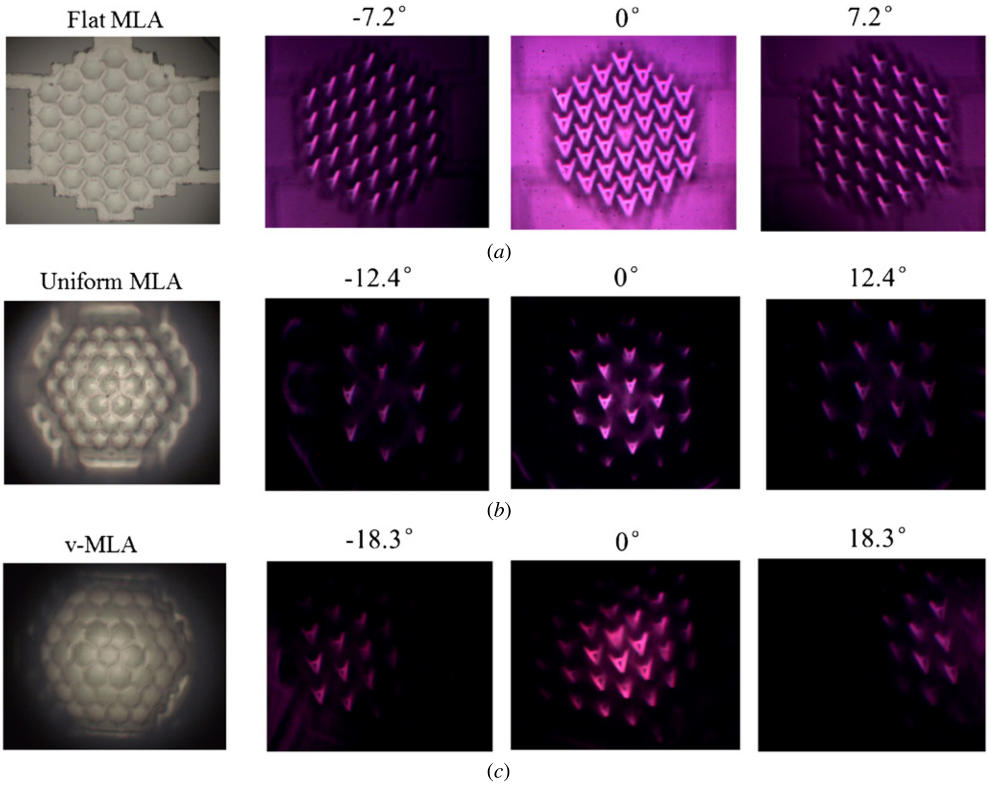
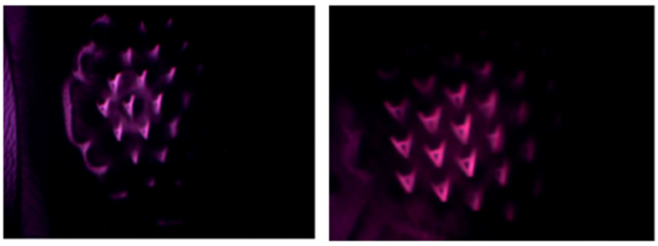


Figure 6. The test results of the flat, uniform and v-MLA: optical microscopy of the testing sample and the images recorded by the CCD at positions I, II, III are shown from left to right, respectively.



(*a*) (*b*)

Figure 7. Optical images captured by the CCD through the uniform MLA (*a*) and the v-MLA (*b*) at the same position with an inclined angle of -12°

Because the aspect ratio of SU-8 is up to 10, if the depth of SU-8 cavity remains 15 μm, the minimize width of the SU-8 bank is about 2 μm, so the filling factor can reach 95% in this case.

The optical performance of the fabricated microlens can be predetermined by simulation [31]. The electric field distribution at a certain applied voltage was figured out by electromagnetic field simulation. Next, the deformation of the template by the electromagnetic field was obtained by finite element analysis. A three-dimensional body enclosed by the deformed surface and a flat surface was generated and input into an optical software to simulate its optical performance. In [30], the relation of the focal lengths and the applied voltages was given experimentally and it is consistent with the simulated result.

The surface roughness of the polymeric template is about 2 nm [30], which is competitive with most of the available MLAs. The following molding process will not degrade the smoothness of the lens significantly [20–23]. Therefore, the surface smoothness of the prepared MLAs is acceptable for optical applications.

The fabrication process of the conductive template is simple and reproducible. In the earlier experiments, some wrinkled pixels were found because the AZ 4620 underneath was not removed completely. A well-shaped membrane was obtained later by optimizing the stripping process carefully.

In conclusion, a fabrication method was presented in this paper to prepare a v-MLA on curved surfaces, and the focal length of the lenses in the array was variable in order to match the planar photo detectors. This fabrication process is low cost and reproducible, mainly because hundreds of the conductive template can be produced simultaneously in a single wafer. The v-MLA, along with two other kinds of samples, the 'flat MLA' and the 'uniform MLA', were optically characterized. As a result, the field-of-view of the v-MLA and the uniform MLA was more than two times larger than that of the flat MLA because they are built on curved surfaces. Compared to the uniform MLA, the v-MLA showed better imaging performance because its focal length can be preset for better focalization on planar photo detectors. Generally, this technology is promising for many applications such as endoscopy, machine vision or 3D imaging for obtaining an extended field-of-view and better optical performance simultaneously.

Acknowledgments

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