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Variable-focusing microlens with microfluidic chip

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Abstract
A new polymer microlens with variable focusing properties is designed and fabricated. The microlens consists of a thin diaphragm with 3D convex lens, chamber and microchannel, which are made of polydimethyl-siloxane (PDMS). A novel fabrication approach has been developed to cast the PDMS microlens film using a PDMS mold. The elastomeric PDMS microlens film acts as a diaphragm. The flexible PDMS microlens and diaphragm are integrated on a microfluidic chip. By varying the pressure in the microfluidic chamber, which produces a shift in the microlens' focal plane, this can change the back focal length of lens. The new fabrication method provides easy fabrication, low-cost production and precise dimension control. Measurement with an atomic force microscope reveals that the surface roughness of the lens is 18.6 nm, and real-time contact-angle measurements show the back focus length tuning range is from 3.8 mm to 10.6 mm. The variable focal length of the microlens is critical to increase the efficiency of the light detection in optical or biophotonic applications. In this paper, the fabrication processing, mechanical and optical property testing, and simulation results are presented in detail.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The study of variable focusing microlenses has been an area of activity for many years. Variable focal length is a necessary attribute in many optical applications if the object being imaged is not in a fixed position. Several recent publications have recognized the potential for the variable microlens to impact significantly on the field of optical applications [1, 2]. The variation of focal length can be provided by a focalizing mechanism that causes the focal plane to shift. Different approaches using liquid crystal [3, 4] and the electrowetting method [5, 6] have been investigated by some researchers, but the liquid crystal lens is limited to small lenses and the electrowetting liquid concept lens requires a high voltage source. Both methods require electrodes, which are immersed in the electrolyte solution, causing severe optical distortion. A variable focusing liquid-filled lens with a pressure-driven mechanism was also demonstrated [7]. However, the numerical aperture of this lens is limited because the lens was made by a planar glass diaphragm.

A new concept has been developed to fabricate a flexible polydimethyl-siloxane (PDMS) microlens with a microfluidic chip. The microlens is a 3D convex polymer lens on a thin diaphragm. The diaphragm is integrated on a microfluidic chamber to simultaneously control the focal length of mcirolens. The microchamber on the microfluidic chip is filled with working fluid. By changing the fluid pressure, it causes a change of curvature of the polymer lens and this induces focal plane shift. Together with the deflection of the PDMS diaphragm, a microlens, which is attached to the diaphragm, can provide much higher numerical aperture than a planar glass or polymeric membrane. Moreover, the 3D convex lens provides a focal point when the diaphragm is at an initial position. This design of microlens, working as the human eye's crystalline lens, provides more flexibility on back focal length and higher numerical aperture than previous research on liquid-filled variable focal lenses. The numerical aperture of the new PDMS microlens can reach 0.24 which is about four times that of a conventional planar glass diaphragm (NA $\approx$ 0.05) [7]. The higher numerical aperture microlens integrated on a microfluidic chip will perform high resolution and high signal-to-noise detection in optical MEMS applications. The high numerical aperture of a microlens is critical to increase the efficiency of the detection ability. This design has the advantages that it can be used as a microoptical component with high numerical aperture, variable focal length and low optical distortion. They make this design attractive for the optical pickup in many applications, such as optical switches, cameras, microscopes and optical signal processing.

In addition, a novel batch process for making polymer lens arrays has been developed. It is a cast method to fabricate convex PDMS microlenses on a thin diaphragm by using a cured PDMS concave microlens master mold. This method can produce high dimensional accuracy, high optical quality, and high production rate with low cost. The design, simulation, fabrication and characterization are presented in the following sections.

2. Fabrication

A conventional lens has a fixed focal length. However, a variable focus lens should work like a human eye's crystalline lens that can be deformed by muscles. A variable focal length microlens was successfully designed and fabricated and includes two parts: microlens diaphragm and microfluidic chip. The PDMS thin film with convex lens is a passive diaphragm while the microfluidic chip acts as the actuating part. PDMS is selected as the lens material, because it features good optical properties with large elongation and bio-compatiblility.

2.1. Microlens film fabrication

New design and fabrication technology of microstructures for optical elements are strongly demanded with the diversification of optical devices and systems. One of the key processes is 3D microlens fabrication. Several fabrication processes for microlenses have been reported, such as reactive ion etching (RIE) [8], ion diffusion [9], deep proton irradiation [10], and physical methods such as hot embossing [11], injection molding micromachining [12] and photoresist reflow [13]. The microlens materials are varied depending on the fabrication methods, which include polymethyl methacrylate (PMMA), photosensitive glass, photopolymers and UV curable resins [14]. However, each microlens, which is produced from the above methods, has a rigid structure with a unique focal length. Most of their fabrication processes are complicated and require specific facilities for producing microlenses.

A novel PDMS casting fabrication process has been developed. The processing schematic is shown in figure 1. To fabricate the microlens by molding, a mother lens of the same shape as the final PDMS lens is needed. The photoresist reflow method is used to make the mother lens. The first step is to generate a photoresist pattern by conventional photolithography. Secondly, the photoresist pattern is thermally treated for reflowing into a lens shape. The photoresist reflow method, suggested by Prpovic in 1988, is to melt photoresist structures to form small lens shapes due to the surface tension of the liquid resist [14]. SEM photographs

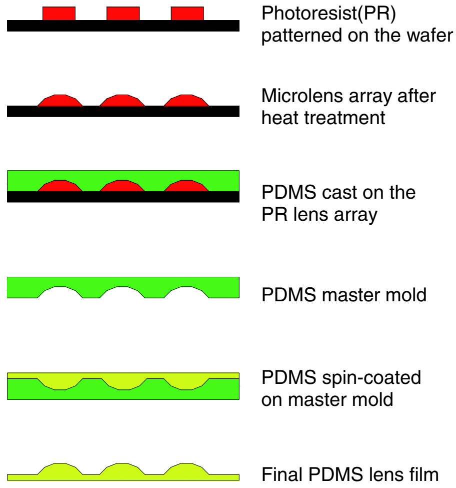


Figure 1. Fabrication sequence for an array of polymer microlenses.

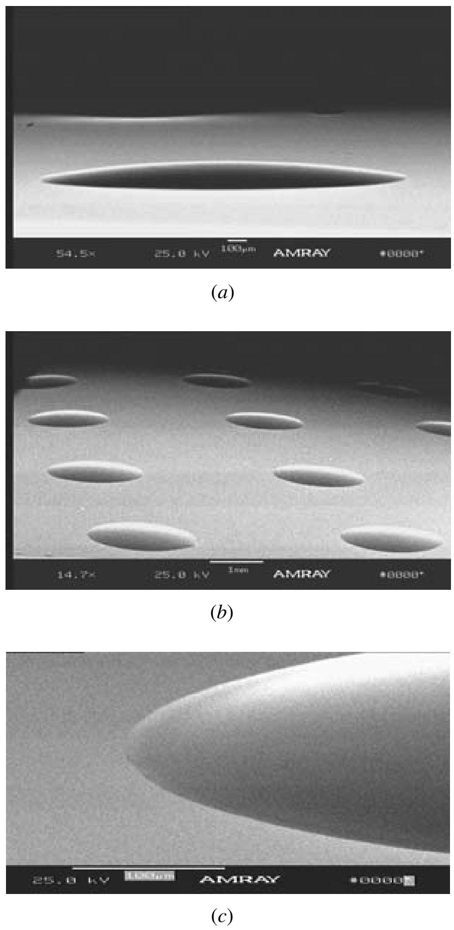
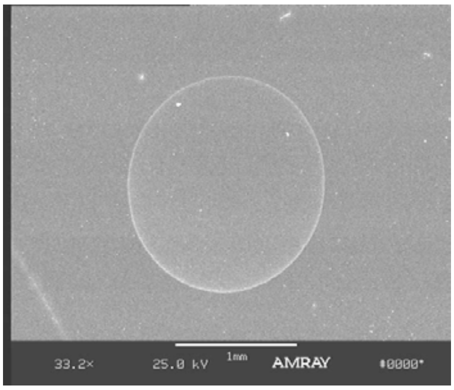
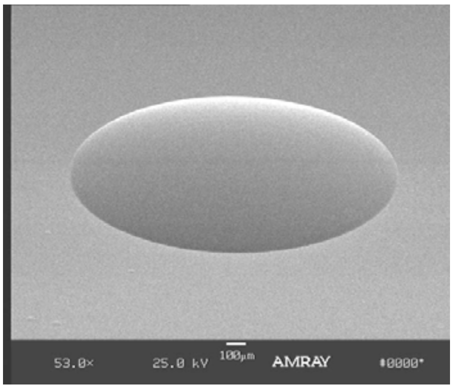


Figure 2. SEM images of 1400 μm diameter photoresist microlens: (*a*) single spherical lens, (*b*) an array of microlenses and (*c*) closer view of the edge of a photoresist microlens.

of a photoresist microlens with a diameter of 1400 μm and an array after the thermal reflow process are shown in figure 2. The photoresist we used is AZ 100XT. The photoresist patterns are thermally treated on a hot plate, and the reflow temperature is 120 °C, and the reflow time is 60 s.



(*a*)



(*b*)

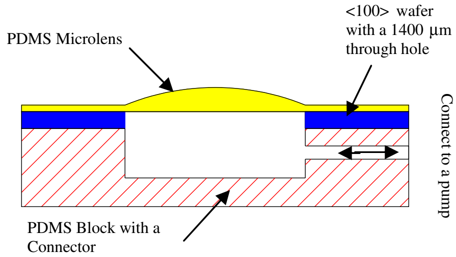
Figure 3. SEM photographs for (*a*) PDMS concave master and (*b*) final PDMS film with convex lens.

After completing the photoresist mother lens, the next step is the transfer of the photoresist microstructure to a PDMS master by a casting method. PDMS is chosen as a master material because it provides high-dimensional accuracy, and easy fabrication. Dupont Sylgard 186 silicone is used as the master material. After the PDMS master is cured in a vacuum oven for 2 h at 5 mTorr of pressure at 75 °C, the mold is peeled off from the mother lens wafer. The PDMS master consists of a concave microlens array. Figure 3(*a*) shows the SEM images of the master. The diameter of the concave surface is 1400 μm.

The final step is spin-coating PDMS on the PDMS master. Depending on the spinning speed, a thick or thin film with a unique dimension of microlens can be obtained. Then, PDMS film is cured for 2 h at 5 mTorr of pressure at 75 °C. Finally the lens film was peeled off the PDMS master. Since the new PDMS layer does not crosslink with the cured PDMS master mold at the interface during curing process, it is easy to peel off the film from the master mold. The SEM pictures in figure 3 show a PDMS mold and PDMS microlens film with a microlens (1400 μm at diameter and 85 μm height at the center of lens).

2.2. *Microfluidic chip fabrication*

The microfluidic chip includes a silicon chamber, and a PDMS chamber block with an inlet channel. Figure 4(*a*) shows a cross-section view of the microfluidic chip structure. It



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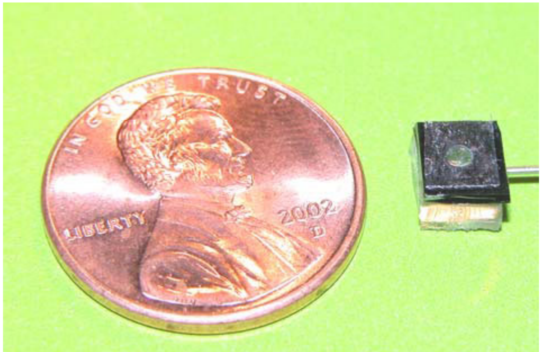


(*b*)

Figure 4. (*a*) Schematic cross section for microfluidic chip structure and (*b*) a prototype of variable focal lens with microfluidic chip.

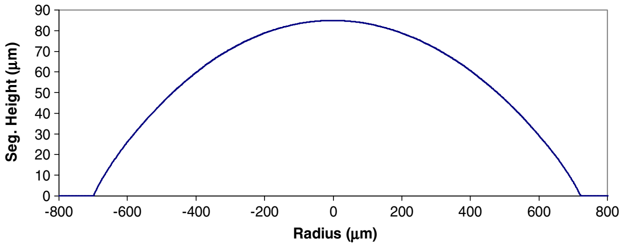


Figure 5. Surface profile for the photoresist microlens.

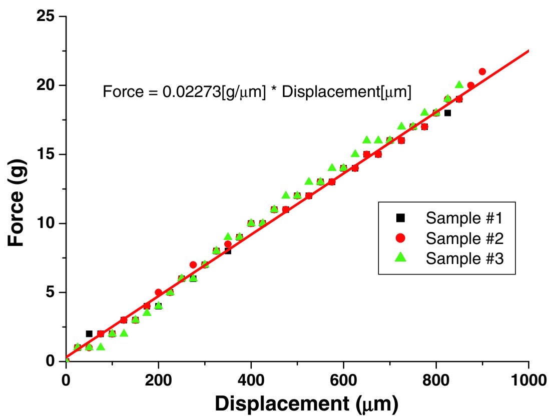


Figure 6. The plot for force versus displacement.

is necessary to have a silicon wafer between the PDMS microlens film and PDMS chamber block. The silicon wafer provides a smooth and rigid surface for bonding with both the PDMS microlens film and PDMS chamber block. A through hole on the silicon wafer with a diameter of 1400 μm is formed

Table 1. Comparison of surface roughness for the photoresist microlens, the PDMS master and the final PDMS microlens.

	Photoresist microlens	PDMS master	Final PDMS microlens
Average roughness (nm)	8.61	17.2	18.6

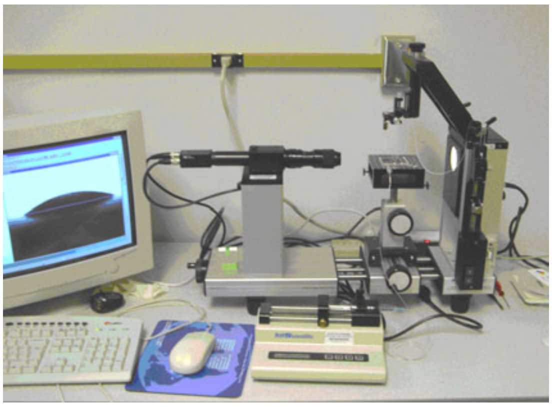


Figure 7. Experimental setup for contact-angle measurement.

by inductively coupled plasma (ICP) dry etching. A chamber mold is designed and built to create a circular chamber with an inlet channel. PDMS prepolymer mixture is then cast to form the body of a 1400 μm chamber and a channel. The PDMS mixture is subsequently cured in an oven for 2 h at 75 °C. The cured PDMS chamber is peeled off from the mold.

Finally both the lens film and PDMS chamber block are bonded to the silicon substrate by using a high strength epoxy to avoid any leakage (Devcon All Purpose Epoxy). The overall dimension of the prototype, as shown in figure 4(*b*), is about 5 mm × 4.5 mm × 2.5 mm ($L \times W \times H$).

3. Experimental results

PDMS microlenses, diameter range from 600 μm to 1400 μm, are successfully fabricated. In this paper, a microlens with 1400 μm diameter is used for characterization. The surface profile, mechanical and optical properties of the PDMS microlens have been characterized. In addition, a simulation with finite element analysis (FEA) has been performed.

The surface profile of the melted photoresist microlens is measured using a Tencor Alpha Step 500 System. This equipment uses a stylus with a 2 μm chisel head as a probe and scans the sample surface. Figure 5 shows the surface profile of a photoresist lens. The height of the photoresist mother lens is 85 μm at the center point and the diameter is 1400 μm (figure 5).

The surface roughness of the mother lens and PDMS master mold are the very important parameters, which may affect the optical properties of final lens. An atomic force microscope (Quesant Instruments scanning probe microscope, AFM) is used to examine the surface roughness. AFM provides true 3D topographic images, which also yield surface roughness data on the nanometer scale. The analysis results of the photoresist microlens, PDMS master and final PDMS lens film are shown in the table 1. The results indicate that surface roughness is changed after each processing step of the PDMS coating and peel-off process. However, the surface roughness of the PDMS master and the final PDMS microlens film do not have a significant change. The roughness for both the master mold and final PDMS microlens film is about 17–18.6 nm, which is still in an acceptable range for optical lens requirements.

The mechanical properties of the PDMS film were examined by applying a load at the center of the PDMS film. The corresponding deflections with various loadings are measured. Figure 6 shows a linear relationship between applied load and deformation at the center of the film. The maximum loading force for 100 μm thick PDMS film is about 20 g. The PDMS film can be ruptured if the force is larger than this value.

The back focus length has been characterized using a contact-angle measurement system (Data Physics, Future Digital Scientific Corp.). Figure 7 shows the contact-angle experiment setup. The different pressure of pumped-in fluid changes the lens curvature, as shown in figure 8. As the fluid volume increases, the contact angle also increases. Each contact angle for a different pumped liquid volume is measured carefully for further lens optical property calculations, such as curvature and back focal length. The curvature (R) can be obtained by the following equation [15]:

$$R = \left[\frac{3V}{\pi(2+\cos\theta)(1-\cos\theta)^2}\right]^{\frac{1}{3}}$$

where V is lens volume and θ is the contact angle.

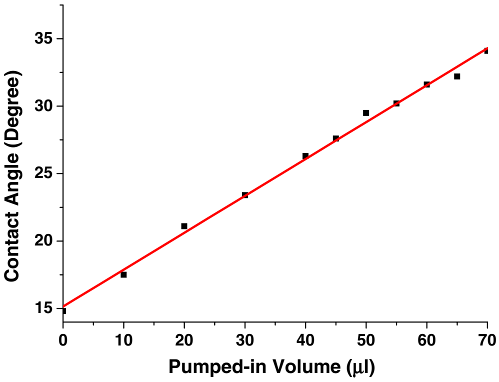
The curvature changes of the lens cause the focal plane to shift. Figures 9(*a*) and (*b*) show the relationship of the pumped-in volume, contact angle and curvature. The back focal lengths with different pumped-in volume are calculated. A microlens on a microfluidic channel is considered as a plane convex refractive lens assuming that the lens profile is spherical. The back focal length (f_B) can be obtained by the

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

Figure 8. Photos for the curvature changes of the PDMS film lens with different volumes of pumped-in fluid: (*a*) initial position, (*b*) 20 μl and (*c*) 45 μl.

Table 2. Optical properties of a 1400 μm diameter microlens with different pumped-in volumes.

Photos						
Pumped-in volume (μl)	0.0	10.0	30.0	50.0	60	70.0
Chamber pressure (psi)	0.71	1.06	2.12	2.83	3.54	4.24
Contact angle (°)	14.8	17.5	23.4	29.5	31.6	34.1
Curvature (μm)	3238	2538	1677	1488	1312	1210
Back focal length (μm)	10 640	8307	5430	4751	4167	3815
Numerical aperture (NA)	0.09	0.11	0.17	0.19	0.22	0.24



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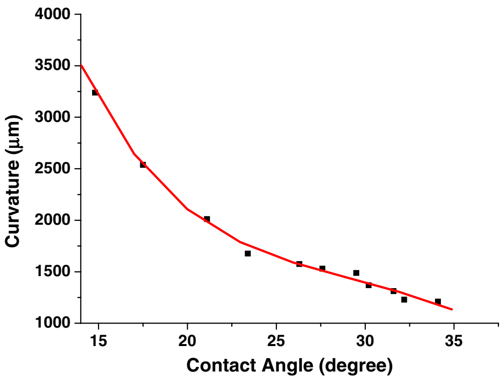


(*b*)

Figure 9. (*a*) Linear relationship between pumped-in volume and contact angle. (*b*) Relationship between contact angle and curvature.

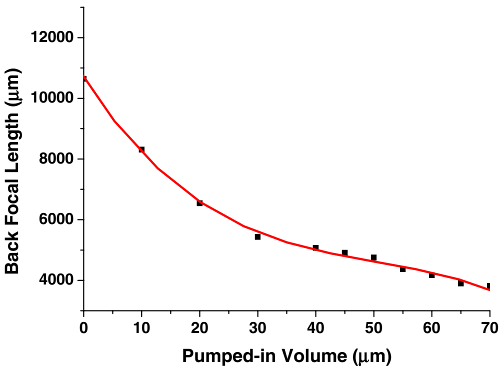
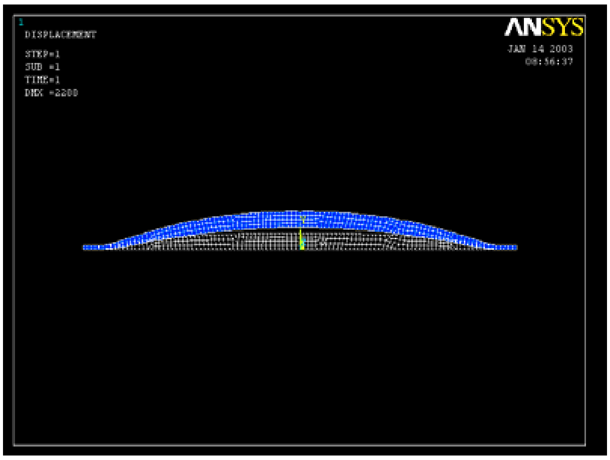


Figure 10. Relationship between back focal length and pumped-in volume.

following equation [15]:

$$f_B = n_2 \frac{1 + (n_1 - 1)\cos\theta}{n_1(n_1 - 1)} R.$$



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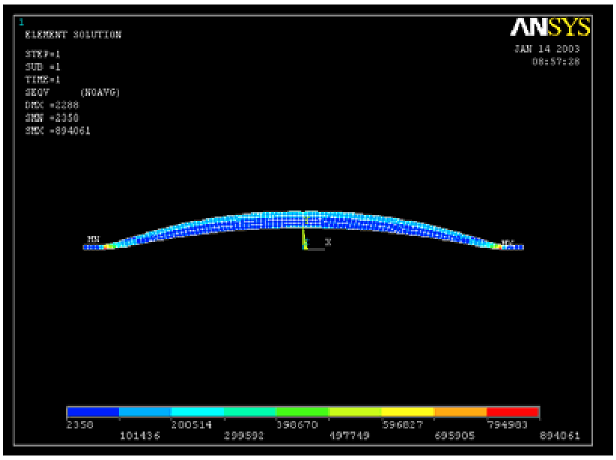


(*b*)

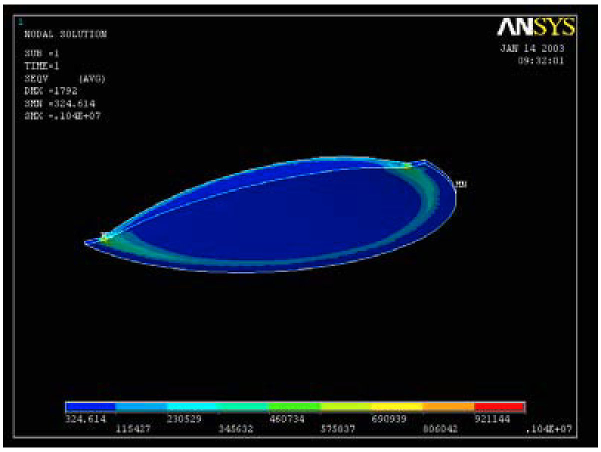
Figure 11. 2D ANSYS simulation of microlens (*a*) for deformation and (*b*) for stress distribution.

Where n_1 and n_2 are the refractive indexes for the PDMS microlens and water, respectively ($n_1 = 1.401$ and $n_2 = 1.33$). The range of back focal length is from 3.82 mm to 10.64 mm. Figure 10 shows the relationship between pumped-in volume and back focal length.

In addition, numerical aperture can be calculated by the following equation:

$$\mathrm{NA} = n_2 \left\{ \frac{n_2^2 [1 + (n_1 - 1)\cos\theta]^2}{n_1^2 (n_1 - 1)^2 \sin^2\theta} + 1 \right\}^{-\frac{1}{2}}.$$

The numerical apertures with various focal lengths have been determined and listed in table 2. The numerical aperture can be tuned between 0.09 and 0.24. Table 2 presents a



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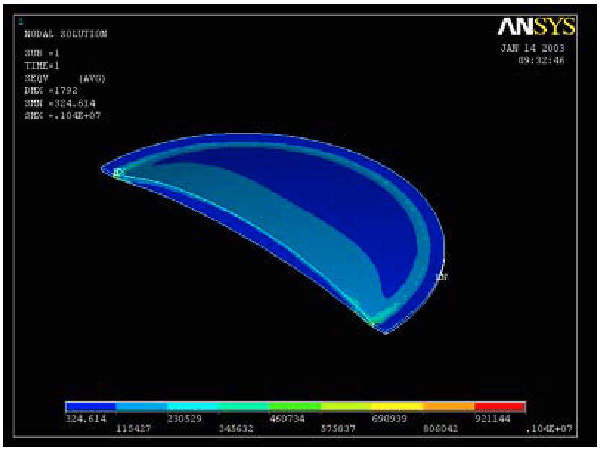

(*b*)

Figure 12. 3D ANSYS simulation of microlens (*a*) for stress on bottom surface and (*b*) for stress on top surface.

detailed summary of the optical properties of a variable focus microlens.

A comprehensive finite element analysis for a PDMS microlens under various internal pressures has been performed. In figure 11, it shows the lens deformation and stress distribution on a cross section of the microlens. Furthermore, a 3D model has been created to provide more accurate results in figure 12. The maximum stress occurs on the outer most ring of the lens' bottom surface. An outer ring of the lens's body is thinner than one at the center of lens. By applying a uniform pressure on the bottom surface, the stress on the outer ring will increase more than the other areas of the lens. The results for curvature changes due to the pressure applied agree with the experimental results.

4. Discussions and conclusions

A new flexible PDMS microlens and a controllable focus module are successfully fabricated and characterized. A novel PDMS casting process with a PDMS mold to fabricate the microlens film is developed. This fabrication process provides good optical properties, high dimensional accuracy and low cost for mass production. Microlenses with a diameter of 600–1400 μm are fabricated using this fabrication technique. The optical and mechanical properties of a prototype are characterized. The surface roughness of the lens was 18 nm. The curvature changes of the microlens were from 1210 μm to 3238 μm. With this wide range of curvature changes, we can control the back focal length from 3.82 mm to 10.64 mm, and numerical aperture between 0.09 and 0.24. These results prove the possibility of using the present lens model for many optical applications. Its benefits are applicable not only to various optical MEMS applications such as tunable range wavefront sensors, beam spanning control for free-space optical actuation, but also to biomedical applications.

Acknowledgment

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