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Fabrication of tapered SU-8 structure and effect of sidewall angle for a variable focus microlens using EWOD

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Abstract

Electrowetting on dielectric (EWOD) is a promising technology for variable focus liquid microlens. When an electrical field is applied across a liquid droplet and a dielectric layer, the contact angle of the liquid can be tuned with different applied voltages. Therefore, the focal length of a microlens would vary by simply applying an electrical field without any moving mechanical components. In this paper, SU-8 is employed as dielectric layer and structural material in the design of a variable focus liquid microlens using EWOD. A tapered SU-8 structure is created by UV overexposure to confine the droplet and provide the droplet-centering mechanism. The angle of the sidewall is controlled by the width of the exposed area. Contact angle variation of water droplets on SU-8 is measured and favorably compared with the Lippmann–Young equation. The working microlens is demonstrated using images of numbers and laser beam focusing.

Keywords: Electrowetting; SU-8; Microlens

1. Introduction

Tunable microlenses, with variable focal length, have attracted significant interest in optical and biomedical applications, such as cameras in cell phones, optical storage systems, optical fiber communication systems, and microscopes. Several techniques have been developed, such as liquid crystal with immersed surface relief photoresist microlenses [1], fluidic lens with external pump [2], the fluidic microlens with integrated heating elements [3], and electrowetting on dielectric (EWOD) [4,5]. Such microlenses do not require any mechanical moving parts for changing the focal length. The most attractive technology for tunable microlenses is EWOD due to its simplicity. In EWOD, the surface energy of a liquid droplet on a dielectric layer is modified by application of an electric field. Consequently, the droplet's contact angle can change, which results in droplet shape change, and therefore change of focal length. Microlenses using EWOD with metal or glass structure have been applied in the design of miniaturized optical systems, such as mini-cameras for portable electronic devices [6–8]. However, such technologies are not easily integrated into microsystems. Electrowetting microlenses have also been microfabricated on silicon substrates [9]. Due to the square shape of etched silicon holes, however, the optical performance of such microlenses is limited. We have demonstrated a microlens with SU-8 structure recently [10]. Smoother and more uniform electrical fields occur in the circular structure than in the square one, therefore, the optical distortion is less.

SU-8 is a photosensitive material commonly used to form thick, high aspect ratio polymeric microstructures with vertical sidewalls [11,12]. Due to the thickness of a SU-8 layer, the exposure dosages are different at the top and at the bottom of the layer [13]. A SU-8 structure with a smooth sidewall at a certain angle can be achieved by UV overexposure. Since SU-8 is an epoxy-based negative-tone photoresist, the hole developed after exposure tends to be smaller at the top than at the bottom. SU-8 has favorable mechanical properties, high thermal stability, and high dielectric constant. The SU-8 structure can withstand high temperatures, up to 350 °C, without dramatic weight loss. Moreover, the mechanical properties of SU-8 structures are stable when the temperature is less than 150 °C [14]. The dielectric constant of SU-8 is 3 in our measurement, described later in this

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paper. Therefore, SU-8 is not only suitable as the structure but also as a dielectric material in EWOD.

In this paper, we demonstrate a variable focus microlens consisting of two immiscible liquids on a tapered SU-8 structure. The densities of the liquids are chosen to be close to each other. The light-weight, tapered SU-8 structure provides the confining and centering mechanism for the liquids. The angle of the slanted sidewall can be controlled by the width of the exposed area and affects the tunable range of focal length of a microlens. We use images of numbers positioned under the microlens and the focusing of a laser beam at different applied voltages to demonstrate operation of the microlens.

2. Principle

The principle of this variable focus liquid microlens is based on electrowetting on dielectric (EWOD). When a small droplet of liquid is at rest on an insulated metallic substrate in air or in other surrounding medium, the shape of the droplet is spherical and the contact angle of the droplet is determined by the balance of the surface tension in each interface between the substrate and the liquid, between the substrate and surrounding medium, and between the liquid and the surrounding medium. The contact angle of a liquid droplet on a planar solid substrate can be expressed by Young's equation:

$$\gamma_{\mathrm{LA}} \cos(\theta) = \gamma_{\mathrm{SA}} - \gamma_{\mathrm{SL}}, \tag{1}$$

where γ denotes the surface tension between two media, S denotes the substrate, L denotes the droplet, A denotes the surrounding medium, and θ denotes the contact angle of the droplet on the substrate.

When the voltage is applied to the liquid and the metallic substrate, the contact angle would change due to the additional force caused by the static electricity at the interface between the substrate and the liquid. The relationship of the surface tension and the applied voltage can be expressed by Lippmann's equation:

$$\gamma = \gamma_0 - \tfrac{1}{2} c V^2, \tag{2}$$

where γ_0 is the surface tension without applied voltage and c is the capacitance per unit area in the interface.

In Fig. 1, the schematic view of contact angle change is shown. The shape of droplet without applied voltage is shown by the solid line, while the shape with applied voltage is shown by the dashed line.

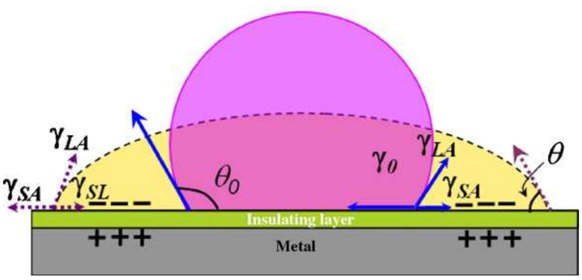

Fig. 1. Schematic view of principle of EWOD.

The relationship between the applied voltage and the surface tension of a droplet on a dielectric surface can be expressed by the modified Lippmann equation:

$$\gamma_{\mathrm{SL}} = \gamma_0 - \frac{1}{2} \frac{\varepsilon \varepsilon_0}{d} V^2, \tag{3}$$

where ε and ε_0 are the permittivities of the dielectric layer and vacuum, respectively, d is the thickness of dielectric layer, and V is the voltage applied across the dielectric layer. Consequently, Young's equation is extended, resulting in the Lippmann–Young equation where the contact angle change is then given by

$$\cos(\theta) = \cos(\theta_0) + \frac{1}{2} \frac{\varepsilon \varepsilon_0}{2 \gamma_{\mathrm{LA}} d} V^2. \tag{4}$$

The contact angle of a droplet without application of a voltage is given by θ_0. It has been discovered recently that the contact angle change can be enhanced by inserting a hydrophobic layer between a conductive liquid and the electrode. From the Lippmann–Young equation, it is clear that a lower voltage is needed to change contact angle with a thinner dielectric layer. It should be noted that the saturation of contact angle is not considered in the equations.

3. Characterization of SU-8 layer

SU-8 (2000 series, Microchem Corp., USA) is an epoxy-based photoresist suitable for making high aspect ratio structures and is a dielectric material. We test the dielectric properties of SU-8 by measuring the contact angle of a water droplet. First, a 5 μm thick SU-8 layer is spin-coated on a gold-plated substrate. After pre-baking at 65 °C and 95 °C for 1 min each, UV exposure is performed for 50 s (3.5 mW/cm^2 at 365 nm). Then the SU-8 layer is post-baked on a hotplate at 65 °C and 95 °C for 1 min each and cooled down on the hotplate to room temperature. A 300 nm thick Teflon layer (AF1601S, Dupont) is coated on top of the SU-8 by spinning and serves as a hydrophobic layer. A drop (∼5 μL) of de-ionized (DI) water (resistivity ∼17 M-Ω cm) is placed on the hydrophobic surface. A dc voltage is applied with micro-probes between the bottom gold electrode and the liquid. Fig. 2(a) shows the water contact angle without the application of voltage, while Fig. 2(b) shows the change of contact angle at 140 V.

The contact angle is measured by taking a picture of the droplet using a CCD camera through a microscope. The initial contact angle of 115° with 0 V is measured. Fig. 3 shows the contact angle change with various applied voltages. Saturation of contact angle is observed after 160 V, which is not shown in Fig. 3. The solid line is the theoretical calculation based on the Lippmann–Young equation. The dielectric constants of SU-8 and Teflon used in the calculation are 3 and 1.9, respectively. The black dots are the experimental measurements. SU-8 photoresist behaves well as a defect-free dielectric material layer.

4. Design of microlens

The schematic view of the variable focus lens is illustrated in Fig. 4. Drop-centering mechanism is necessary in the design.

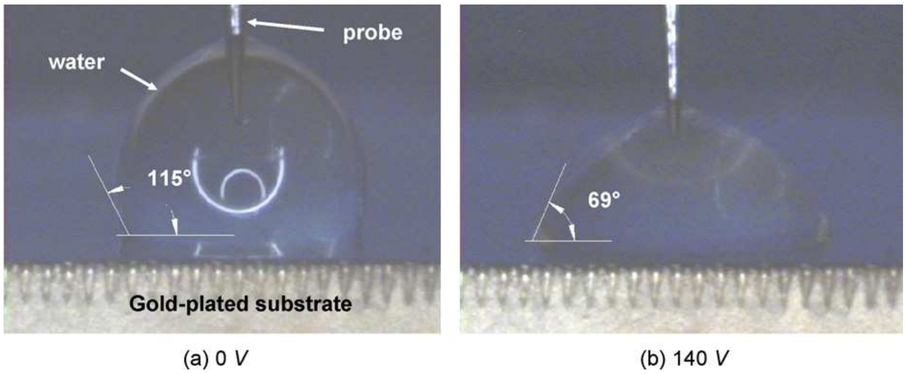

Fig. 2. Change of the contact angle of water on SU-8 coated substrate.

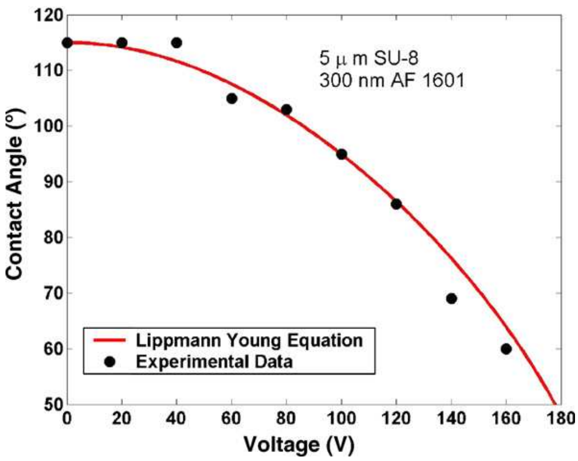

Fig. 3. Performance of EWOD of SU-8 dielectric layer.

Otherwise, the liquids can be easily moved out of optical axis due to the vibration, gravity effect, or mechanical shock. The SU-8 structure is patterned on a glass substrate to form the cavity of the microlens. The angular sidewall provides the stable drop-centering confining mechanism to keep the optical axis in position. Meanwhile, the angular sidewall is needed for the follow-on metal deposition and spin-coating steps. Introducing two immiscible density-matched liquids is another necessary centering mechanism. This would allow the lens to work at any orientation and eliminate the gravity effect. The lens in this paper consists of a non-polar liquid, silicone oil (T11, Gelest Inc.), and water. The density of silicone oil is 0.94 g/cm^3 and the index of refraction is 1.4. The densities of the two liquids are chosen to be close to each other in order to minimize the effects

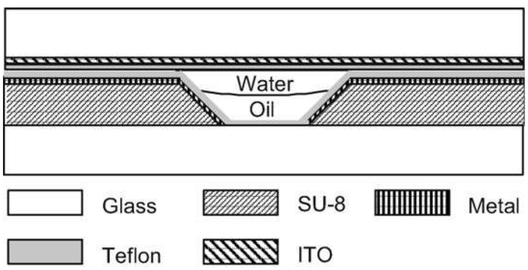

Fig. 4. Schematic view of the variable focus microlens.

of gravity or mechanical vibrations. It should be noted here that the indexes of refraction of two liquids could be designed by choosing different liquids. Higher difference in refractive indexes between two liquids allows larger optical power tuning range. For electrowetting actuation, a metal layer on the SU-8 sidewall is required. The metal layers, gold and Ti, are deposited on top of the tapered SU-8 structure as an electrode in EWOD in the design. The metal layers deposited by e-beam evaporation on SU-8 structures have been used in MEMS devices [15]. The metal deposition is achieved at low temperature in order to reduce the thermally induced stress between SU-8 structure and glass substrate. In addition, the adhesive layer, Ti, is needed to improve the poor adhesion between gold and exposed SU-8 [16]. The metal on the bottom of the cavity is removed by optical photolithography to open a window for light to pass through. Another SU-8 and Teflon layer are spin-coated as the dielectric and hydrophobic layer for EWOD, respectively. During device assembly, a cover glass with an indium tin oxide (ITO) electrode coated by a layer of Teflon is positioned over the bottom substrate structure, which is filled with oil and water. The planar ITO layer is used as the counter-electrode in electrowetting to avoid inserting a probe and destroying the spherical liquid–liquid interface. Non-conductive epoxy is then applied around the perimeter of the substrate stack to seal off the liquid lens hermetically.

5. Effects of UV overexposure on SU-8

A smooth sidewall on the SU-8 structure is needed for the follow-on thin dielectric SU-8 and hydrophobic Teflon coatings deposited by spinning. We use backside exposure of a double-layered SU-8 through a 1 mm thick glass microslide to form angular SU-8 sidewalls. The tapered SU-8 structure is achieved by overexposure with conventional UV mask and contact printing technology. The mask pattern is a ring with inner diameter of 3 mm and outer diameter of 8 mm. The UV exposure is performed with a broadband UV system. A 200 W Mercury short arc lamp (Advanced Radiation Corp.) is used in the UV system, which emits the light at four different wavelengths: 305 nm, 365 nm, 405 nm, and 435 nm. The intensity at 305 nm is about a third of the intensity at the wavelength

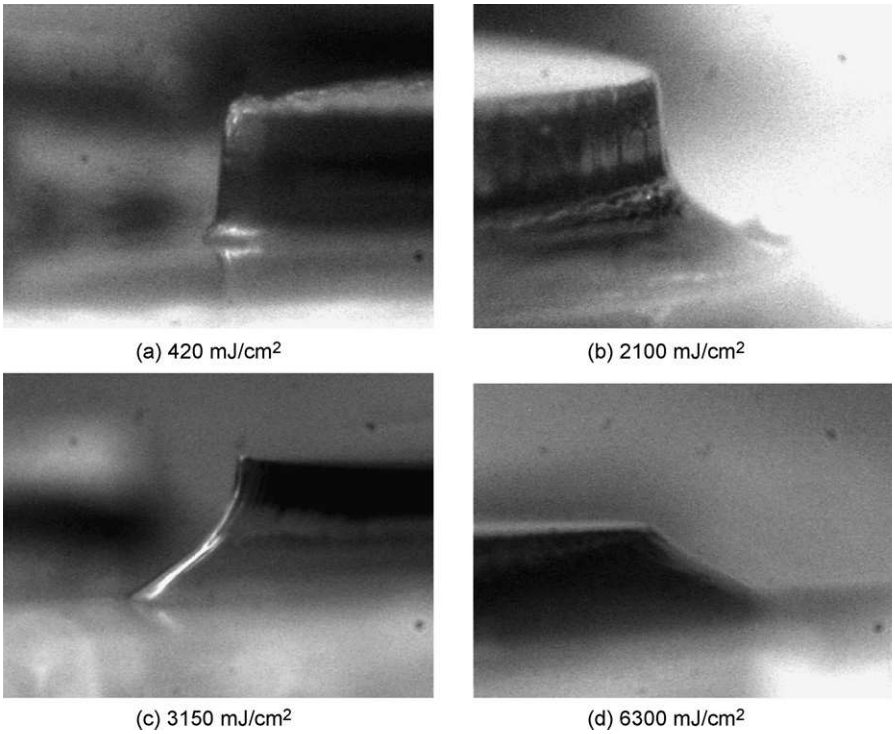

Fig. 5. Profile of SU-8 sidewall with different exposure dosages.

of 365 nm. The intensity at 365 nm is 3.5 mW/cm^2. For SU-8 material, there is no absorption above 400 nm and there is strong absorption below 350 nm. Due to the strong absorption, the light at 305 nm cannot penetrate thick SU-8 and only affects a thin layer of SU-8 on the top. Therefore, the structure is mainly obtained by the exposure to light with a wavelength of 365 nm. A layer of 2 μm thick SU-8 is first spun on a glass microslide as the adhesive layer for the follow-on thick SU-8 layer. A thickness of 700 μm is obtained by spinning two layers of SU-8 2100. The baking process is described in the following section. Different exposure dosages are performed and the fabrication results after 20 min development are shown in Fig. 5. The dosages are 420 mJ/cm^2, 2100 mJ/cm^2, 3150 mJ/cm^2, and 6300 mJ/cm^2, which is calculated from the intensity of 365 nm wavelength times the exposure time. The SU-8 structure with a dosage of 420 mJ/cm^2 shows a vertical sidewall profile, while it shows a smooth angular sidewall with dosage of 6300 mJ/cm^2.

6. Fabrication

Microlens fabrication starts with the fabrication of the bottom substrate structure which is capped by a glass with an ITO electrode after filling with two immiscible liquids. The fabrication process of the bottom substrate structure is illustrated in Fig. 6. First, a 2 μm thick SU-8 layer is spun on a 1 mm thick glass substrate to form an adhesive layer for the follow-on thick SU-8 coating. The thin SU-8 layer is pre-baked at 65 °C and 95 °C for 1 min each and cooled down to room temperature on a hotplate. A 550 μm thick SU-8 layer is achieved by spinning two SU-8 layers. Both layers are pre-baked at 65 °C for 30 min and at 95 °C for 4 h on a hotplate separately.

In all follow-on steps, slow heating and cooling processes are required to avoid cracking of the thick SU-8 layer. A broadband UV system is used to overexpose the SU-8 from the backside of

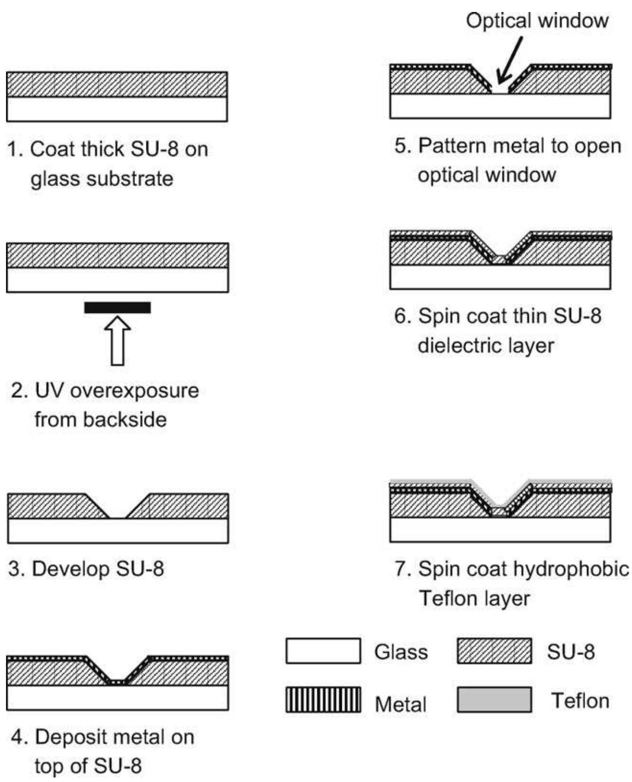

Fig. 6. Fabrication process of bottom substrate structure.

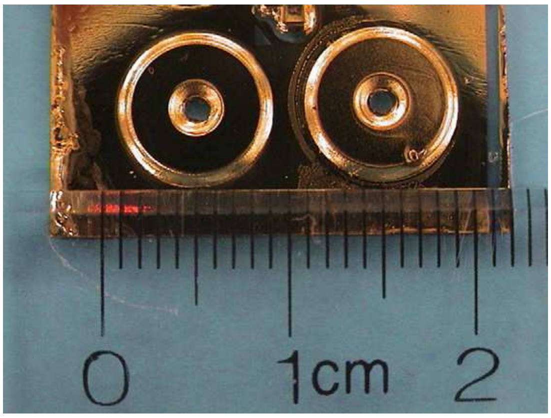

Fig. 7. Tapered SU-8 structure (top view).

the glass for 30 min (5220 mJ/cm^2 at 365 nm). The whole substrate is then post-baked at 65 °C and 95 °C for 30 min and 1 h, respectively. A SU-8 structure with smooth angular sidewalls is created after development for 20 min in the SU-8 developer (PGMEA, Microchem Corp., USA).

Titanium (10 nm) and gold (200 nm) layers are then deposited by e-beam evaporation. The temperature of the substrates during e-beam evaporation is around 66 °C. The metallic layers are then patterned to open an optical window on top of the glass substrate. Another 2 μm thick SU-8 layer is spun on top of the metallic layers as a dielectric layer. The pre-bake process takes place at 65 °C for 1 min and 95 °C for 5 min in an oven. The dielectric SU-8 layer is cross-linked by UV exposure for 50 s. The post-bake is performed at 65 °C for 1 min and 95 °C for 5 min. Finally, a 300 nm hydrophobic Teflon layer is applied. The Teflon layer is baked at 90 °C for 1 h and cooled down to room temperature in an oven. This completes the formation of the bottom substrate structure.

The top view of the tapered SU-8 structure is shown in Fig. 7. The outer diameter of the SU-8 structure is 8 mm at the top, while the diameter at the bottom is 9.5 mm. The inner diameter of SU-8 cavity is 3 mm at the top and 1.5 mm at the bottom. The diameter of the open window is 1 mm. The angle of the sidewall is measured to be 36° and is shown in Fig. 8. A top cover glass plate with ITO electrode is spin-coated with a 300 nm Teflon hydrophobic layer. Silicone oil and DI water are the two liquids used for the lens and are manually placed inside the SU-8 cavity. After filling the liquids in the cavity, the device is sealed around its perimeter by epoxy.

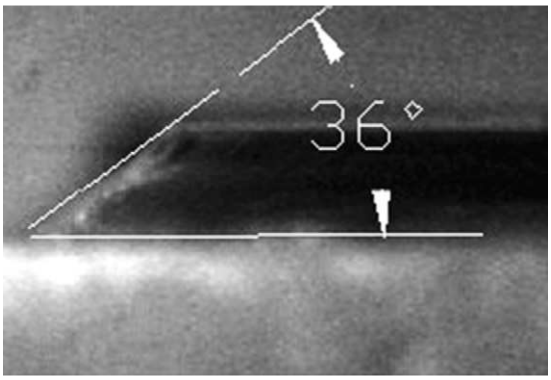

Fig. 8. Angle of sidewall of the SU-8 structure.

7. Effect of angle of SU-8 structure on device performance

The angle of the SU-8 structure affects the range of the optical power of a microlens. The theoretical calculation of the effect of different sidewall angles on the power of the microlens is shown in Fig. 9. The interface is assumed to be spherical and the effect of gravity is ignored. The initial contact angle of water with respect to the sidewall is 115°. The volume of oil is constant and given as 0.3 mm^3. The aperture of the lens is 1.5 mm. A 2 μm thick SU-8 dielectric layer coated with 300 nm of Teflon is used to calculate the curvature of the interface with different applied voltages. The indexes of refraction of water and oil are 1.33 and 1.4, respectively. The optical power of microlens, D, can be calculated by the following equation:

$$D = \frac{2\sin(\theta+\alpha)(n_{\text{oil}} - n_{\text{water}})}{W(\theta)} = \frac{1}{f}, \qquad (5)$$

where W is the diameter at the liquid–oil interface (a function of contact angle, thus, a function of the applied voltage), θ is the contact angle with respect to the sidewall (a function of the applied voltage), α is the angle of sidewall from the substrate, (Fig. 8), n_{oil} is the index of refraction of silicone oil, n_{water} is the index of refraction of water, and f is the focal length of the microlens. As shown in Fig. 9, the angle of the sidewall determines the initial value as well as the tunable range of the optical power. The initial power of the microlens changes from 31.6 m^{-1} to −56.3 m^{-1} when the sidewall angle changes from 50° to 90°. Because of the initial contact angle, the lens has the capability to change from concave to convex lens with a sidewall angle larger than 65°. Meanwhile, a 70 V change results in an optical power change of 66 m^{-1} for a 50° sidewall and 72 m^{-1} for a 90° sidewall.

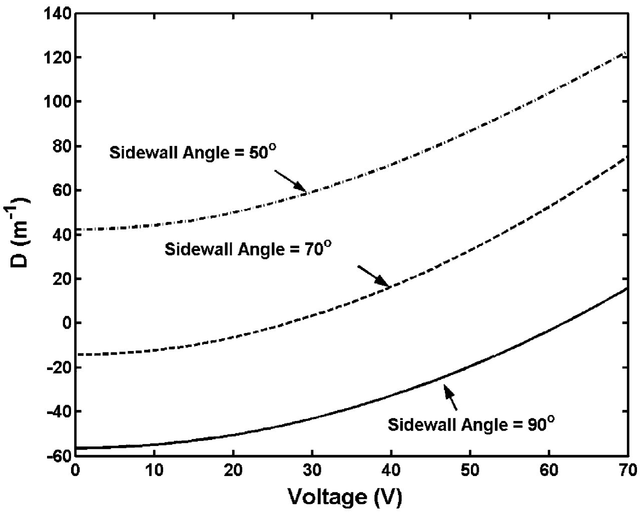

Fig. 9. Optical power of microlens as a function of voltage for sidewall angles of 50°, 70°, and 90°.

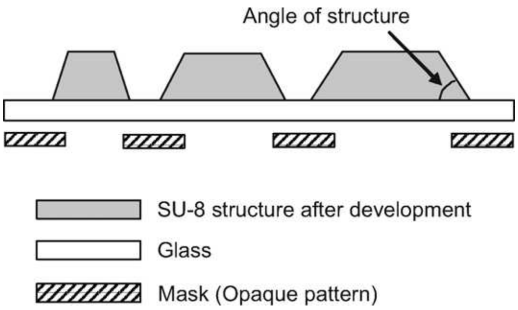

Fig. 10. Control of angle of slanted SU-8 structure (not to scale).

8. Control of angle of slanted structure

The sidewall angle is controlled by the width of the exposed area on the mask as depicted in Fig. 10. Two SU-8 layers at 2 μm and 250 μm thickness are spun on a glass substrate in series. The substrates are, then, pre-baked at 65 °C for 30 min and at 95 °C for 2 h. In order to achieve a straight sidewall, the exposure time needs to be accurately controlled. Initially three samples are exposed to UV at 5 min, 10 min, and 15 min, respectively. After the post-bake process is performed at 65 °C for 10 min and at 95 °C for 1 h, the samples are developed in PGMEA for 10 min. The results are shown in Fig. 11. As depicted in Fig. 11, for 300 μm and 500 μm wide lines, exposure dosage of 2100 mJ/cm^2 and 3150 mJ/cm^2 are needed, respectively, in order to acquire a straight slope. The angles are measured to be at 59° (Fig. 11(b)) and 51° (Fig. 11(d)), respectively. Less exposure time results in a curved sidewall as shown in Fig. 11(a) and (c). For a SU-8 layer of specific thickness, lines of different width require different exposure times in order to obtain straight slope sidewalls. Larger angle of structure can be obtained with smaller line width and less exposure time.

9. Microlens demonstration

Several microlenses are fabricated using the method described in Section 6. Tuning capability of these microlenses are investigated by taking an image of numbers (‘3’ and ‘4’) printed on a paper and positioned under the device. The images are captured through a microscope. The microscope is first focused on the numbers under the device with no applied voltage. Then different voltages are applied to the microlens device and the defocused images of the numbers are captured with the microscope camera. In Fig. 12, the images of numbers at 0 V and 60 V are shown, where the numbers are clearly out of focus when a 60 V is applied.

Another demonstration of the working device is performed by taking the image of a laser beam. The experiment setup is shown in Fig. 13. A collimated He–Ne laser beam is passed through a pinhole 1 mm in diameter. The laser beam then passes through the microlens from the water side. A reflective surface is placed behind the microlens when the applied voltage is zero and the image is taken by a camera. Images are then taken when the different voltages are applied. The images of the laser beam at 0 V and 60 V are shown in Fig. 14. It is observed that the laser beam expands uniformly across the beam width when the voltage is applied to the microlens, thus proving uniformity of the lens shape.

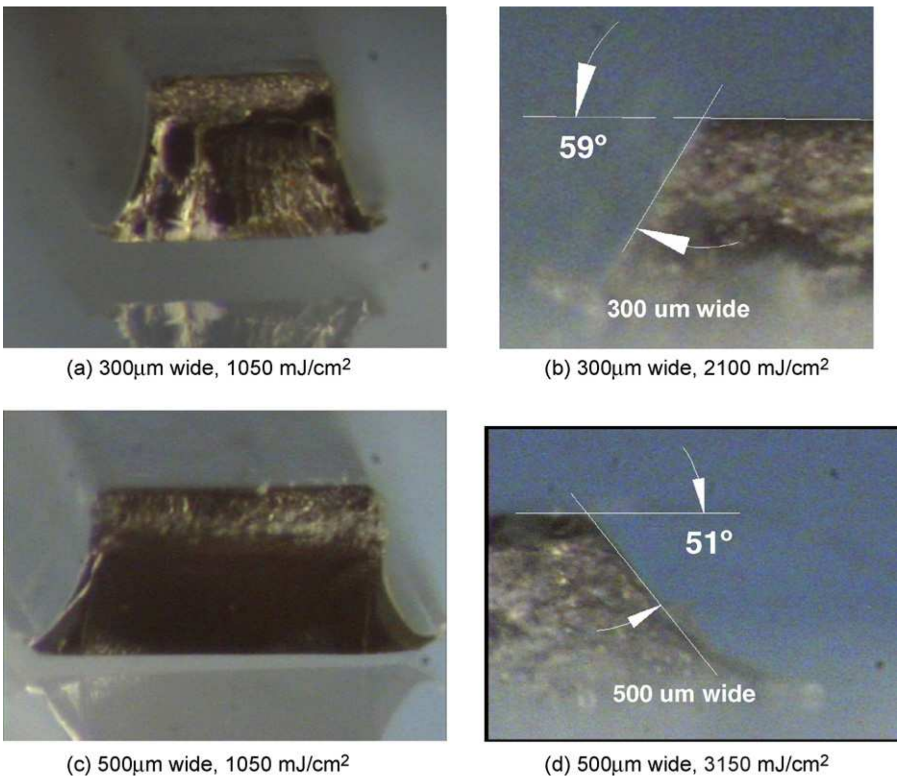

Fig. 11. SU-8 sidewall angles controlled by varying mask line widths and exposure times.

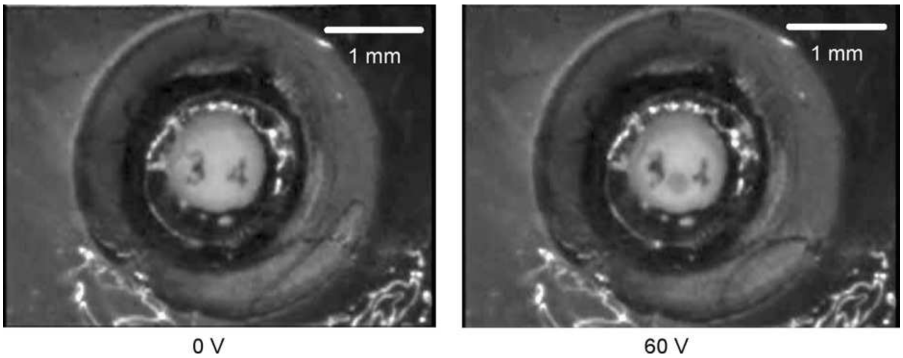

Fig. 12. Images (numbers '3' and '4') captured at 0 V and 60 V applied to the microlens.

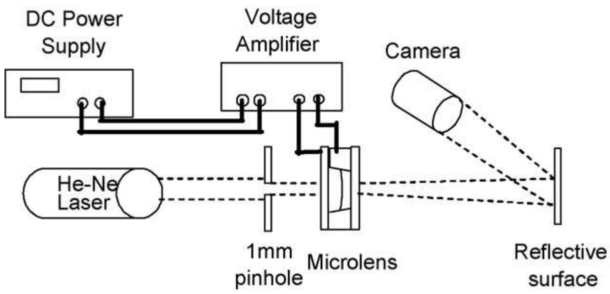

Fig. 13. Schematic of experiment setup.

10. Discussion

In this paper, a novel tapered SU-8 structure has been used for a variable focus lens based on EWOD. A tapered sidewall profile was obtained by UV overexposure of the SU-8. The process was time-consuming and the shape of sidewall was not easy to control by overexposure, i.e. the yield of the structure is low. Inclined UV exposure might be a possible solution for obtaining an angular SU-8 structures in a less time-consuming manner [17]. Moreover, inclined UV exposure controls the angle of the SU-8 sidewall more easily and is not limited by the exposed area, as shown in Fig. 10.

A thin SU-8 layer was spin-coated on top of the metallic sidewall as the dielectric layer in EWOD. Due to the thick structure of the lens, the thin SU-8 coating was not uniformly distributed on the sidewall; therefore, the change of contact angle is not even along the water–oil interface on the sidewall with the applied voltages. Low temperature vapor deposition of dielectric materials could solve this problem, such as Parylene deposition [18]. Atomic layer deposition (ALD) of Al_2O_3 may also be used in forming the dielectric layer in EWOD [19]. The ALD layer is a conformal, smooth, and pinhole-free coating with precisely controlled thickness, which may also be deposited at temperature as low as 33 °C. The dielectric constant of Al_2O_3 is 6.8, which is much higher than SU-8. A conformal hydrophobic coating could also be obtained by ALD with deposition temperatures around 100 °C [20]. The conformal coatings on top of the thick SU-8 structure could obtain uniform change of contact angle along the interface on the sidewall and improve the optical performance of the lens. The high dielectric constant of ALD Al_2O_3 could reduce the operating voltage.

11. Conclusions

A variable focus microlens based on EWOD on a tapered SU-8 structure has been demonstrated. SU-8 is suitable to be a structural material for micro-devices and a dielectric material in EWOD. The slanted sidewall of the SU-8 structure is achieved by overexposure. With a particular thickness of SU-8, a specific exposure dosage is needed in order to achieve a structure with a smooth sidewall. Meanwhile, different sidewall angles can be obtained by controlling the width of exposed area. Images of printed numbers positioned under the microlens and the focusing of a laser beam passing through the microlens at different applied voltages successfully demonstrate a working device. Using SU-8 photoresist as a structural material, a wide range of sizes of

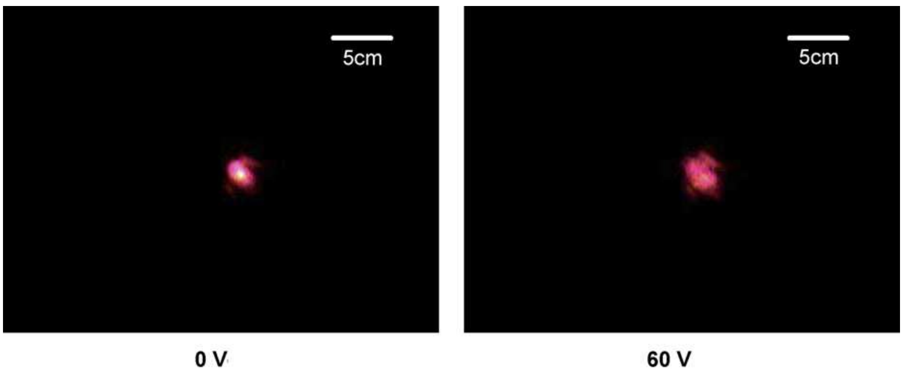

Fig. 14. Images of a laser beam passing through the microlens with 0 V and 60 V applied.

microlenses can be fabricated. In addition, the SU-8 structures are easily integrated into other microsystems.

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