A VARIABLE FOCUS MICROLENS USING EWOD ON A TAPERED SU-8 STRUCTURE

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ABSTRACT

Electrowetting on dielectric 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, we demonstrate that the dielectric structure of the lens can be made of SU-8. The tapered SU-8 structure, obtained by UV overexposure, confines the droplet and provides the droplet-centering mechanism. SU-8 has high dielectric constant and is suitable as a dielectric layer in electrowetting. The measured contact angle change of the water droplet matches the Lippmann-Young equation. It is shown that by choosing two similar-density liquids, the effect of gravity and mechanical vibration can be minimized. The working microlens is demonstrated using the images of numbers and laser beam focusing.

INTRODUCTION

Tunable microlenses, with variable focal length, have attracted significant interest in optical and biomedical applications [1-6]. Such microlenses do not require any mechanical moving parts. An attractive technology for tunable microlenses is Electrowetting on Dielectric (EWOD). 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 [7-9]. However, such technologies are not easily integrated into microsystems. Electrowetting microlenses have also been microfabricated on silicon substrates [10]. Due to the square shape of etched silicon holes, however, the optical performance of such microlenses is limited.

SU-8 is a photosensitive material commonly used to form thick, high aspect ratio polymeric microstructures with vertical sidewalls. Due to the thickness of a SU-8 layer, the exposure dosages are different at the top and at the bottom of the layer [11]. 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. Therefore, SU-8 is not only suitable as the structure but also as a dielectric material in the liquid lens using 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. 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.

PRINCIPLE OF OPERATION

The contact angle of a liquid droplet on a planar solid substrate can be expressed by Young's equation:

$$\gamma_{LG} \cos(\theta) = \gamma_{SG} - \gamma_{SL}, \quad (1)$$

where γ denotes the interfacial energy between two media, S denotes the substrate, L denotes the droplet, and G denotes the surrounding medium. θ is the contact angle of the droplet on the substrate.

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

$$\gamma_{SL} = \gamma_0 - \frac{1}{2} \frac{\epsilon \epsilon_0}{d} V^2, \quad (2)$$

where γ_0 is the surface tension of the solid-liquid surface interface at zero voltage, 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

$$\cos(\theta) = \cos(\theta_0) - \frac{\epsilon \epsilon_0}{\gamma_{LG} d} V^2. \quad (3)$$

The contact angle of a droplet without application of a voltage is given by θ_0 . From the Lippmann-Young equation, it is obvious 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.

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 one minute each, UV

exposure is performed for 50 seconds (3.0 mW/cm^2 at 365nm). Then the SU-8 layer is post-baked on a hotplate at 65°C and 95°C for one minute each and cooled down on the hotplate to room temperature. A 300nm thick Teflon layer (AF1601S, Dupont) is coated on top of the SU-8 by spinning and serves as a hydrophobic layer. A drop ($\sim 5\mu\text{L}$) of de-ionized (DI) water (resistivity $\sim 17 \text{ M}\Omega\text{-cm}$) is placed on the hydrophobic surface. A DC voltage is applied with micro-probes between the bottom gold electrode and the liquid. Figure 1.(a) shows the water contact angle without the application of voltage, while Figure 1.(b) shows the change of contact angle at 140 V .

Figure 1. Change of the contact angle of water on SU-8 substrate.

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. Figure 2 shows the contact angle change with various applied voltages. Saturation of contact angle is observed after 160 V , which is not shown in Figure 2. The dielectric constants of SU-8 and Teflon used in the calculation are 3 and 1.9, respectively. The solid line is the theoretical calculation based on the Lippmann-Young Equation. The black dots are the experimental measurements. SU-8 photoresist is a defect-free dielectric material layer.

Figure 2. Voltage vs. Contact angle

DESIGN OF MICROLENS

The schematic view of the variable focus lens is illustrated in Figure 3. The SU-8 structure is patterned on a glass substrate to form the cavity of the microlens. The angular sidewall provides the 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. The metal layer is deposited on top of the SU-8 structure as an electrode in EWOD. The metal on the bottom of the glass is removed 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. The lens 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 of gravity or mechanical vibrations. The cover glass with an indium tin oxide (ITO) electrode is coated by a layer of Teflon, and positioned over the bottom substrate structure filled with oil and water. The ITO layer is used as the counter-electrode in electrowetting. Non-conductive epoxy is then manually applied around the perimeter of the substrate stack to seal off the liquid lens.

Figure 3. Schematic view of the variable focus microlens.

EFFECTS OF UV OVEREXPOSURE

A smooth sidewall on the SU-8 structure is needed for the follow-on thin dielectric SU-8 and hydrophobic Teflon coatings by spinning. We use backside exposure of a double-layered SU-8 through a 1mm thick glass microslide to form angular SU-8 sidewalls. The tapered SU-8 structure is achieved by over-exposure with conventional UV mask and contact printing technology. The mask pattern is a ring with inner diameter of 3mm and outer diameter of 8mm . The UV exposure is performed with a broadband UV system. A layer of 2-micrometer thick SU-8 is first spun on a glass microslide as the adhesive layer for the follow-on thick SU-8 layer. 700-micrometer thickness is obtained by spinning two layers of SU-8 2100. The baking process is described in the following section. Different exposure times are performed and the fabrication results after 20-minute development are shown in Figure 4.

Figure 4. Profile of SU-8 sidewall with different exposure times.

The SU-8 structure with 2-minute exposure time shows a vertical sidewall profile, while it shows a smooth angular sidewall with 30-minute exposure time. Longer exposure time results in a smoother sidewall. Therefore, 30-minute exposure time with our broadband UV system is chosen for all microlens fabrication in order to get smooth sidewalls on SU-8 structures.

FABRICATION

Microlens fabrication starts with the fabrication of the bottom substrate which is capped by a glass with an ITO electrode after filling with two immiscible liquids. The fabrication process of the bottom substrate is illustrated in Figure 5. First, a 2-micrometer thick SU-8 layer is spun on a 1mm 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 one minute each and cooled down to room temperature on a hotplate. A 550-micrometer thick SU-8 layer is achieved by spinning two SU-8 layers. Both layers are pre-baked at 65°C for 30 minutes and at 95°C for 4 hours on a hotplate separately. In all follow-on steps, a slow heating and cooling processes are required to avoid cracking of the thick SU-8 layer. A broadband UV system is used to over-expose the SU-8 from the backside of the glass for 30 minutes (5220 mJ / cm² at 365nm). The whole substrate is then post-baked at 65°C and 95°C for 30 minutes and 1 hour, respectively. A SU-8 structure with smooth angular sidewalls is created after development for 20 minutes in the SU-8 developer (PGMEA, Microchem Corp. USA).

Figure 5. Fabrication process of bottom substrate.

10nm thick titanium and 200nm thick gold layers are then deposited by electron beam evaporation. The temperature of the substrates during electron beam evaporation is around 66°C. The metallic layers are then patterned to open a window on top of the glass substrate. Another 2-micrometer 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 minute and 95°C for 5 minutes in

an oven. The dielectric SU-8 layer is cross-linked by UV exposure for 50 seconds. The post-bake is performed at 65°C for 1 minute and 95°C for 5 minutes. Finally, a 300nm hydrophobic Teflon layer is applied. The Teflon layer is baked at 90°C for one hour and cooled down to room temperature in an oven. This completes the formation of the bottom substrate structure. The tapered SU-8 structure is shown in Figure 6. 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 aperture of the lens is 1 mm. The angle of the sidewall is measured as 36 degrees, and is shown in Figure 7. A top cover glass plate with ITO electrode is spin-coated with a 300nm Teflon 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.

Figure 6. Tapered SU-8 structure

Figure 7. Angle of sidewall of the SU-8 structure

MICROLENS DEMONSTRATION

The demonstration of the working microlens is performed by taking the image of numbers ('3' and '4') printed on 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 images of the numbers are captured with the microscope camera. In Figure 8, the images of numbers at 0 V and 60 V are shown. From the images with 60 V applied, the defocused numbers can be clearly observed.

Another demonstration of the working device is performed by taking the image of a laser beam. A collimated He-Ne laser beam is passed through a pin hole of 1mm in diameter. The laser beam then passes through the microlens from the water side. A reflective surface is placed at the focal plane of 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 Figure 9. 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.

Figure 8. Images (number '3' and '4') captured at 0 V and 60 V applied to the microlens.

Figure 9. Images of a laser beam passing through the microlens with 0 V and 60 V applied.

CONCLUSIONS

A variable focus microlens based on EWOD on a tapered SU-8 structure has been demonstrated. Images of printed numbers positioned under the microlens and the focusing of a laser beam passing through the microlens at different applied voltage levels successfully demonstrate a working device. Using SU-8 photoresist as a structural material, a wide range of sizes of microlenses can be fabricated. In addition, the SU-8 structures are easily integrated into other microsystems.

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