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Electrowetting-driven variable-focus microlens on flexible surfaces

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We demonstrate a flexible, electrowetting-driven, variable-focus liquid microlens. The microlens is fabricated using a soft polymer polydimethylsiloxane. The lens can be smoothly wrapped onto a curved surface. A low-temperature fabrication process was developed to reduce the stress on and to avoid any damage to the polymer. The focal length of the microlens varies between −15.0 mm to +28.0 mm, depending on the applied voltage. The resolving power of the microlens is 25.39 line pairs per mm using a 1951 United States Air Force resolution chart. The typical response time of the lens is around 50 ms. © *2012 American Institute of Physics*.
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Microlenses are important components in modern miniaturized optical systems.[1–9] Among these microlenses, emerging liquid-based variable-focus microlenses are of special importance, because they do not require complicated mechanical systems to adjust optical performance, and they are widely used in photonics, display and biomedical systems.[1–4] Meanwhile, microlenses made on flexible and curved substrates could have significant advantages over microlenses on flat substrates in improving the field of view (FOV)[5,6] and creating three-dimensional (3-D) effect.[7,8] For example, microlenses have been fabricated on spherical surfaces as artificial compound eyes.[9,10] Current microlenses can be either tunable in focus[1–4] or made on curved surfaces,[9,11] but not both. Pressure-based variable-focus microlenses require an external mechanical control system and are difficult to be extended to a lens array.[12] Tunable lenses based on phase modulation have relatively small magnitude of change in the focal length due to material properties.[13] It was previously reported that variable-focus liquid microlenses actuated by thermo-sensitive hydrogel could be formed on curved surfaces.[6] However, they have complicated structures and suffer long response time due to their actuation mechanisms. Robustness and quick response are both of importance to any optical system. Benefitting from short response time, low electrical power consumption, compact structure and the robustness under voltage cycling, electrowetting-driven liquid microlenses have drawn much attention and have been commercialized.[1,14–16] However, traditional electrowetting microlenses are normally fabricated on rigid substrates, such as glass, silicon, and polyethylene terephthalate,[1,14–17] and are consequently not compatible with curved surfaces. Flexible electrowetting microlenses could bring electrowetting lenses into a broader field of applications.

Here, we present an electrowetting-driven liquid microlens fabricated on a flexible polymer polydimethylsiloxane (PDMS). The lens has a thin soft polymer substrate, which can be smoothly wrapped on a curved surface, e.g., spherical or cylindrical surfaces. As demonstration, a lens has been made on the surface of a contact lens to show its flexibility. We also describe the processing steps and the materials used for a low-temperature fabrication process, which is critical to prevent damaging the polymer structure and to reduce its distortion. The focal length of the lens, which is controlled by an externally applied voltage varies between −66.7 and 35.7 diopters, or −15 mm to +28 mm. The resolving power of the lens is approximately 25.39 line pairs per mm, measured using a United States Air Force (USAF) resolution chart. The typical response time of the lens is around 50 ms.

Fig. 1(a) is the 3-D schematic showing an electrowetting-driven liquid microlens formed on a spherical surface. The substrate of the lens is a cross-shaped PDMS film, which is much thinner than the PDMS chamber that contains the liquids and defines the lens aperture. Therefore, the stress on the PDMS chamber and the resulting distortion are significantly reduced when the substrate film is stretched and wrapped on a spherical surface.[6] The PDMS substrate is approximately 200–300 μm thick and is soft and thin enough to conform to a curved surface. It is also optically transparent. Fig. 1(b) illustrates the cross-section schematic of the lens. The PDMS substrate is patterned with an electrode, and the wall of the chamber is coated with an electrode, a dielectric layer, and a hydrophobic coating subsequently. The liquid in the chamber consists of water (refractive index $n_1 = 1.33$) and silicone oil (refractive index $n_2 = 1.47$). The radius of curvature of the water-oil interface that forms the lens is controlled by V_o, the voltage applied on the two electrodes. The dioptric power (D) of the lens can be expressed by

$$D = D_0 + \frac{\varepsilon(n_2 - n_1)}{2\gamma_{12} d \cdot R} {V_o}^2, \quad (1)$$

where D_0 is the dioptric power at $V_o = 0$, n_2 and n_1 are refractive indices of silicone oil and water, respectively, ε is the dielectric constant of the dielectric layer, d is its

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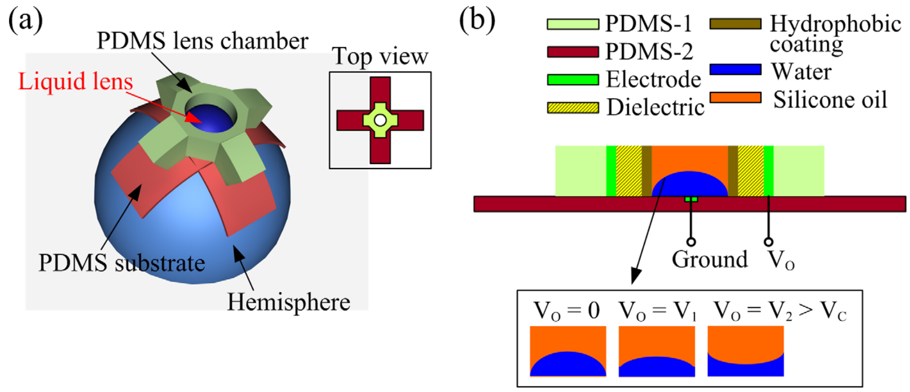

FIG. 1. (a) 3-D schematic of a flexible electrowetting-driven liquid lens on a spherical surface. The PDMS substrate is much thinner than the PDMS chamber where the liquid lens resides to reduce the stress on the lens structure when the flexible microlens is wrapped on a curved surface. (b) Cross-section schematic of the microlens. The internal sidewall of the PDMS chamber is coated with an electrode, a dielectric layer, and a hydrophobic coating subsequently. The radius of curvature of the water-oil interface is controlled by the voltage applied on the electrodes. At zero or low voltage (V_1), the water-oil interface bends upward and the microlens is diverging. When the applied voltage exceeds a critical value (V_c), the water-oil interface bends downward and the lens becomes converging.

thickness, γ_{12} is the interfacial tension between water and silicone oil, and R is the radius of the chamber. When no voltage is applied, the water-oil interface bends upward due to the hydrophobility of the chamber surface, thus a diverging lens. When a voltage is applied and increases, the water-oil interface flattens and the lens becomes less diverging. After the voltage reaches a critical value, the water-oil interface starts to bend downward and turns into a converging lens.

Fig. 2 illustrates the fabrication process of the lens. The PDMS structure of the lens is prepared by a soft lithography technique, as shown in Figs. 2(a) and 2(b). First, isobornyl acrylate (IBA) prepolymer in a 700-μm-deep channel on a microscope slide was photopatterned under an ultra-violet exposure (intensity, $I = 9$ mW/cm^2; and time, $t = 20$ s).[18] Next, the IBA mold was covered by a PDMS prepolymer mixture that was subsequently cured at 75 °C for 4 h. The pattern of the IBA mold was transferred to a PDMS film that had a 5-mm diameter aperture. The sidewall of the aperture was coated with an indium tin oxide (ITO) conductive film, a silicon oxide (SiO_2) dielectric layer, and a trichlorosilane hydrophobic coating subsequently, as shown in Figs. 2(c)–2(e). The processes were performed at low temperature (30 °C) to prevent cross-linked PDMS from deformation. In Figs. 2(f) and 2(g), a cross-shaped PDMS thin film (thickness ~ 300 μm) was prepared in a process similar to Figs. 2(a) and 2(b) and an ITO electrode was sputter-coated and patterned on its surface. The two PDMS layers were bonded after oxygen (O_2) plasma treatment,[19] and the open chamber was filled with water and silicone oil, as shown in Figs. 2(h) and 2(i). Finally, the chamber opening was covered by a PDMS slip and Fig. 2(j) shows a picture of a flexible electrowetting-driven liquid lens, which was conformally wrapped on the surface of a commercial contact lens. Note the difference in thickness between the PDMS substrate and the PDMS chamber on top. The substrate sustains most of the stress incurred when the lens is wrapped on a curved surface.[6] Therefore, the stress on the lens structure (PDMS chamber) and the resulting deformation are effectively reduced.

Each electrode in the flexible microlens was bonded to one end of a copper wire by conductive silver epoxy and the other end of the wire was connected to an external voltage source. The microlens was placed on a flat microscope slide and its imaging ability and dynamic tunability were tested utilizing the setup shown in Fig. 3(a). The object was a transparent film with letter "W" placed 50 mm below the lens plane. A camera above the lens recorded the images formed by the liquid lens as the applied voltage increased from 0 V to 125 V. Fig. 3(b) shows the images obtained at 0 V, 60 V, 90 V, and 125 V, respectively. The lens was initially a

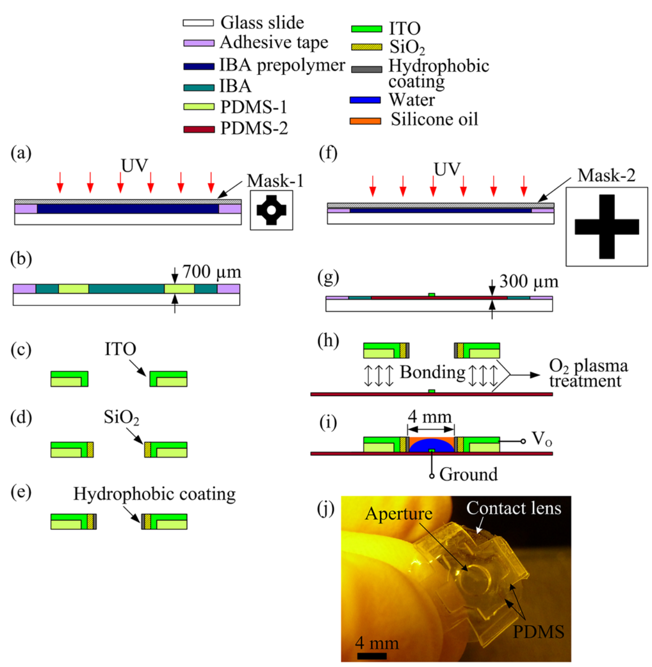

FIG. 2. Fabrication process of the flexible electrowetting-driven microlens. (a) A channel defined by adhesive tapes is filled with IBA prepolymer and is then photopatterned with mask-1. (b) The pattern of IBA mold is transferred to PDMS (PDMS-1). The thickness of PDMS-1 is around 700 μm. (c) The internal sidewall of the PDMS-1 layer is sputter-coated with 50 nm of ITO at 30 °C. (d) 120 nm of SiO_2 is then sputter-coated onto the ITO electrode as the dielectric layer. (e) The SiO_2 surface is evaporated in vacuum with a layer of trichlorosilane (~10 nm) as the hydrophobic coating. (f) and (g) IBA is photopatterned and its pattern is transferred to a 300-μm thick PDMS (PDMS-2) substrate layer, which is then patterned with ITO electrode. (h) The bottom of PDMS-1 and the top of PDMS-2 are treated with O_2 plasma and then bonded together. (i) The chamber is filled with water and silicone oil to form the liquid lens. The lens aperture is around 4 mm. (j) A picture of a flexible electrowetting-driven microlens wrapped on the surface of a commercial contact lens. The diameter of the contact lens is 15 mm.

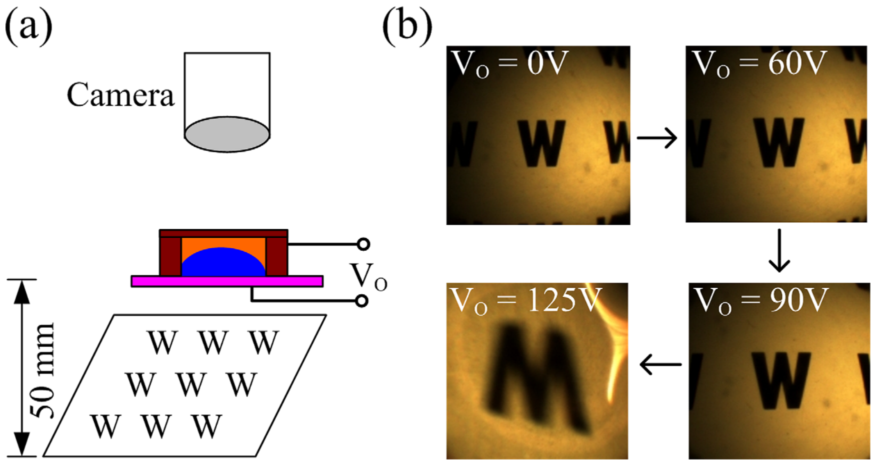

FIG. 3. (a) Setup for testing the imaging ability and dynamic tunability of the microlens. The microlens was placed on a flat microscope slide. A transparent film with letters of "W" was used as the object, and the images formed by the lens were recorded by a camera above it. (b) Images formed by the lens when the applied voltage (V_O) was increased from 0 V to 125 V. At 0, 60, and 90 V, the microlens is diverging and forms erect virtual images. The absolute value of the focal length increases with the voltage applied. At 125 V, the microlens becomes a converging lens and forms an inverted real image.

diverging lens; erect virtual images were thus formed. The absolute value of the focal length increased with the voltage applied. The liquid lens became a converging lens at 125 V, and an inverted real image was observed.

Fig. 4(a) shows the focal length f versus the applied voltage. When the voltage increased from 0 V to 145 V, the focal length changes from -15 mm to infinity first, and then to $+28$ mm. The critical voltage to change the lens from diverging to converging was around 115 V. The dioptric power of the lens could thus be adjusted between -66.7 and 35.7 diopters, much wider than the range of a human eye (between 20 and 24 diopters).[1] The resolving power of the lens was measured by imaging a 1951 USAF resolution test chart. Fig. 4(b) shows the image obtained at $f = 30$ mm. The smallest features to resolve were 25.39 line pairs per mm. The response time of the microlens was approximately 50 ms. The microlens was tested for over 20 cycles and no apparent change in the lens performance was observed.

The operating voltage of an electrowetting-driven microlens depends heavily on the materials used for the dielectric layer and the hydrophobic coating. Meanwhile, a low temperature fabrication process is required to reduce the stress on the PDMS substrate and to avoid the damage to PDMS during the fabrication. For this reason, the selection of the dielectric layer and the hydrophobic coating is very important. Silicon nitride (SiN) and teflon are often used in previously reported electrowetting-driven lenses as the dielectric layer[16,20] and hydrophobic coating,[1,14] respectively. These materials were tested in our flexible lens structure. SiN was coated on the sidewall of the PDMS chamber by a low temperature (100 °C) plasma-enhanced chemical vapor deposition (PECVD) process. The stress on the PDMS surface induced during the cooling step led to the cracking of the SiN film. Teflon (Teflon® AF1600, Dupont, Wilmington, DE) was also tried as the hydrophobic coating. It required a surface treatment at 165 °C during which PDMS was vitrified. Therefore, SiN and Teflon were not suitable for our flexible electrowetting-driven microlens structure.

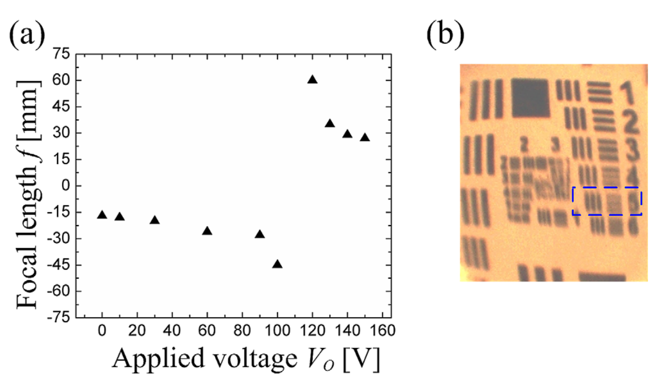

FIG. 4. (a) Focal length f versus applied voltage. The critical voltage for the lens to turn into a converging one is around 115 V. (b) Image of a USAF resolution chart when the microlens is at $f = 30$ mm. The smallest features are 25.39 line pairs per mm, corresponding to group 4, element 5 in the resolution chart (blue rectangle).

In summary, we demonstrated the design and fabrication process of a flexible electrowetting-driven variable-focus liquid microlens formed on PDMS. The flexible microlens consists of a PDMS chamber, and a thin PDMS substrate that effectively reduces the stress on the microlens structure when it is wrapped on a curved surface. A low-temperature fabrication process was developed to prevent PDMS from damage during the fabrication and to reduce the stress and distortion of the lens structure. One of our microlens was wrapped on the surface of a commercial contact lens to show its flexibility. The dependence of focal length on the applied voltage was measured. The microlens was a diverging lens at low applied voltage and turned into a converging lens when the applied voltage was higher than a critical value of approximate 115 V. The optical power of the microlens varied between -66.7 and 35.7 diopters when the applied voltage was adjusted between 0 V and 145 V. In the future, we will work on reducing the voltage needed to achieve a wide focal length range by exploring other suitable materials for the dielectric layer and hydrophobic coating. The aperture of our microlens can be reduced to at least 1 mm by the current fabrication process. By reducing lens size, we could fabricate a microlens array and integrate it with a spherical surface to improve the FOV. For this purpose, the subsequent device packaging and imager sensor alignment will also be addressed. In addition, the deformation of the PDMS chamber under stress will be measured and its effect on optical properties of the microlens will be analyzed. A flexible eletrowetting-driven adaptive microlens operated at low voltages could potentially be packaged into a contact lens for presbyopia correction.

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