Polymer Deformable Mirror for Optical Auto Focusing

Jen-Liang Wang, Tyng-Yow Chen, ChingWei Liu, Chen-Wei Edward Chiu, and Guo-Dung John Su

ABSTRACT—A low-stress organic polymer membrane is proposed as a deformable mirror that can be incorporated into a cellular phone camera to achieve auto focusing without motor-type moving parts. It is demonstrated that our fabricated device has an optical power of 20 diopters and can switch focus in 14 ms. The surface roughness of the organic membrane is measured around 15 nm, less than λ/20 of the visible light. With curve fitting, we found that the actuated membrane is almost parabolic in shape, which leads to less aberration than spherical surfaces. It is suitable for reflective-optics systems.

Keywords—Reflective optics, variable focus, parabolic curvature, organic deformable mirrors.

I. Introduction

Traditionally, the focusing function is achieved by moving lenses in most cameras. A moving displacement of 0.25 mm to 2 mm is required for auto-focusing [1]. With the continuing reduction in the size of mobile devices, the displacement-to-thickness ratio is increasing; therefore, it is difficult to place a mechanical motor system inside some types of mobile devices such as cellular phones. The miniaturization of these systems is also challenging with regards to the assembly of small components. With increasing surface-to-volume ratio, movement becomes more difficult because of mechanical parts friction. With these constraints, conventional motor systems might not be feasible. Some solutions have been proposed to change focusing power without moving lenses. One is the use of liquid lenses [2] which change their interface shape between two immiscible liquids by an electro-wetting method [3]. With this approach, however, it is difficult to choose materials that fulfill the two requirements of large refractive index contrast and small density difference. Another solution is the use of liquid crystal lenses [4], [5], but the incident light must be linearly polarized. It was also proposed in [6] and [7] to adopt deformable mirrors in a reflective optics configuration. Recently, reflective optics has attracted more attention as a means of achieving a long lightpath in thin products because of the folded light-path design. Deformable mirrors have an advantage of low color dispersion, but the optical power of silicon-based deformable mirrors [8] is relatively small. We propose an organic polymer deformable mirror which can be operated over a large optical power range of up to 20 diopters, which is one order of magnitude higher than the range of previously reported devices. Experimental results of its actuated shape and surface roughness will also be discussed.

Manuscript received May 15, 2007; revised Aug. 06, 2007.

Jen-Liang Wang (email: b90901071@ntu.edu.tw), Tyng-Yow Chen (email: b90501054@ntu.edu.tw), ChingWei Liu (email: r95941015@ntu.edu.tw), Chen-Wei Edward Chiu (email: chenweic@yahoo.com), and Guo-Dung John Su (phone: + 886 2 33663652, email: gdjsu@cc.ee.ntu.edu.tw) are with the Graduate Institute of Electro-Optical Engineering, National Taiwan University, Taipei, Taiwan.

II. Device Design and Fabrication

Since deformable mirrors are typically made of brittle silicon-based semiconductor materials, their deformation is generally limited to deflections of less than 10 µm over a 10 mm aperture, which is around 2 diopters. As a result, organic polymers with high yield stain and low Young's modulus are more desirable than semiconductor materials. It is reported that the yield strain of organic polymer is around 5%, which far exceeds the breaking limit of semiconductor materials. Besides, Young's modulus of polymer is about two orders of magnitude lower than most inorganic semiconductor materials [9].

We selected amorphous fluoropolymer, CYTOP, from Asahi Glass to fabricate the organic membrane for the deformable mirrors. CYTOP has excellent chemical resistance to TMAH (tetra-methyl ammonium hydroxide) wet etching. The adhesion of CYTOP to silicon and metals is excellent below the glass transition temperature (T_g), which is 108°C. These properties make it ideally compatible with existing semiconductor fabrication processes, during which the

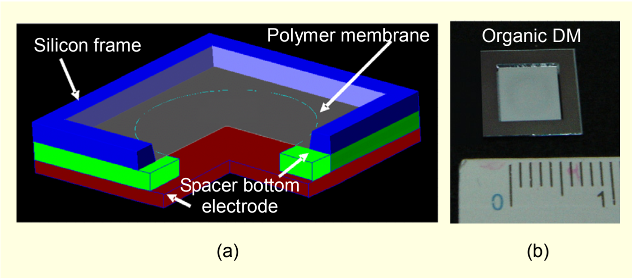

Fig. 1. (a) Schematic drawing of organic deformable mirror and (b) photograph of a fabricated device.

temperature is below T_g of CYTOP. The yield strain of CYTOP is about 5%, which is considered high compared to that of silicon-based semiconductor membranes such as silicon nitride. The high yield strain is critical for large deformation.

The schematic drawing of an organic deformable mirror is shown in Fig. 1(a). An aluminum-coated polymer membrane is supported by a silicon frame. A silicon bottom electrode coated with aluminum is attached to the silicon frame by a dielectric tape spacer. The spacer has a circular opening to define the deformation shape of the polymer membrane. When a voltage difference is applied between the bottom silicon electrode and the aluminum-coated polymer membrane, the electrostatic force pulls the CYTOP membrane down toward the bottom electrode due to its mechanical flexibility. The polymer membrane works as a reflective mirror surface to variably focus the light by adjusting the voltage difference.

The organic deformable mirror was fabricated by a CMOS-compatible micromachining process [10]. Starting with a silicon wafer, the organic thin film was spin-coated on the top of the silicon wafer. We applied TMAH to etch through the wafer from the back for about 8 hours so that the polymer membrane would be exposed. Both sides of the polymer membrane were coated with aluminum by an e-beam evaporator to reflect light and to protect the polymer membrane from air and moisture. A dielectric tape was used as a spacer to bond the silicon frame and the bottom electrode. The polymer membrane was 6 mm wide and 2 μm thick. The gap between the polymer membrane and the bottom electrode was approximately 70 μm, and the circular opening of the dielectric tape spacer was punctured by a perforator. A photograph of the fabricated device is shown in Fig. 1(b).

III. Experimental Measurement

To evaluate the device performance, we first investigated the optical quality of the reflecting surface. For imaging applications, we normally consider λ/20 a bench mark for surface roughness at visible wavelengths. The measurement was performed by using a WYKO white light interferometer. The average roughness was 12nm and root-mean-square roughness was

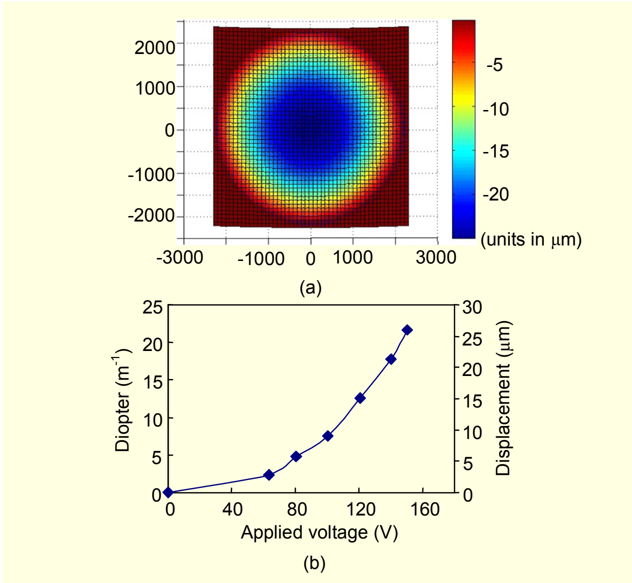

Fig. 2. (a) 2D contour plot of an actuated polymer membrane surface and (b) optical power versus applied voltage.

14.8 nm. When the polymer membrane was actuated, the surface roughness was improved slightly because surface tension makes the surface smoother. The tensile stress inside polymer films also helps stretch the films flat. When the polymer surface was coated with aluminum 0.3 μm thick, the reflectivity was higher than 96%.

Figure 2(a) shows the simulation results of an actuated polymer membrane obtained by using finite element method (FEM) analysis with 3,600 meshing elements. The theoretical 2D contour plot indicates that the curved mirror surface is rotationally symmetrical, and the maximum center displacement of the polymer membrane is approximately 25 μm. We took a 4.5 mm diameter circular shape for curve fitting. We found that it is more accurate to describe the actuated surface with a parabolic curve than a spherical curve because the variances of curve fitting are 7.89×10^{-3} μm^2 for a spherical curve and 0.48×10^{-3} μm^2 for a parabolic curve. Since the surface is almost parabolic in shape, theoretically, the aberration is less than that for a spherical shape when the object is at a relatively long distance.

We conducted an experiment of optical power versus applied voltage. The polymer membrane was actuated by electrostatic force, and deformation of the polymer membrane could be adjusted by changing the voltage difference continuously. The optical power is about reciprocal of half the radius of the curvature of the mirror surface. Using the first-order paraxial rays approximation [11], the radius of the curvature is calculated by the expression $R=\frac{D^2}{8x}$, where R is the radius of the curvature, D is the diameter of the polymer membrane (4.5 mm in this experiment), and x is the deformation of the mirror from the center to the edge. The optical power and deformation versus the applied voltage is plotted in Fig. 2(b). The maximum optical power achieved is around 20 diopters when 160 volts is applied, corresponding to 27 μm deformation. The optical power of an organic deformable mirror can be adjusted continuously. Even though a high voltage difference is required, the current through the device is almost negligible so that the power consumption is quite low. The low power consumption makes it a potential candidate for use in portable devices.

To verify the focusing function, we set up a simple image-taking system as shown in Fig. 3(a). A solid lens was placed directly in front of an organic deformable mirror, which was used to adjust the combined optical power of lenses. A beam splitter was used to construct the reflective optics configuration. The distance between the beam splitter and the solid lens was about 1.5 cm. Without applying voltage difference to the deformable mirrors, an object at 8 cm could be seen clearly. Once the deformable mirror was actuated, the optical power of the lenses increased so that an object at 3 cm was in focus, as shown in Fig. 3(b). Blurring was mainly due to aberration from the spherical solid lens and misalignment. Image quality could be improved by proper aspherical lens design and precise mechanical housing. The speed of switching focus was demonstrated experimentally to be around 14 ms [12]. A closed-loop method [13] will be adopted to control the deformable mirror by checking image sharpness.

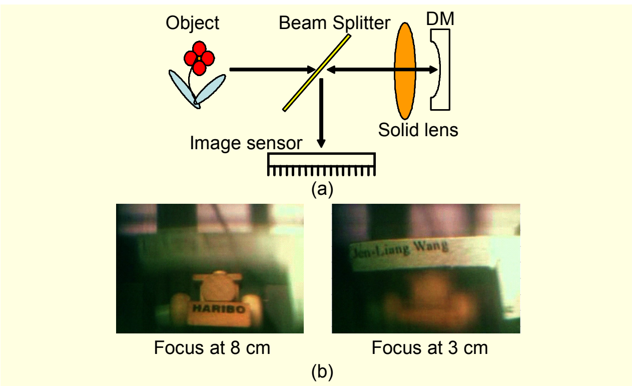

Fig. 3. (a) Schematic drawing of imaging system setup and (b) images focused at different distances.

IV. Conclusion

An organic polymer membrane to be used as a deformable mirror was demonstrated. The operating power range of 20 diopters can be achieved by applied voltage of 160 V. The optical power range is one order of magnitude higher than that of a silicon-based device, and the required voltage is half that. The focus switching speed is 14 ms. The surface roughness of the organic membrane is measured to be around 15 nm, which is less than λ/20 of the visible light. These characteristics of the polymer deformable mirror are suitable for imaging systems. Our initial results are encouraging, and we will incorporate the mirror into a more compact design in the near future.

References

[1] http://www.newscaletech.com.

[2] S. Kuiper and B.H.W. Hendriks, "Variable-Focus Liquid Lens for Miniature Cameras," *Applied Physics Letters,* vol. 85, no. 7, 2004, pp. 1128-1130.

[3] S. Kuiper, B.H.W. Hendriks, R.A. Hayes, B.J. Feenstra, and J.M.E. Baken, "Electrowetting-Based Optics," *Optical Information Systems III, Proc. SPIE*, vol. 5908, 2005, pp. 59080-59087.

[4] Y. Kozawa and S. Sato, "Focusing Property of a Double-Ring-Shaped Radically Polarization Beam," *Optics Letters,* vol. 31, no. 6, Mar. 2006, pp. 820-822.

[5] B. Wang, M. Ye, and S. Sato, "Liquid Crystal Lens with Focal Length Variable from Negative to Positive Values," *IEEE Photonics Technology Letters*, vol. 18, no. 1, Jan. 2006, pp. 79-81.

[6] D. Wick and T. Martinez, "Adaptive Optical Zoom," *Optical Engineering,* vol. 43, no. 1, 2004, pp. 8-9.

[7] H. Kinoshita, K. Hoshino, K. Matsumoto, and I. Shimoyama, "A Thin Camera with a Zoom Function Using Reflective Optics," *Sensors and Actuators A,* vol. 128, no. 1, 2006, pp. 191-196.

[8] P. Kurczynski, H. Dyson, B. Sadoulet, J. Bower, W. Lai, W. Mansfield, and J. Taylor, "Fabrication and Measurement of Low-Stress Membrane Mirrors for Adaptive Optics," *Applied Optics*, vol. 43, no. 18, 2004, pp. 3573-3580.

[9] P. Hsu, M. Huang, S. Wagner, Z. Suo, and J. Sturn, "Plastic Deformation of Thin Foil Substrates with Amorphous Silicon Islands into Spherical Shape," *Materials Research Society Proc.*, vol. 621, 2000, pp. Q8.6.1-Q8.6.6.

[10] Y.W. Yeh, C.W. E. Chiu, and G.D.J. Su, "Organic Amorphous Fluoropolymer Membrane for Variable Optical Attenuator Applications," *Journal of Optics A: Pure and Applied Optics,* vol. 8, no. 7, 2006, pp. S377-S383.

[11] G.D.J. Su, H. Toshiyoshi, and M.C. Wu, "Surface-Micromachined 2-D Optical Scanners with High-Performance Single-Crystalline Silicon Micromirrors," *IEEE Photonics Technology Letters*, vol. 13, no. 6, June 2001, pp. 606-608.

[12] G.D.J. Su , Y. Yeh, C. Chiu, C. Lee, and T. Chen, "Fabrication and Measurement of Low Stress Polyimide Membrane for High Resolution Variable Optical Attenuator," *IEEE J. Selected Topics in Quantum Electronics*, vol. 13, no. 2, Mar./Apr. 2007, pp. 312-315.

[13] Y. Zhang, C. Wen, Y. Soh, and A. Fong, "Adaptive Focusing: A Closed-Loop Perspective," *Journal of Optical Society of America. A,* vol. 22, no. 4, Apr. 2005, pp. 625-635.