Optical properties of microlenses fabricated using hydrophobic effects and polymer-jet-printing technology

Hyuck Choo and Richard S. Muller
Berkeley Sensor & Actuator Center
University of California at Berkeley

We describe high-precision microlenses with excellent optical characteristics. The lenses are formed precisely at desired locations on a wafer using a polymer-jet system in which hydrophobic effects define the lens diameter and surface tension creates a high-quality optical surface. To make the lenses, we defined hydrophilic circular regions at desired locations using photolithography to pattern a 0.2-μm thick Teflon (hydrophobic) layer on a quartz substrate, as shown in Figures 1 and 2. Then, using a polymer-microjet printing system (Figure 3), we dispense an exact amount of UV-curable polymer within hydrophilic circles to obtain microlenses having desired optical properties [1]. Figure 4 shows that adjusting the volume of the UV-curable optical epoxy within a hydrophilic circle of a given diameter changes the curvature of the microlens. The step resolution of the microlens volume is determined by the average droplet size (~25pL) of the polymer-jet print head. This hybrid method enables us to define the locations and diameters of microlenses with a ± 1 μm precision as well as to control the curvatures of the microlenses accurately.

We measured the quality of our lenses using several precise optical-characterization systems. Figures 5 and 6 are scanning-electron microscope pictures showing several of our microlenses. AFM measurements show that the surface roughnesses of our microlenses are lower than 5nm. We used a WYKO NT3300 to measure the curvature and volume of the microlenses. The maximum deviation of the surface profile from an ideal circle was approximately 0.15μm for most cases (range ~0.05-0.23μm). The effective focal lengths measured are shown in Figure 7. The *f*-numbers range from 1.5-2.1, 2.0-5.5, 3.4-6.3, and 2.9-7.4 for 200 μm-, 400 μm-, 600 μm-, and 1 mm-diameter microlenses, respectively. The Seidel aberrations, root-mean-square wavefront errors (rms WFE), peak-to-valley optical-path differences (p-v OPD) of the microlenses were measured at $\lambda = 635$ nm using a commercial Shack-Hartmann system with an accuracy of $\lambda/100$ [2], [3]. The rms WFE values of our microlenses were between $\lambda/5$ and $\lambda/80$, depending on the aperture size, diameter, and volume of the microlenses. The average p-v OPD values were 0.14, 0.25, 0.33, and 0.46 μm for 200 μm-, 400 μm-, 600 μm-, and 1mm-diameter microlenses, respectively. Decreasing the aperture size of the microlenses produced much smaller rms WFE and p-v OPD values, as shown in Figure 8. These values were sometimes as low as $\lambda/80$. The fabrication process showed good repeatability as well; twenty 400-μm-diameter microlenses showed ~1.43% variations in measured volumes and effective focal lengths.

The fabrication of microlenses using surface tension and/or hydrophobic effects has attracted considerable research because of this method's potential applicability to micro-optical systems. A previously reported dipping method produced lenses, but did not provide a reliable means to vary or control optical properties if, for example, several lenses at differing locations on a wafer were needed in a microsystem [4]. The dipping technique is especially cumbersome when (as in the usual case) microstructures have already been fabricated onto the wafer surface. If, instead of dipping, a polymer-jet-printing technique is used without hydrophobic pattern definition, it is difficult to obtain uniform diameters or to build closely packed microlens arrays because uncured liquid polymer tends to flow and merge with adjacent microlens patterns [5]. Recent research described polymer-jet-printing of lenses having a range of focal lengths but a single fixed diameter [6]. The authors mentioned the use of 'surface treatments', but without fully describing the process.

References

[1] Paul Watson, Microfab Technologies Inc, Plano, Texas USA

[2] P. D. Pulaski, D. R. Neal, J. P. Roller, "Measurement of aberrations in microlenses using a Shack-Hartmann wavefront sensor," *SPIE-Int. Soc. Opt. Eng. Proceedings of Spie - the International Society for Optical Engineering, vol.4767,* 2002, pp. 44-52. USA.

[3] Dr. P. D. Pulaski, Wavefront Sciences, Albuquerque, New Mexico USA

[4] Hartmann DM, Kibar O, Esener SC, "Optimization and theoretical modeling of polymer microlens arrays fabricated with the hydrophobic effect," *Applied Optics, vol.40, no.16,* June 1, 2001, pp.2736-46.

[5] MacFarlane DL, Narayan V, Tatum JA, Cox WR, Chen T, Hayes DJ, "Microjet fabrication of microlens arrays," *IEEE Photonics Technology Letters, vol.6, no.9,* Sept. 1994, pp.1112-14. USA.

[6] Ting Chen, Cox WR, Lenhard D, Hayes DJ, "Microjet printing of high-precision microlens array for packaging of fiber optic components," *SPIE-Int. Soc. Opt. Eng. Proceedings of Spie - the International Society for Optical Engineering, vol.4652,* 2002, pp.136-41. USA.

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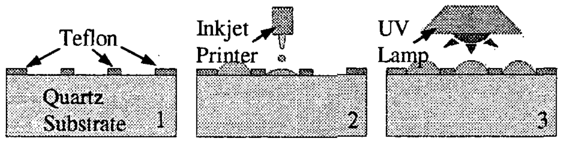

1. Spin-coat a 0.2 μm thick Teflon (hydrophobic) layer on quartz wafer. Then, photolithographically pattern and dry-etch the Teflon layer using low power O_2 plasma.
2. Using the inkjet print head, dispense the desired amount of UV-curable polymer within the hydrophilic circles.
3. Fully cure the polymer under a high-intensity UV lamp.

Figure 1 Fabrication process

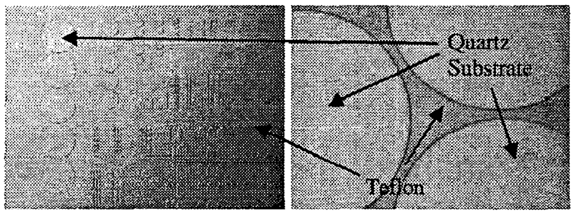

Figure 2 Various hydrophilic patterns created on a hydrophobic Teflon layer on quartz substrate

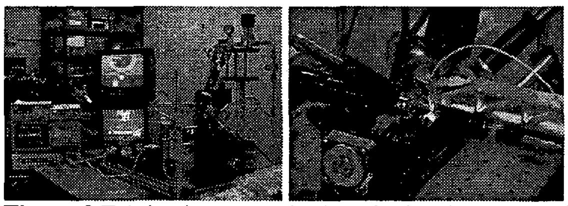

Figure 3 Fabrication setup: inkjet print head, automated stage, viewing system, and print head driver

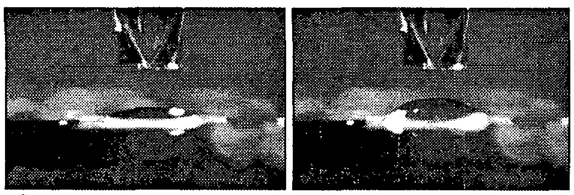

Figure 4 Controlling the curvature of 1000 μm-diameter microlens: change in volume clearly changes the curvature/height of the microlens for a given diameter

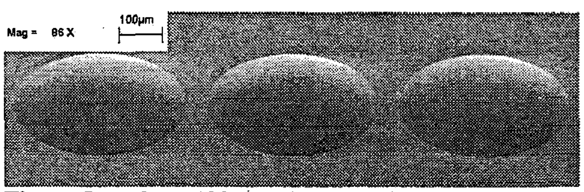

Figure 5 Uniform 400 μm-diameter microlenses

Figure 6 Variation of microlens curvatures for 400 μm diameter

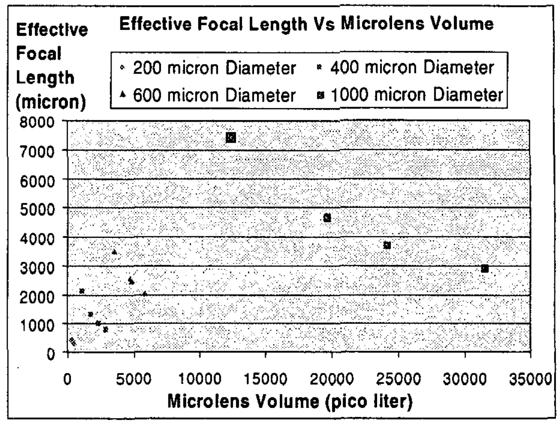

Figure 7 Effective focal length Vs microlens volume

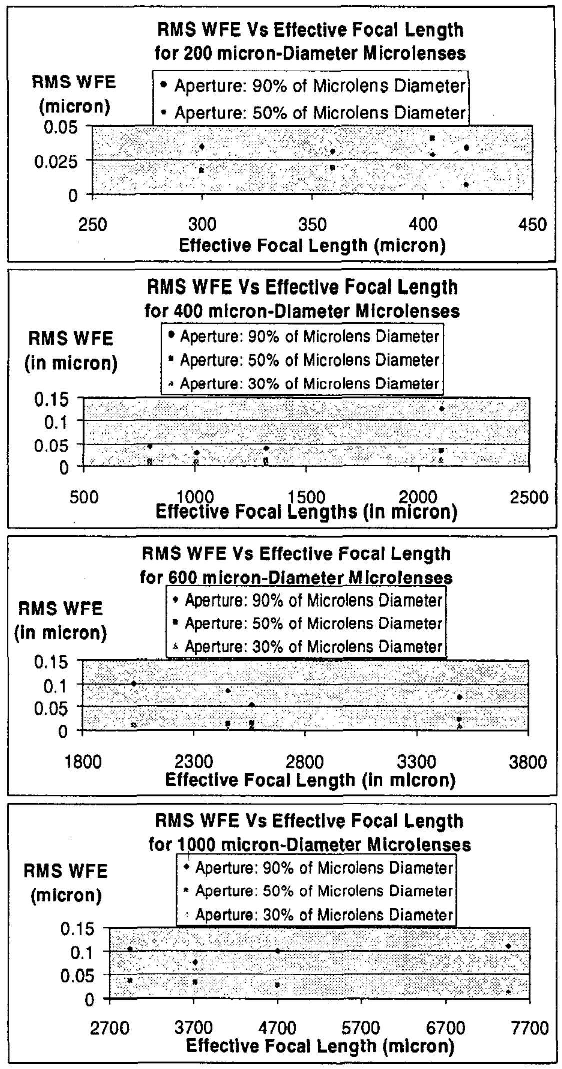

Figure 8 rms wavefront error Vs effective focal length for various microlenses