# Self-Organization of Microlens Arrays Caused by the Spin-Coating-Assisted Hydrophobic Effect

Fang-Chung Chen, Wen-Kuei Huang, and Chu-Jung Ko

***Abstract*—A simple, low-cost, low-temperature, and shape-controllable approach has been demonstrated to fabricate polymer microlens arrays (MLAs). By using microcontact printing of the self-assembled monolayers and then spin coating, the microlenses were able to organize themselves on the patterned glass substrate. High-quality MLAs made of NOA65 prepolymer with lens-diameters of 50, 75, and 100 $\mu$m have been fabricated by this method. Lens shapes can be controlled by changing the spin rates of the prepolymer coating. Optical measurements have revealed an excellent light-collecting capability from the fabricated MLAs. It is anticipated that the technique will be ideally suited to low-cost and high-volume production.**

***Index Terms*—Hydrophobic and hydrophilic, microcontact printing, microlens array (MLA), self-assembled monolayers (SAMs), surface energy.**

## I. Introduction

REFRACTIVE microlens arrays (MLAs) have received much attention due to their various applications in modern optical systems [1], such as optical data storage, optical communications, laser beam shaping elements, and information displays [2]. Numerous techniques, for examples, photoresist reflow and etch transfer [3], ink-jet printing (IJP) [4], laser ablation [5], laser direct-writing [6], and gray-scale mask methods [7], have been adopted to fabricate MLAs. However, each of the aforementioned methods still has its own drawbacks. For instance, the reflow method requires high process temperature and a complicated etch transfer process. Furthermore, limitation in lens-size and alignment accuracy makes IJP undesirable. For laser ablation, one has to face the problems of high facility-cost and high energy consumption. For laser direct-writing, the surface roughness of lens presents a problem. For the gray-scale mask method, it is difficult to fit the desired shape precisely and to distinguish the gray levels in a sharp edge. The lens surface is usually too rough as well. Consequently, there is still a need for a fast, cost-effective, and shape-controllable method to fabricate MLAs.

Among the methods of MLA fabrication, one interesting approach is using the hydrophobic effect [8], [9]. This method is based on the self-assembly of a liquid prepolymer and is affected by the different surface-energy patterns on the substrate. The techniques used in the creation of patterns include microcontact printing ($\mu$CP) of self-assembled monolayers (SAMs) [8], and adhesive lithography [9]. This provides a much simpler method to fabricate MLAs using the hydrophobic effect. However, the major disadvantages involve the attachment of the lens-material on the reverse side of the substrate and it is difficult to apply to a large area. In this work, the self-assembly phenomena of MLAs caused by the so-called "spin-coating-assisted hydrophobic effect" on glass substrates are presented. The operation parameters of the spin-coating process, such as the spin rate, provide another dimension to control the lens shape. In addition, in contrast to the dip-casting method, spin coating is a more reliable and popular method used in laboratories and industries. Only one side of the substrate is coated in the spin-coating process and the other side can be keep clean. The new approach reported in this letter provides a simple, low-cost, and mass-production approach to fabricate MLAs.

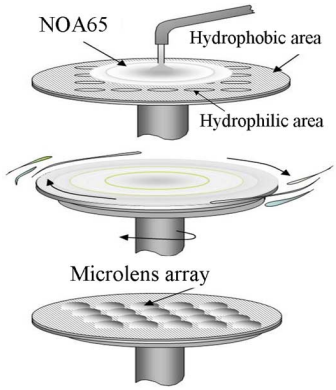


Fig. 1. Fabrication process flows of an MLA. The pattern of the hydrophobic region was defined by $\mu$CP of SAMs. The unmodified regions (the circle areas) remained hydrophilic. After spin-coating the prepolymer onto the substrate, the microlenses were self-assembled in the hydrophilic regions.

## II. Experiment

The fabrication process of the self-assembly MLA is illustrated in Fig. 1. The pattern of hydrophobic regions was defined by $\mu$CP of the SAMs. The stamp used in $\mu$CP were made of poly(dimethylsiloxane) (PDMS) and were replicated from a solid mold. The mold was fabricated on a silicon wafer with 2-$\mu$m-height pillars using photolithography and then the patterns were transferred using reactive ion etch. The resulting PDMS stamp was inked with a solution of 1H, 1H, 2H, 2H-perfluorooctyltrichlorosilane (FOTS) dissolved in heptane for 30 s, and then placed on a UV-ozone treated glass substrate. After the stamp and the substrate were separated, the SAM of FOTS was formed as a hydrophobic region. Due to the UV-ozone treatment, the glass surface exhibited high water-absorption ability such that the measured contact angle (CA) with water was less than 5°. By contrast, the FOTS-treated surface had extremely low surface energy (CA $>$ 110°) [10]. As a result of the stamp's

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Color versions of Figs. 1, 2, 4, and 5 are available at http://ieeexplore.ieee.org.

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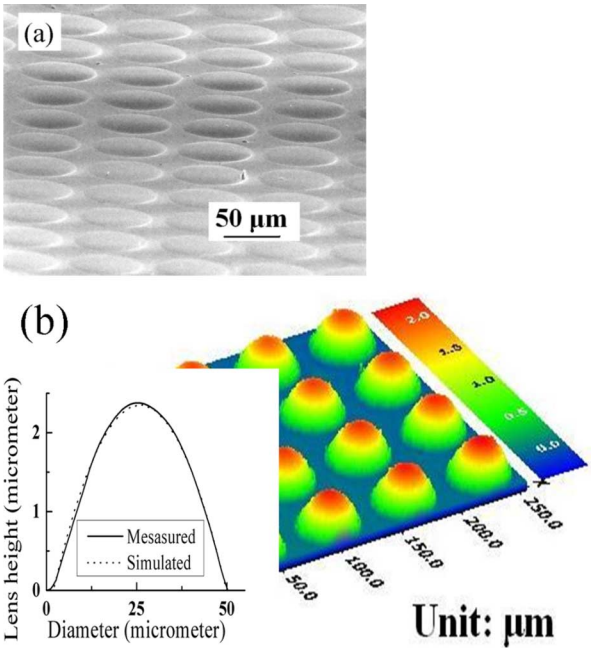


Fig. 2. (a) Image of an MLA obtained on an SEM. The lenses have a 50-$\mu$m diameter and 10-$\mu$m spacing. (b) Vertical view of the MLA acquired using an interferometer. The lens-profile, which is obtained on an alpha-step, shows a good surface roughness [insert of (b)].

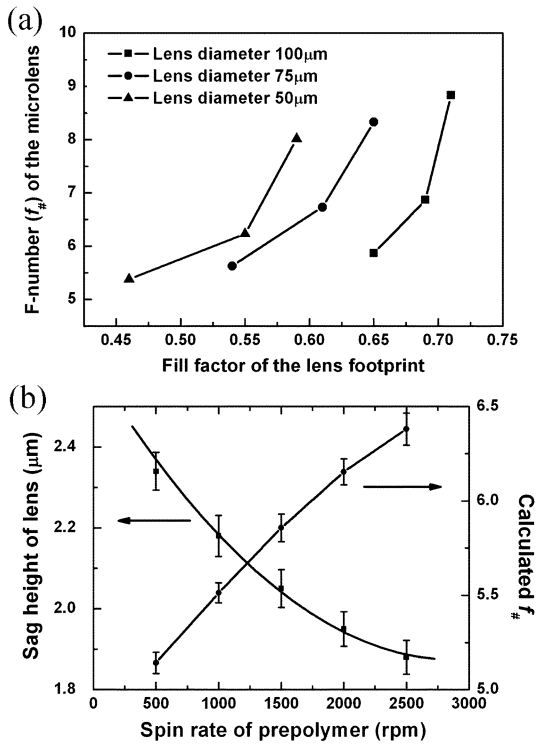


Fig. 3. (a) The $f_\#$ depends on the FFs of MLAs. The lens diameters are 50, 75, and 100 $\mu$m with either 5-, 10-, or 15-$\mu$m spacing. Different FF was obtained from the MLA with the same diameter but different spacing. (b) Corresponding sag-heights $(h)$ and calculated f-numbers $(f_\#)$ of the MLAs versus spin rates of the prepolymer coating. The lens diameter is 50 $\mu$m.

pattern, the surface of the glass substrate was divided into hydrophobic and hydrophilic regions. After spin-coating of the prepolymer, NOA65 (Norland Optical Adhesive 65, Thorlabs INC.), the lens material was self-assembly as plano-convex structures on the hydrophilic regions. Finally, the microlenses were hardened and stabilized by a UV-light curing.

## III. Results and Discussion

The scanning electron microscope (SEM) image of the representative MLA with a 50-$\mu$m diameter and 10-$\mu$m spacing is shown in Fig. 2(a). The vertical view of the MLA was also acquired on an interferometer [Fig. 2(b)]. The parameters of lens shape, such as the radius of footprint $(r)$ and sag-height $(h)$, were obtained from the interferometer. The lens-profile, which is obtained on an alpha-step p-1 profilometer (KLA-Tencor Corporation), shows a smooth surface [inset of Fig. 2(b)]. The surface roughness is less than 1 nm from the surface analysis by an atomic force microscopy. In addition, the measured lens-profile is also very similar to the simulated one, implying high quality of the lenses. The measured lens diameter is exactly identical to that of the dimension of a circle designed on the PDMS mold, which implies that precise pattern transfer has been achieved. In addition, one can also observe that perfect plano-convex lenses were formed in the hydrophilic regions due to a minimum surface-energy of the prepolymer. Moreover, the well-defined pattern with distinct boundary indicates that the hydrophobic SAMs can effectively repel the adhesive prepolymer liquid on the FOTS-treated regions. The difference in CAs of NOA65 between the hydrophobic and hydrophilic regions is more than 60°, indicating that a large surface energy difference is created by the surface structure. The large difference in surface properties between the two regions is actually one of the keys to obtain high quality MLAs.

For a thin plano-convex lens, the focal length $(f')$ and $f$-number $(f_\#)$ can be calculated using the following relations:

$$R = \frac{h^2 + r^2}{2h}, \quad f' = \frac{R}{n-1}, \quad f_\# = \frac{f'}{2r}$$

where $R$ is the curvature radius of the lens surface, and $n$ is the refractive index of the lens material ($n = 1.524$ for NOA65). For example, the $f_\#$ is 5.14 for a lens with a 50-$\mu$m diameter and 2.34-$\mu$m sag-height. The relationship between the $f_\#$ and the fill factor (FF), that is the area ratio of a microlens to a pixel, is illustrated in Fig. 3(a). It can be seen that the $f_\#$ decreases with a decrease in the FF. This suggests that more lens material is gathered in the smaller hydrophilic region to form a stronger (lower $f_\#$) microlens when the FF is smaller. In other words, the greater amount of NOA65 is repelled to the UV-ozone-treated areas, the stronger lenses are formed.

However, the $f_\#$ is not only determined by the FF but also by the spin rates. To further investigate the effect of spin-coating process, different spin rates were used to fabricate the MLAs. Conventionally, the polymer film thickness $(t)$ was evaluated by the following empirical equation [11]:

$$t \propto s^{-1/2} v_0^{1/3}$$

where $s$ and $v_0$ are the spin rate and the viscosity of the polymer, respectively. Fig. 3(b) illustrates the relationship between the lens sag-heights $(h)$ and the corresponding spin rates. The data shown fits well within the above empirical equation. As the spin-rate decrease from 2500 to 500 rpm, the lens sag-height increase from 1.89 to 2.34 $\mu$m. The $f_\#$ of microlens as a function of the spin rates is also presented in Fig. 3(b) and ranges

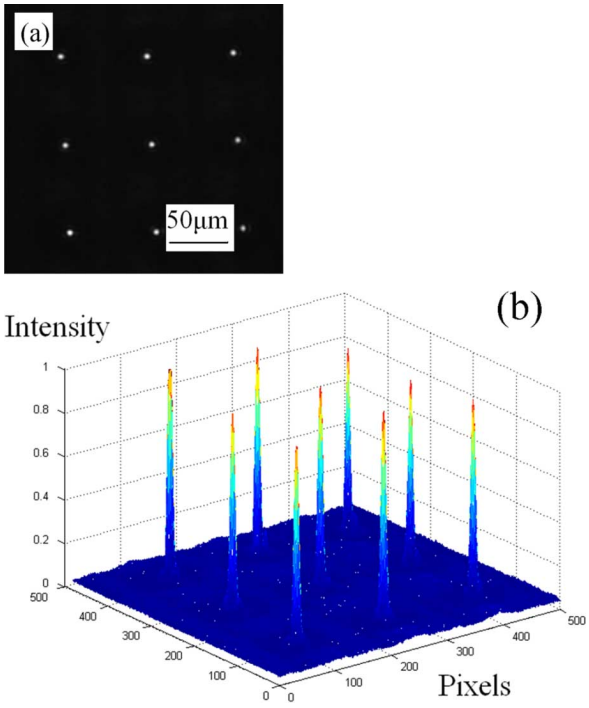


Fig. 4. (a) Focused light spots image of an MLA on the focal plane. The lens has a 50-$\mu$m diameter and 15-$\mu$m spacing. (b) 3-D energy distribution of light spots.

from 5.14 to 6.38. The results demonstrate clearly that the lens sag-heights can be completely controlled by the spin-rates. In addition, for the uniformity of MLAs, as shown in Fig. 3(b), the average derivation of focal length $\Delta f'/f'$ is less than one percent at 1000 rpm, implying a high level of uniformity.

A configuration of 100 by 100 MLA has been successfully developed. The focusing property is also evaluated by a beam profiler. Fig. 4(a) shows the image plane produced by a collimated laser beam illuminated through the MLA. The focused light spots demonstrate the strong focusing ability and the high uniformity. Fig. 4(b) shows a three-dimensional (3-D) energy distribution of light spots. This energy distribution reveals a high level of uniformity because the deviation of the energy peak is smaller than 10%. The full-width at half-maximum of the light spots measured from the cross-sectional view is $4.95\pm0.25\mu$m, which is very close to its theoretical value. These data suggest that a high-quality MLA has been fabricated.

The method presented here is quite unique from several aspects. First, the spin-coating is adapted instead of the complicated lithography and reflow methods to fabricate MLAs. Second, instead of using gold for $\mu$CP of the SAMs with alkanethiolates, glass is used as the substrate material. The high transparency of the glass substrate ensures minimum reflection and absorption of light. Furthermore, the NOA65 is an index-matched material which can reduce the reflection at the lens–substrate interface and the absorption is low in the range of visible light. Finally, the UV-ozone treatment is used to obtain a hydrophilic surface. This process not only makes the substrate hydrophilic by chemically oxidizing of the surface but also provides the oxygen moieties for the formation of covalent bonds between the substrate and the organosilanes. Consequently, a variety of substrate materials may be used, as long as they can be oxidized. For example, Fig. 5 demonstrates

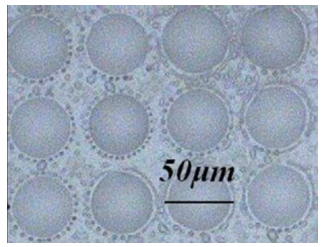


Fig. 5. MLA fabricated on a PES substrate. The lenses have a 50-$\mu$m diameter and 15-$\mu$m spacing.

that the MLA was fabricated on a polymer substrate, polyethersulphone (PES). This feature is quite important for the future development of flexible display technology, since MLAs on flexible substrates can be integrated into them directly.

## IV. Conclusion

One fast, low-cost, low-temperature, and profile-controllable approach has been demonstrated to fabricate polymer MLAs. By the simple process of microcontact printing and spin-coating, the microlenses become self-assembled on the glass substrates. The demonstrated MLAs are made of NOA65 prepolymer with lens sizes of 50, 75, and 100 $\mu$m in diameter. The microlenses have $f_{\#}$ ranging from 5.14 to 8.83, depending on the lens diameters and the spacings. Lens shapes can be controlled by changing the spin rates of prepolymer coating. The lens profile obtained on the interferometer and alpha-step shows good surface roughness and uniformity. Finally, optical measurements have demonstrated an excellent light-collecting capability from the fabricated MLAs.

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