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Self-positioning microlens arrays prepared using ink-jet printing

Jhih-Ping Lu
National Chiao Tung University
Institute of Electro-optical Engineering
1001 Ta Hsueh Road
Hsinchu, 300
Taiwan
and
Industrial Technology Research Institute
Hsinchu, 310
Taiwan

Wen-Kuei Huang
National Chiao Tung University
Institute of Electro-optical Engineering
1001 Ta Hsueh Road
Hsinchu, 300
Taiwan

Fang-Chung Chen
National Chiao Tung University
Department of Photonics
and
Display Institute
1001 Ta Hsueh Road
Hsinchu, 300
Taiwan
E-mail: fcchen@mail.nctu.edu.tw

Abstract. We have employed ink-jet printing (IJP) technology to fabricate self-positioning microlens arrays (MLAs). The glass substrates were first prepatterned through microcontact printing (μCP) hydrophobic self-assembled monolayers (SAMs) to divide the surface into hydrophobic and hydrophilic regions. After IJP of the hydrophilic prepolymer liquids, the lenses were effectively repelled by the patterned SAMs. We obtained high-quality MLAs having diameters of 75 and 100 μm after polymerization of the prepolymers. The lenses' shapes could be controlled by varying the number of printed droplets. *© 2009 Society of Photo-Optical Instrumentation Engineers.* [DOI: 10.1117/1.3180868]

Subject terms: microlens array; self-assembled monolayer; ink-jet printing.

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1 Introduction

With the growing number of applications of electro-optical systems in our daily lives, the role of reflective microlens arrays (MLAs) in enhancing their performance is becoming increasingly crucial, making it important to develop simple methods for the efficient mass production of MLAs. Although several approaches have been reported for the fabrication of MLAs, including the use of photoresist reflow and etch transfer,[1] hot embossing,[2] laser ablation,[3] and direct laser writing,[4] these methods are technically complicated and/or expensive. Ink-jet printing (IJP)[5] is an attractive alternative because of its several advantageous features, including the freedom to control the shape and position, low consumption of the lens material, and the simplicity of the fabrication processes. Moreover, IJP is a relatively environmental friendly and energy-saving procedure. Several groups have attempted to fabricate MLAs by using IJP technology[5–8]. For example, Danzebrink and Aegerter constructed high-quality MLAs by ink-jet printing of a hybrid organic-inorganic sol.[6] More recently, Pericet-Camara et al. used a commercial drop-on-demand device to make concave microlenses. After the evaporation of the printed solvent, a cavity was left behind due to the dissolving of the polymer substrates, thereby forming a spherically shaped lense.[7] Nevertheless, the spreading of printed droplets makes it difficult to fabricate MLAs having both high fill-factors and low f numbers.[8] In this study, we developed a method for the fabrication of MLAs through IJP on a substrate prepatterned—through microcontact printing (μCP)—with self-assembled monolayers (SAMs)[9] to confine the extension of the droplet. Using this approach, we obtained MLAs possessing finer structural features than could otherwise be achieved.

2 Experiment

The process used for the fabrication of the MLAs is illustrated in Fig. 1. The stamp used for μCP was made of polydimethylsiloxane (PDMS, Dow Corning Sylgard Elastomer 184). A liquid PDMS mixture (silicone elastomer:curing agent=10:1) was poured onto a Si mold presenting relief structures. After baking the mixture at 60°C for 30 min, the solid PDMS was separated from the Si mold. The ink used for μCP was a solution of $1H,1H,2H,2H$-perfluorooctyltrichlorosilane (FOTS, Aldrich) diluted in heptane (1 mM). After absorbing the ink, the stamp was brought into contact with UV/ozone–treated glass substrate to print the FOTS ink onto the substrate following the pattern of the mold. As a result, the surface of the glass substrate presented both hydrophilic (UV/ozone–treated) and hydrophobic (FOTS-treated) regions. The dif-

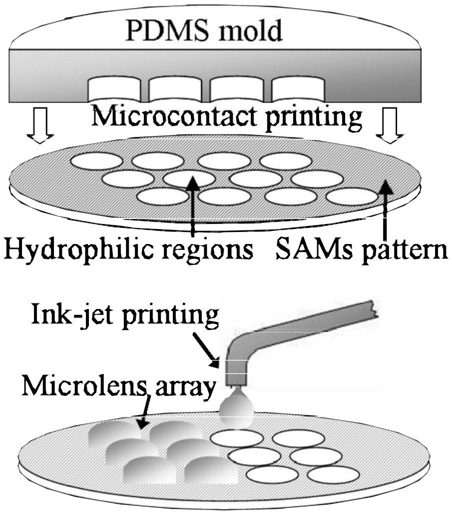

Fig. 1 Representation of the process used for the fabrication of MLAs. The hydrophobic region was defined through μCP of SAMs; the unmodified region remained hydrophilic. After IJP of the prepolymer (NOA65), microlenses formed in the hydrophilic regions; these microlenses were then solidified under irradiation with UV light.

ference in contact angles between the UV/ozone–treated surface and the FOTS-treated surface was greater than 110 deg, i.e., a significant surface energy difference existed between the two types of surface.[10] After depositing the lens material (NOA65, Thorlabs, Inc.) on the substrate through ink-jet printing, the hydrophilic NOA65 molecules were repelled by the FOTS-presenting regions to form convex structures as a result of its surface tension. Last, the convex structures were solidified under irradiation with UV light to form the MLA. The parameters of the lens shape, including the radius of the microlens (r) and the sag-height (h), were measured using an interferometer.

3 Results and Discussion

Figure 2(a) displays the profile of a typical microlens obtained on an alpha-step. The lens diameter fits the pattern of the PDMS stamp very well, indicating that the lens material was indeed repelled by the SAM. The inset to Fig. 2(a) presents the image of an MLA obtained under an optical microscope. Figure 2(b) provides a scanning electron microscopy (SEM) image of an MLA. We conclude that the MLAs had smooth lens surfaces and high levels of uniformity in terms of their shapes. Each lens had a diameter of 100 μm and a spacing of 15 μm—dimensions that fit the cavity of the PDMS mold exactly—implying that precise pattern transfer occurred when using this method.

The inset in Fig. 2(b) displays the focused light spot image of an MLA acquired on a laser beam analyzing system, revealing that each microlens had strong focusing ability. The uniform spot sizes and intensities confirmed the high degree of uniformity of the MLA. The measured spot size of the microlens was 2.58 μm, which is very close to the value of its diffraction limit (2.20 μm).

We used the following formulas to calculate the curvature radius (R), focal length (f'), and f number ($F_{\#}$) of the microlenses:

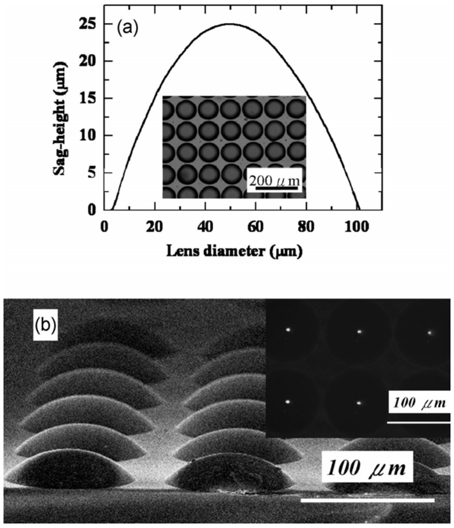

Fig. 2 (a) Profile of a microlens obtained using an alpha-step. The inset shows the image of an MLA obtained using a microscope. (b) A representation of the morphology of an MLA obtained using a scanning electron microscope (SEM). The inset shows the focused light-spot image of the MLA acquired using a laser-beam analyzing system.

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

where n is the refractive index of the lens material (NOA65; $n = 1.52$). For a plano-convex lens, the volume of the lens (V) is a function of R, r, and h; it can be expressed as

$$V = \int_{R-h}^{R} \pi(R^2 - y^2)\mathrm{d}y = \pi h^2\left(R - \frac{h}{3}\right) = \frac{1}{2}\pi h\left(\frac{h^2}{3} + r^2\right). \tag{2}$$

We determined the volume of a microlens in terms of the number of printed droplets and the volume of a single droplet (15 pL in this study). The volume of a single droplet can be controlled by changing the diameter of the jet nozzle or the operating voltage of the piezoelectric device. Figure 3 presents plots of the sag height (h) and f number ($F_{\#}$) of a

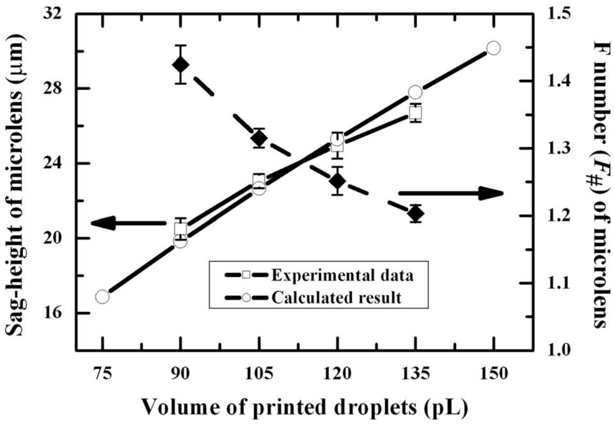

Fig. 3 The sag-height and f-number of the fabricated MLAs plotted against the function of the volume of printed droplets.

microlens with respect to the volume of printed droplets. The sag height increased from 20.5 to 26.7 μm upon increasing the volume from 90 to 135 pL. The measured sag heights matched the calculated values of h very well. This result demonstrates that the shape of a microlens can be determined precisely by controlling the number of printed droplets. The fabricated MLAs had values of $F_{\#}$ ranging from 1.20 to 1.45, revealing that our MLAs were stronger (i.e., smaller values of $F_{\#}$) than those prepared previously on substrates patterned using conventional photolithography approaches ($F_{\#} > 1.5$) (Ref. 11).

Using this proposed method, the surface of the substrate became hydrophobic, thereby reducing the adhesion of the lens material to the substrate. As a result, we obtained MLAs having high fill factors because the SAMs confined to the hydrophilic lens material. Following the patterns of the SAMs (FOTS), the present fill factor of the fabricated MLA was 65%. We suspect that this value could potentially reach 90% if the circle pattern were to be replaced by a rectangular one and if the spacing were as short as 5 μm. Furthermore, because NOA65 is highly transparent and acts as an index-matched material to glass and other plastic substrates, most of the optical loss, such as internal reflections and wave-guiding effects, are eliminated. Most importantly, the fabrication of these MLAs can be performed at room temperature using a procedure that is simpler than those employing traditional lithographic techniques. We anticipate that our new approach could also be integrated into the preparation of flexible devices.

4 Conclusion

We have fabricated self-organized microlens arrays through ink-jet printing on prepatterned substrates presenting self-assembled monolayers. The fabricated MLA featured lenses having a diameter of 100 μm, with f numbers ranging from 1.20 to 1.45. Our proposed fabrication method is simpler than those reported previously using traditional approaches. Most importantly, the entire fabrication process can be performed at room temperature, so the fabricated MLAs have the potential to be integrated into flexible devices.

Acknowledgments

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Jhih-Ping Lu received his MS in industrial engineering from the National Tsing Hua University at Taiwan in 1998. He is now a PhD student in the Department of Photonics and Institute of Electro-optical Engineering, National Chiao Tung University. He is also a process integration engineer in the Panel Integration Division, Display Technology Center of Industrial Technology Research Institute in Taiwan. His work primarily focuses on the display process development of industrial ink-jet printing, especially in microlenses, polymer light-emitting diodes, color filters, organic thin-film transistors, and Ch-LCD.

Wen-Kuei Huang received both MS and PhD degree in optoelectronic engineering from National Chiao-Tung University in 1999 and 2007, respectively. His research interest is the fabrication of optical components. His work primarily focuses on the process development of photovoltaic devices. Now, he is a process integration engineer in Auria Solar, a thin-film solar cell company in Taiwan.

Fang-Chung Chen received a BS and a master's degree in chemistry from National Taiwan University in 1996 and 1998, respectively, and a PhD degree in materials science and engineering from the University of California, Los Angeles (UCLA) in 2003. He was a postdoctoral research associate in the Department of Materials Science and Engineering, UCLA, in 2003. He joined the faculty of the Department of Photonics and Display Institute, National Chiao Tung University, as an assistant professor in 2004. He is currently an associate professor. Professor Chen's research centers on the development of high-performance organic electronics, including polymer light-emitting diodes, plastic solar cells, and organic thin-film transistors.