High fidelity fabrication of microlens arrays by nanoimprint using conformal mold duplication and low-pressure liquid material curing

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The authors present a novel hyperfidelity fabrication method for microlens arrays. The method consists of the steps of (a) fabrication of a sacrificial master mold of a microlens array in a soft polymer by photolithography and thermal reflow, (b) conformal duplication of a daughter mold of complementary patterns in a hard material by dispensing an UV-curable material liquid on top of the polymer mold, planarizing the liquid with a flat quartz substrate, and curing the material, and (c) fabrication of microlens array using the hard daughter mold and nanoimprinting with an UV-curable lens material. This method has several advantages over conventional fabrication methods of microlens arrays including hyperfidelity, low cost, and high throughput. © *2007 American Vacuum Society.* [DOI: 10.1116/1.2713405]

I. INTRODUCTION

Microlens arrays (MLAs) play important roles in many areas of modern technologies, such as sensitivity enhancement of complementary metal-oxide semiconductor imagers, maskless lithography, microcameras, outcoupling enhancement of light-emitting diodes, high-speed interconnection, and stereo display. Previous fabrication methods of microlens arrays include ion doping of planar glass for graded index,[1] thermal reflow of photoresist and pattern transfer by etching,[2] grayscale lithography and pattern transfer,[3] free dropping of curable liquid,[4] and hot embossing using a mold formed by electroplating.[5] These approaches have drawbacks such as process complexity, poor controls in pattern transfer, high pressing pressure, low throughput, and/or high processing temperature. For example, it is difficult to transfer a reflowed photoresist lens pattern into glass by etching with high fidelity due to the etching rate differences between the glass and photoresist. In a hot embossing method, high temperature and high pressure are necessary, which leads to poor pattern transfer due to stress-induced distortion and the thermal expansion coefficient difference. The maskless methods such as printing suffer from low throughput especially for large area MLAs and lack of high fidelity. Table I further summarizes the advantages and disadvantages of previous fabrication methods of MLAs.

In this article, we present a novel fabrication of microlens arrays via novel mold fabrication and nanoimprint technology. The advantages of our approach include room temperature processing, relatively low imprinting pressure, high patterning fidelity, high throughput, and low cost.

II. FABRICATION OF MICROLENS ARRAY BY NANOIMPRINT USING CONFORMAL MOLD DUPLICATION AND LOW-PRESSURE LIQUID MATERIAL CURING

Our approach consists of three key steps: (i) making a master mold with a microlens array in a soft polymer, (ii) conformal duplication of the master mold into a hard material daughter mold, and (iii) patterning the microlens array using a nanoimprint of the hard daughter mold with an UV-curable optical lens material.

A. Microlens array master mold in soft polymer

One effective way to generate the topology needed for microlenses is to thermally reflow photolithography patterned pillars into lens shaped beads. However, due to the viscosity requirement and temperature limitations, the materials good for thermal flowing are soft polymers and poor lens materials. To solve this problem, we do not use the thermal reflowed soft polymer microlens array as the final lens, but as a sacrificial master mold for duplicating a hard NIL daughter mold to be used later for real lens fabrication.

As shown in Fig. 1(a), in making a master MLA mold in a resist, photolithography was used to pattern round disks in photoresist (AZ5214) on a silicon substrate. The thickness of photoresist later determines the height of the microlenses. Then the sample was heated in an oven at 200 °C for 2 h to let the photoresist reflow [Fig. 1(b)]. Due to the surface tension of the molten photoresist, the heating turned the resist disk into lens shape beads on the silicon substrate (the effect of gravity is negligible).

B. Conformal duplication of hard daughter mold from soft polymer master mold

To faithfully duplicate a daughter mold from the master, we used a novel conformal duplication, rather than etching. As shown in Fig. 2(a), first, a 10 nm layer of silicon dioxide was deposited by plasma enhanced chemical vapor deposition (PECVD) on the surface of the polymer master mold.

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TABLE I. Comparison of different methods of fabrication of microlens array.

	Photoresist reflow	Gray-scale photolithograhy	Electroplating	Wet etching	Surface treating	Maskless (print)
Dry etching	High cost, low throughput	High cost, low throughput				
Hot embossing			High cost, low throughput	Hard to control the shape		
Conventional imprint			Hard to duplicate 3D pattern	Hard to duplicate 3D pattern		
Dispensing imprint	Low cost, high throughput			Density, compact lens array		
Without transfer					Low cost, low throughput	Low cost, low throughput

The deposition was done at 250 °C, a temperature that did not cause any distortion of lens shape. The deposition was also conformal, ensuring hyperfidelity of the duplication. Then a quartz plate was glued to the SiO_2 film by dropping an UV-curable liquid with a viscosity of 4 cP between the SiO_2 and the quartz plate, and pressing the plate on the liquid by relatively low pressure (10 psi). The curable liquid flowed and filled the gap between the mold and the quartz plate [Fig. 2(b)]. After curing under UV light [Fig. 2(c)], the curable material has a property close to SiO_2 with a hardness of 0.5 GPa (which can be adjusted by doping silica nanoparticles). The SiO_2 film is then glued to the quartz plate, forming a daughter mold [Fig. 2(d)].

The curable liquid was dropped on the mold using a piezonozzle mounted on a motorized *X*-*Y* stage. We used 200 pL/drop and a density of 80 droplets/mm^2.

After separation a concave mold was formed on the glass substrate, as shown in Fig. 2(d). Then the surface of concave mold was treated by an antisticking monolayer for easy separation in imprinting.

C. Fabrication of micronlens array by NIL using a daughter hard mold

Once a hard daughter mold is made, it can be used to fabricate a microlens array with UV-curable materials by using dispensing NIL again. The process is similar to that described in Sec. II B. As shown in Fig. 3, the UV-curable optical material droplets were dispensed on the concave mold with a density of 50 drops/mm^2 (in order to reduce the residue layer this value can be decreased). Then a glass substrate was pressed on the mold with a pressure of 8 psi, using

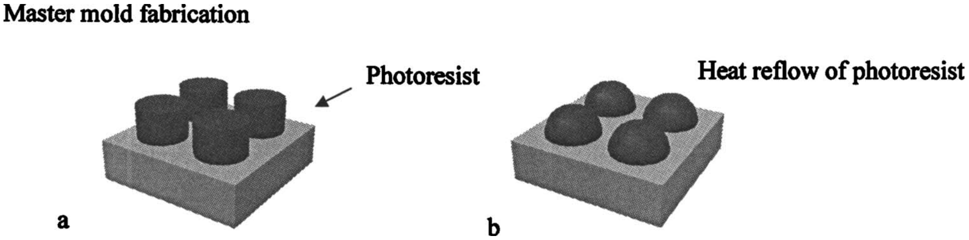

FIG. 1. Master microlens mold fabrication: (a) photolithography of a resist pillar array and (b) thermal reflow of resist to make mother mold.

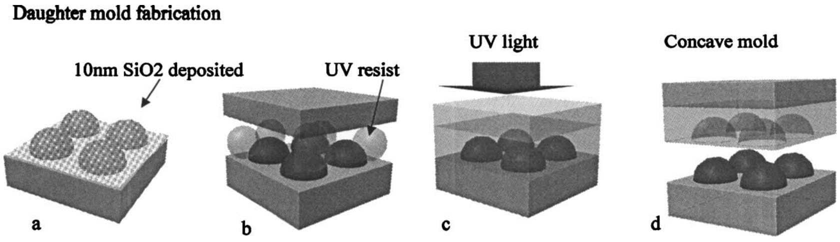

FIG. 2. Daughter mold fabrication: (a) deposit a layer of SiO_2 with PECVD, (b) dispense the UV-curable resist on the reflowed photoresist and imprint a glass substrate, (c) cure the liquid UV resist, and (d) separate the mother mold and the concave daughter mold.

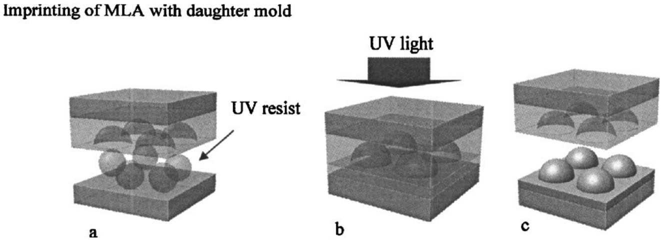

FIG. 3. Fabrication of microlens by dispensing NIL: (a) dispense UV-curable resist on a glass substrate and imprint the concave mold, (b) cure the UV resist, and (c) separate and get the microlens array made by UV resist.

Nanonex imprintor, NX2000, which uses Air Cushion Press, allowing uniform and precise control of the pressure on both the mold and the substrate. After the resist flowed and filled the gap between the mold and the substrate, UV light was used to cure the resist. After separating the mold from the substrate, a microlens array was stuck with the substrate.

III. RESULTS AND DISCUSSIONS

The initial resist pillars made by photolithography (Fig. 4) have significant edge roughness due to poor mask quality, light diffraction, and other noises in the fabrication. But after

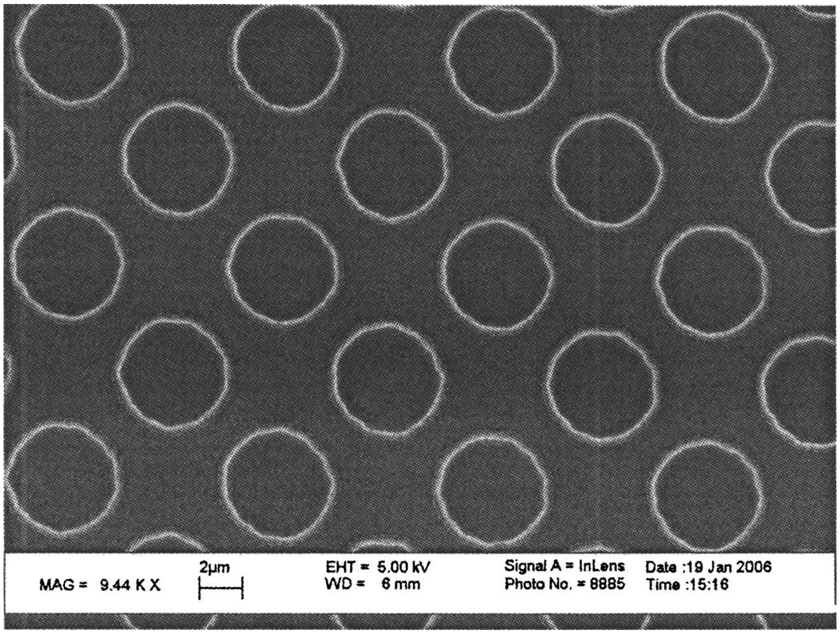

FIG. 4. SEM image of a photoresist pillar array made by photolithography.

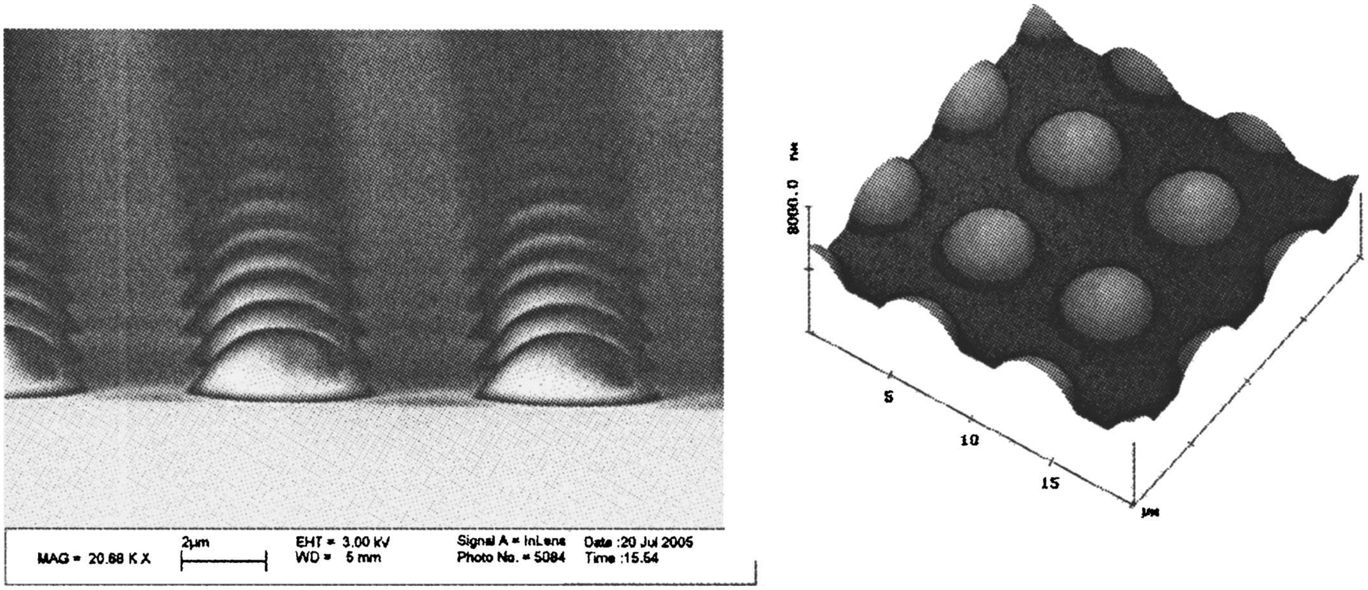

FIG. 5. SEM image and AFM image of reflowed photoresist.

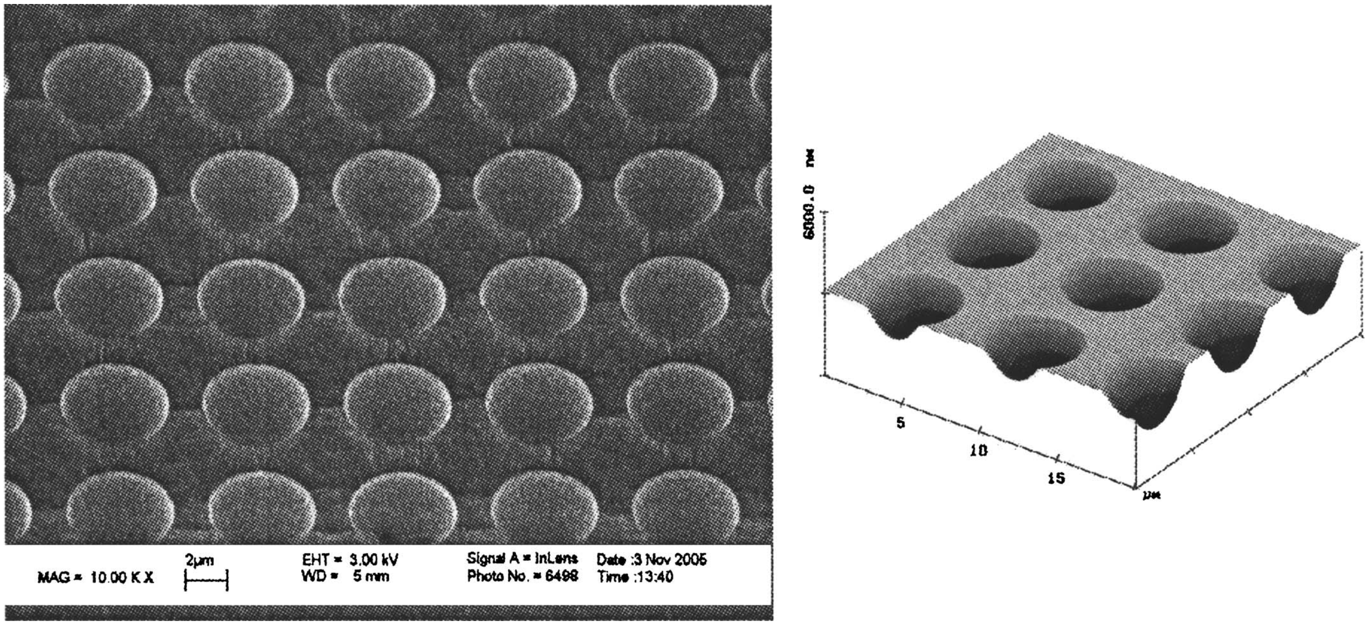

FIG. 6. SEM image and AFM image of the concave mold.

the thermal reflow during the heating, the polymer cylinders became round, and took on a smooth lens shape (Fig. 5). The average diameter of the photoresist pillars is around 5.2 μm and the average height is around 1.75 μm before the reflow. After the photoresist was reflowed, the lens profiles have an average diameter of 5.4 μm and an average height of 2.5 μm. This lens shape is mainly determined by interplay of three surface tensions: the surface tension of (i) molten photoresist, (ii) the substrate, and (iii) the interface between molten photoresist and the substrate.

From the scanning electron microscopy (SEM) and atomic force microscopy (AFM) images of the hard daughter NIL mold duplicated from conformal PECVD deposition (Fig. 6), it can be seen that the shape is well retained and little roughness is introduced in the duplication procedure. AFM measurements showed that after reflow the surface roughness is less than 2 nm—the resolution of AFM. The daughter mold was used for more than 20 times to duplicate MLAs, and no damage was observed.

The SEM and AFM images also showed that the microlens arrays fabricated by nanoimprint using the daughter mold (Fig. 7) have hyperfidelity. From AFM, the curvature radius of the lens shape is around 2.7 μm.

The index of the material used to fabricate MLAs is around 1.5. Given that, a 5.4 μm focal length is estimated in air (for outgoing light), and 8.1 μm is estimated in lens ma-

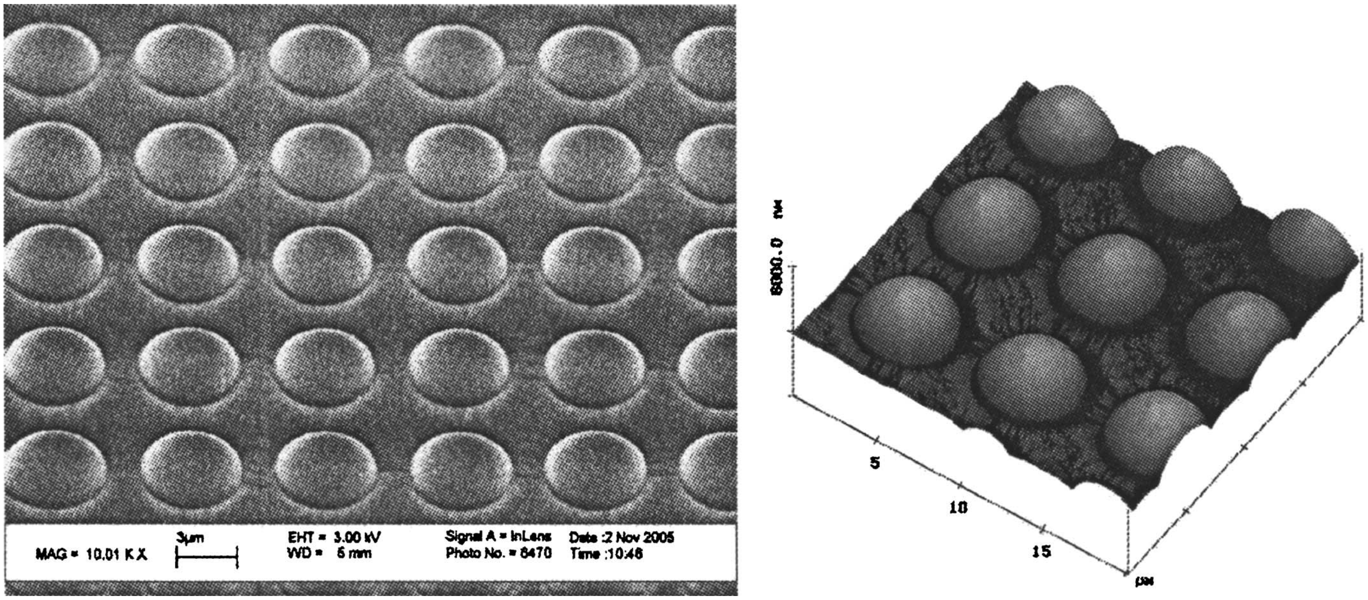

FIG. 7. SEM and AFM images of a microlens array created from the concave mold by using dispensing nanoimprint lithography.

terial (for incoming light). The numerical aperture of these lenses is about 0.3 in air (for outgoing light) and 0.67 in the lens material (for incoming light).

It should be pointed out that the method of making a daughter mold can be used for duplicating from other types of master molds, such as those by wet etching or electroplating methods that allow achievement of MLA profiles with a higher filling factor than the reflow of photoresist method. A mold may be expensive to make, but nanoimprint fabrication can keep each MLA low cost in batch manufacturing.

Another point is that the imprint using low viscosity of UV-curable material allows high fidelity fabrication of many different high aspect ratio structures other than MLAs.

IV. CONCLUSIONS

We demonstrated a novel method to fabricate microlens arrays by using conformal mold duplication and nanoimprint technology with low viscosity UV-curable material. This technology exhibits several advantages, such as it can be carried out in atmosphere and at room temperature (only low pressure is required) there are no air bubbles trapped during the imprint process, and due to the low viscosity of the resist it is a relatively fast process. In conclusion, nanoimprint technology provides a low cost and high throughput fabrication method for microlens arrays.

ACKNOWLEDGMENTS

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[1] I. Iga *et al.*, *Fundamentals of Microoptics* (Academic, London, 1984).
[2] Z. D. Popovic *et al.*, Appl. Opt. **27**, 1281 (1988).
[3] Q. Peng *et al.*, Opt. Lett. **27**, 1720 (2002).
[4] B. P. Keyworth *et al.*, Appl. Opt. **36**, 2198 (1997).
[5] T. Teshima *et al.*, US Patent 6,835,443 (December 28, 2004).