Sequential shrink photolithography for plastic microlens arrays

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Endeavoring to push the boundaries of microfabrication with shrinkable polymers, we have developed a sequential shrink photolithography process. We demonstrate the utility of this approach by rapidly fabricating plastic microlens arrays. First, we create a mask out of the children's toy Shrinky Dinks by simply printing dots using a standard desktop printer. Upon retraction of this pre-stressed thermoplastic sheet, the dots shrink to a fraction of their original size, which we then lithographically transfer onto photoresist-coated commodity shrink wrap film. This shrink film reduces in area by 95% when briefly heated, creating smooth convex photoresist bumps down to 30 μm. Taken together, this sequential shrink process provides a complete process to create microlenses, with an almost 99% reduction in area from the original pattern size. Finally, with a lithography molding step, we emboss these bumps into optical grade plastics such as cyclic olefin copolymer for functional microlens arrays. © *2011 American Institute of Physics*.
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Continual miniaturization of optical and optoelectronic devices drives the need for increasingly low cost, smaller form factor, and monolithic integration of versatile components such as microlens arrays (MLAs). Conventional micromachining to fabricate MLAs is limited in its scalability, with large area production becoming prohibitively expensive.[1] As such, there is a corresponding interest in moving from glass to polymer MLAs (Ref. 2). A myriad of methods to fabricate MLAs in polymers have been demonstrated and include such innovative techniques as photoresist reflow,[3,4] laser ablation,[5] and molding UV photocurable polymers from elastomer molds.[6] Thermal photoresist reflow leverages surface tension to create hemispherical shaped lenses from melted micropatterned photoresist.[3] While this is a pervasive method to create optical molds, this approach has a limited geometry that requires a certain thickness of photoresist. When the deposited photoresist thickness is too thin, significant deviations from a rounded shape ensues; therefore, lenses with NA < 0.15 are not possible.[2] Laser ablation, for example with an excimer laser, can be used to create lenses in plastics such as polycarbonate.[5] While this is an attractive direct write process, it is a slow serial process that requires precision instrumentation. On the other extreme, molding epoxies from elastomer molds such as polydimethylsiloxane (PDMS) allows for low cost replicate molding, but still begs for the creation of the original master.[6,7]

Therefore, the ability to create large arrays of low cost microlens in a plastic substrate from scratch with acceptable optical properties remains a challenge.[8] Photoresist, for example, has a relatively large absorption and is, therefore, not ideal for many applications.[4] Transferring such features into optical grade plastic requires processes such hot embossing, which necessitates both an electro-deposition process to create the metallic mold as well as expensive capital embossing equipment;[9] this approach is, therefore, not amenable to prototyping and/or low volume production.[8]

This is a demonstration of integrating photolithography with the shrink process of patterning at a larger scale and then shrinking to create rounded, high aspect ratio structures.[10] As in a previous study,[11] the ability illustrated here to shrink photoresist features suggests that we can beat the heretofore inherent optical resolution of "top-down" processing with an extra >20 x improvement in size reduction. In addition to demonstrating the compatibility of this process with photolithography, we obviate the need for an expensive chrome mask and a cleanroom altogether. Moreover, this a demonstration of using a "Shrinky-Dink" mask printed with a standard laser jet printer. Taken together, this sequential shrink provides a complete process to create features, with a 99% reduction in area from the original pattern size. This approach also suggests that a more elaborate master-slave sequences with additional sequential size reductions should be possible.

First, we create a mask by using a standard desktop laserjet printer on a polystyrene (PS) sheet known as the children's toy Shrinky Dink (K & B Innovations). Then, using this resultant "Shrinky Dink" mask and a homemade UV flood light, we cross-link positive photoresist on another shrink film. This allows us to rapidly achieve 2 sequential shrinks, with the first mask shrinking by approximately 60% in surface area and the second "wafer-substitute" shrinking an additional 95% in surface area [Figure 1]. This second wafer-substitute that we coat with photoresist is a polyolefin (PO) (D955, 1.5 mil, Sealed Air), available as commodity shrink-wrap film. The resultant small and smooth MLAs that can be either used directly as lenses [data not shown] or subsequently molded into polymers or other plastics, including the optically attractive cyclic olefin copolymer (COC). COC is an attractive plastic because it has higher optical transmission ($>90\%$) than the plastics commonly used for microlenses, such as polymethylmethacrylate (PMMA) or PS.[2] COC is available in sheets (Topas® 8007D-61, 8 mil, Advanced Polymer) that are easy to emboss with PDMS masters. While soft lithography has

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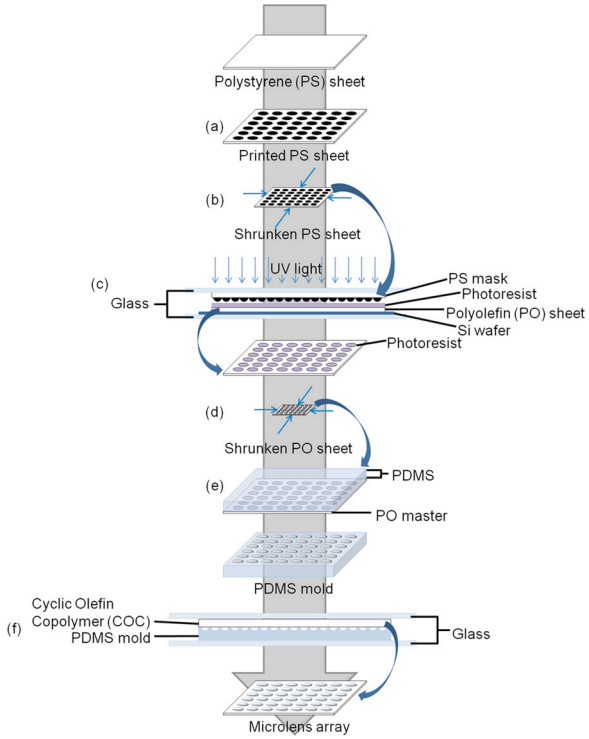


FIG. 1. (Color online) Process flow: (a) Pattern was printed on PS sheet with laser printer. (b) PS sheet was shrunk with heat gun. (c) PS sheet was used as a mask to transfer pattern to photoresist spun onto a PO sheet. (d) PO was shrunk in oven. (e) PO was molded with PDMS. (f) COC was clamped to the PDMS mold, thus conforming to it when heated, producing a MLA.

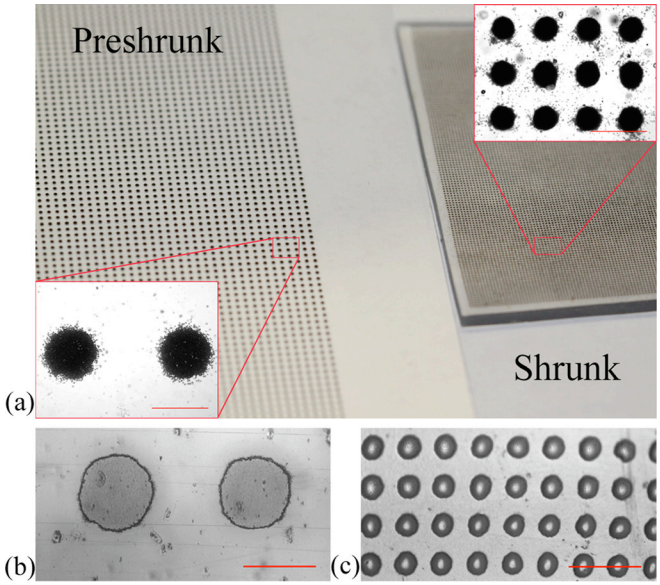


FIG. 2. (Color online) Images of PS mask and PO mold: (a) Macro image of preshrunk and shrunk PS mask. Left inset ink spots on preshrunk PS. Right inset ink spots on shrunk PS. Scale bar = 500 μm. (b) Photoresist spots on preshrunk PO. Scale bar = 200 μm. (c) Photoresist spots on shrunk PO. Scale bar = 200 μm.

been used to create MLAs as well as to serve as molds for epoxies, we demonstrate that they can be used to emboss the MLA into a hard plastic, to yield high fidelity lenses in COC.[6] Demonstration that PDMS can be used to emboss hard plastics has recently been shown for a variety of high aspect structures, and we extend it here for microlenses.[12]

The dot pattern created in AUTOCAD was printed via laser jet printer (Hewlett Packard CP2025) onto a Shrinky Dink polystyrene sheet (Figure 2(a)). When heated briefly with a heat gun (Steinel HL 1810 S), the toner ink coalesces and becomes thicker, blocking out the UV light, and serving as an effective mask for positive photoresist (Figure 2(b)). The positive photoresist (Shipley, 1808) was spin coated onto the PO for 45 s at 4000 rpm to create a 1 μm thick film. For the soft bake, the wafer was heated for 1 min at 115 °C on a hot plate. Using the aforementioned mask, the photoresist was exposed for 20 s with a UV flood lamp and developed (Microposit MF-321). The PO was shrunk in an oven beginning at 115 °C. The temperature was held there for 5 min before ramping to 135 °C. Again, the temperature was held for 5 min before being ramped to 155 °C. The photoresist was then reflowed by heating on a hot plate set at 150 °C for 15 min and then slowly cooling on the hot plate, roughly 10 °C/min.[13] A PDMS mold was made from the shrunk photoresist pattern. COC plastic was molded into lenses by constraining them against the PDMS mold with a glass slide (75 mm × 75 mm, Fisher) sandwich and heating at 160 °C for 10 min in an oven. Lenses of various sizes can thus be fabricated by varying the pattern and the photoresist thickness.

We characterized the lenses by scanning electron micrograph (SEM) (Figure 3(a)), optical profilometer (Figure 3(b)), and atomic force microscopy (AFM). Interestingly, the RMS roughness of our lenses as determined by AFM of ~14 nm over a 100 μm^2 is better than even optical molds created by high precision serial processes such as diamond turning.[14] If we consider the visible spectrum from 350 nm to 750 nm, the measured roughness is only 1/28 to 1/54 of the focused wavelength and should contribute little to wave front distortion or scatter. For this lens, the focal length was determined to be 74 μm.[15]

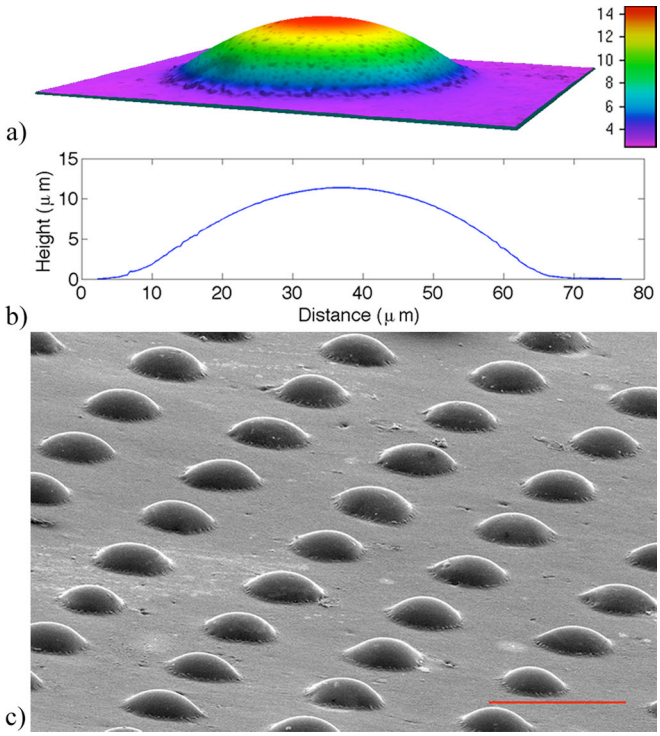
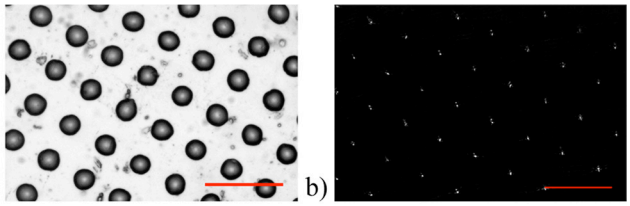
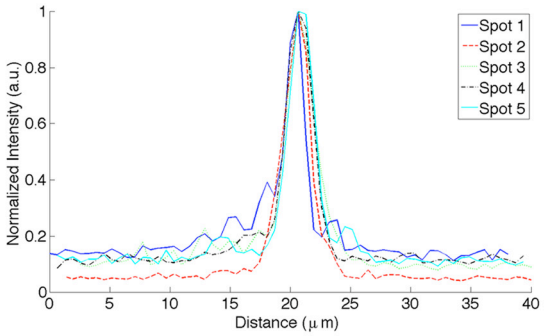


FIG. 3. (Color online) (a) 3D image of lens mold by optical profilometer (μm). (b) Example of microlens mold profile. (c) SEM image of microlens. Scale bar = 100 μm.

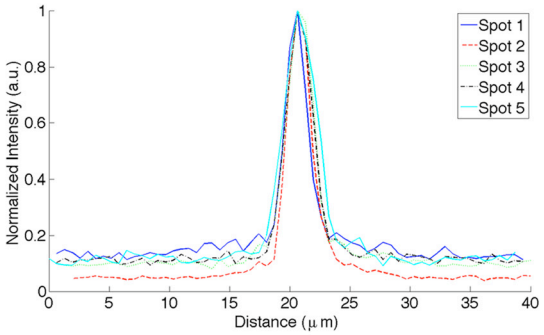
a) b)



c)



d)



e)

	Beam Width (μm)		Numerical Aperture	
	x	y	x	y
Average of Spots	3.431	2.885	0.133	0.152
Standard Deviation	0.357	0.102	0.010	0.005

FIG. 4. (Color online) COC MLA focus spots evaluation: (a) Microscope image of lens. (b) Image of focus spots. (c) Profiles of intensity of five sample focus spots along the x axis. (d) Along the y axis. (e) Table with beam width and numerical aperture data. Scale bar = 200 μm.

To determine the functionality of the MLA, we determined the full width half max (FWHM) of the focus spots in two perpendicular directions (in both the x and y) of several lenses (Figure 4(a)) out of the array. To do this, the MLA was used to focus light from a 660 nm laser onto a microscope objective. Image stacks were captured by scanning the microscope objective along the optical axis through the focal plane of the MLA in 10 μm steps. Images were analyzed by custom software coded in MATLAB.

Z-stacked images (step size = 10 μm) of the focal spots were imaged onto the camera (Hammatsu Orca) using the microscope objective (10x) (Figure 4(b)). The in-focus image plane was selected visually and the image segmented in MATLAB. The brightest pixel in each individual focal spot was selected for analysis. Figures 4(c) and 4(d) show the intensity profile along the x and y directions, respectively. We did this because there are slight variations in the percentage shrinkage in the x and y directions. As a result, we measured both the long axis and short axis of the lenses and found that for the 70 μm MLA, the average x diameter was 70.8 $\pm$ 2.1 μm and the average y was 64.9 $\pm$ 2.6 μm (n = 20). This was most likely due to the non-uniform shrinking of the PO substrate. Finally, the FWHM was calculated as the width of the intensity profile at Normalized Intensity = 0.5.

In summary, we have demonstrated the compatibility of standard photolithography with shrink film size reduction to achieve 99% reduction in area from original pattern size. Using this approach and a sequential shrinking, we achieved a MLA in the optical grade plastic COC. While there are slight variations in the MLA, in part because we use a Shrinky Dink mask and in part due to the imperfections of the commodity shrink wrap film, this demonstration of such an approach opens the potential of shrinking photoresist to beat the inherent limit of resolution of "top-down" fabrication approaches.

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