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Rapid fabrication of various molds for polymer lens arrays

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A one-step method enables the fabrication of molds with concave lens array patterns, which can be used for the replication of polymer lens arrays.

In recent years, polymer lens array devices have been used widely in various fields (e.g., in optical communication systems and portable optoelectronic systems). To date, numerous replication methods have been proposed for the production of polymer lens arrays on millimeter or micrometer scales, such as injection molding, hot embossing, UV molding, and soft replica molding.

In polymer replication processes, however, various molds containing different concave lens array patterns are required. Hence, the development of a low-cost, high-efficiency method for the fabrication of various lens array molds is essential. Many precision-manufacturing technologies for preparing lens array molds with different dimensions have been investigated, such as focused ion beam technology,[1] 3D diffuser lithography,[2] isotropic[3] etching of glass masters,[4] combined thermal reflow and electroforming, and ultra-precision diamond milling.[5] However, the fabrication techniques for molds with concave lens arrays are complex, time-consuming, and require expensive equipment.

Here, we present a low-cost method for the rapid fabrication of various molds for polymer lens arrays.[6] Our method involves an ultrasonic vibration embossing process in which a polymer substrate comes under pressure from a small steel-ball array. Only one embossing step, in which a concave lens array is directly fabricated on a polymer substrate, is required. The total cycle time is less than 20s. Additionally, the diameter and depth of the embossed concave lens arrays on the surface of the polymer substrate can be changed and controlled by adjusting the processing conditions of the ultrasonic vibration embossing process, enabling the fabrication of various lens array molds with different diameters and depths. Further, polymer substrates with different concave lens arrays can be used as molds for the replication of polymer lens arrays in the polydimethylsiloxane (PDMS) casting process.

Our fabrication steps for the creation of polymer lens arrays are illustrated in Figure 1. The equipment that we used for this purpose primarily consisted of a commercial ultrasonic welder and an embossing horn with a pneumatic cylinder. The small steel balls that we used to emboss

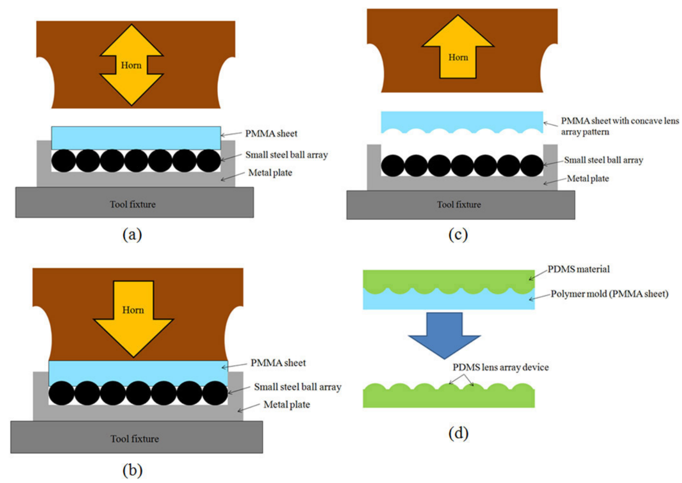

Figure 1. *Schematic showing the fabrication steps of the polymer mold and polymer lens array. Pressure is applied to a sheet of poly(methyl methacrylate)—PMMA—using an embossing horn, and an array of small steel balls (with a diameter of 2mm $\pm$ 0.08μm) leave a series of semi-spherical indentations in the sheet. The sheet is then used as a polymer mold in the creation of a polydimethylsiloxane (PDMS) lens array. (a) The material preparation stage. (b) The ultrasonic vibration (heating) and embossing stage. (c) The demolding stage. (d) Replication of the polymer lens array using the PDMS casting process.*

the arrays had a diameter of 2mm $\pm$ 0.08μm and a surface roughness of 0.01μm.

In the first experiment, we varied the ultrasonic vibration time from 0.5 to 3.5s while maintaining the embossing pressure and hold time at 4kg/cm^2 and 8s, respectively. Our experimental results indicate that the diameter and depth of the embossed concave lens arrays increased dramatically when the ultrasonic vibration time was increased. A possible explanation for this result is that the surface temperature of the poly(methyl methacrylate) (PMMA) substrate markedly increases with ultrasonic vibration time, resulting in more ultrasonic energy being absorbed by the polymer material (which therefore softens or melts).

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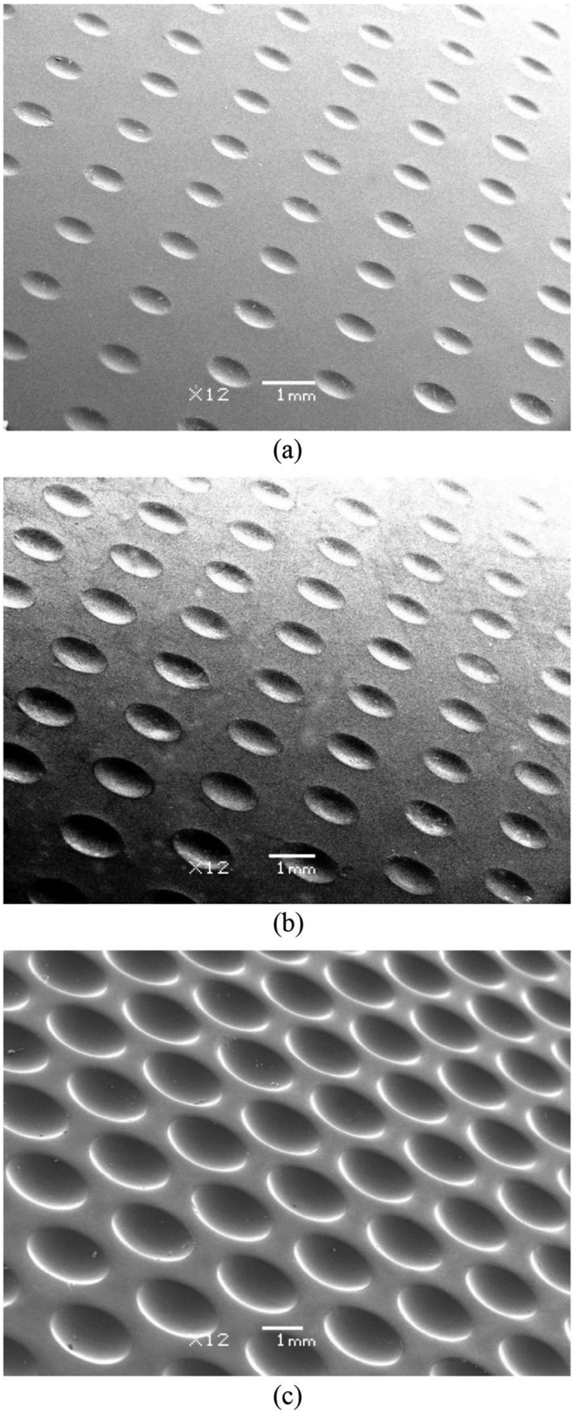

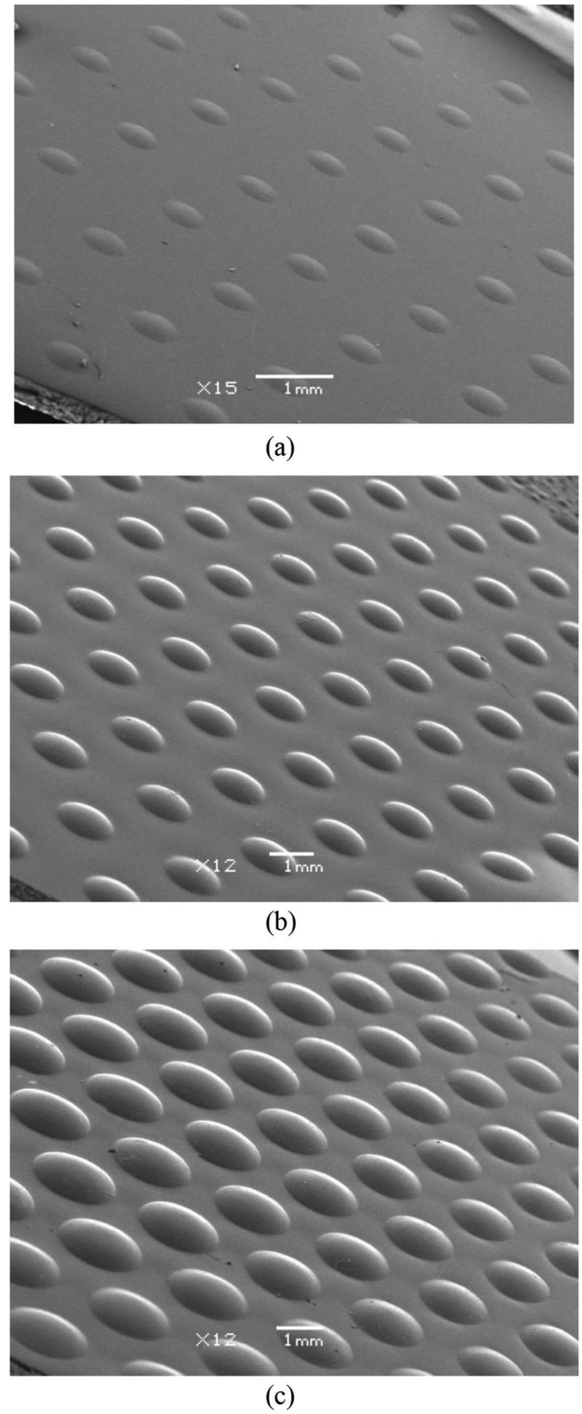

Figure 2. *Scanning electron microscope images of three molds with different concave lens array patterns, achieved under various ultrasonic vibration times of (a) 0.5, (b) 1.5, and (c) 3.5s (with a fixed embossing pressure of 4kg/cm*^{2} *and embossing hold time of 8s).*

Figure 3. *Three types of convex PDMS lens arrays, produced by using the molds shown in (a) Figure 2(a), (b) Figure 2(b), and (c) Figure 2(c).*

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The diameter and depth of the embossed concave lens array is thus substantially increased. Figure 2 presents scanning electron microscope images of the embossed concave lens array produced using ultrasonic vibration times of 0.5, 1.5, and 3.5s.

In our second experiment, we varied the embossing pressure from 3 to 6kg/cm^2 and maintained the ultrasonic vibration time and embossing hold time at 1.5 and 8s, respectively. Our results suggest that a higher applied embossing pressure results in a higher volume of the small steel-ball array being pressed into the PMMA sheet, thereby increasing the average diameter and depth of the embossed concave lens array.

Finally, we varied the embossing hold time from 4 to 16s while fixing the ultrasonic vibration time and embossing pressure at 1.5s and 4kg/cm^2, respectively. An increase in embossing hold time—from 4 to 12s—resulted in a small increase in the diameter and depth of the embossed concave lens array. When the embossing hold time exceeded 12s, we found that the surface temperature of the PMMA sheet was lower than the glass-transition temperature of PMMA. This parameter had no effect on the diameter and depth of the embossed concave lens array, however.

After the PMMA sheets with embossed concave lens arrays had been produced, we cast a liquid PDMS mixture onto them. We then baked the sheets at 75°C for 15min, after which the solidified PDMS material could be easily stripped from the PMMA sheet. We thus obtained a convex PDMS lens array device. Figure 3 shows the three types of convex PDMS lens arrays produced using various molds (i.e., those shown in Figure 2). These images suggest that the replication quality of the PDMS lens produced from the mold was favorable.

In summary, we have reported and demonstrated a one-step method for the fabrication of molds with concave lens array patterns, which can be used for the replication of polymer lens arrays. By adjusting the processing conditions of the ultrasonic vibration embossing process, we fabricated various molds with different concave lens-array patterns. Using these molds, we were able to replicate a range of polymer lens arrays with different shapes. In the next stage of our work, we will investigate the application of this technology for the production of large-area polymer lens arrays for optical systems.

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