Available online at www.sciencedirect.com
SCIENCE DIRECT®

Microelectronic Engineering 83 (2006) 471–475

MICROELECTRONIC ENGINEERING

www.elsevier.com/locate/mee

Fabrication of various curved relief structures through concave surface forming and soft replica molding

Teng-Kai Shih [a,*], Chia-Fu Chen [a], Jeng-Rong Ho [b], Fang-Tzu Chuang [a]

[a] *Department of Materials Science and Engineering, National Chiao Tung University, 1001 Ta Hsueh Road, Hsinchu, Taiwan 300, ROC*
[b] *Graduate Institute of Opto-mechatronic Engineering, National Chung Cheng University, Taiwan, ROC*

Received 13 September 2005; accepted 21 November 2005
Available online 13 December 2005

Abstract

In this case, our groups presented various optical structures through the presented method, involving concave surface forming and soft replica molding. The method of concave surface forming is mainly for the fabrication of concave surface. The method of soft replica molding is mainly for the fabrication of replica. Concave and convex relief structures, including circular curved relief structures, convex relief structures with platform structures on the top, refractive beam-shaping elements, these structures with dual curvatures and asymmetric structures, can be easily made through the presented method, respectively. All processes of manufacture are in several simple steps without multistep optical lithography and complex masks.

Keywords: Soft replica molding; Concave surface forming; Curved relief structures

1. Introduction

Continuous relief structures, applied usually in micro-optical technology, such as micro-lens, have been developed for a long time. The curved relief structure is especially difficult to be fabricated through traditional optical lithography. Different technologies have been developed to form curved relief structures, including surface tension [1], gray mask photolithography [2], and multistep optical lithography [3]. Simple spherical shapes can usually be fabricated by surface tension. However, non-spherical or complex structures are limited. Hence, most of these technologies involve multistep optical lithography or the fabrication of complex mask so that it is difficult to cut the cost of fabrication of curved relief structures. With fast development of soft lithography technology, this can reduce effectively time and cost of optical lithography. Soft lithography uses usually the rubber material, PDMS (polydimethylsiloxane), acted as a main tool of lithography. PDMS has some potential characters, including low surface energy, thermal curing property, optical transparency down to about 300 nm, soft and deformable nature, and surface treatment by plasma. Therefore, a lot of skills of soft lithography are presented, including micro-contact printing, replica molding, micromolding in capillaries, solvent-assisted micromolding, and so on [4].

Here, we presented a new method, connected with soft replica molding and concave surface forming, can change from two-dimension pattern to three-dimension structure. The method of soft replica molding originated from replica molding. In brief, replica molding is by casting the liquid prepolymer of an elastomer against a rigid master that has a patterned relief structure in its surface. However, soft replica molding differs from replica molding in what casts the liquid prepolymer of an elastomer against an original PDMS master that produces from replica molding. But the original rigid master still needs the optical lithography. Hence, the method of concave surface forming, using the viscosity of a liquid polymer suspended on the hollow hole

* Corresponding author. Tel.: +886 3 5712121x55346; fax: +886 3 5724727.
E-mail address: lifish20@yahoo.com.tw (T.-K. Shih).

0167-9317/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.mee.2005.11.011

in substrate, can substitute for the process of optical lithography. Because the weight of a polymeric film was suspended on a pedestal, the concave surface can be produced. Compared with previous lithography, this method can avoid the complex mask and mulistep optical lithography. Another advantage is that both of the concave and convex polymer structures can be fabricated at same time through soft replica molding, respectively.

2. Fabrication method

Referring to the schematic diagram depicted in Fig. 1, steps for fabricating elastomeric molds and curved relief structures are described as the following:

I. The footprint with designed shape and size is defined on a metallic mask through which the excimer laser writes the footprint directly onto a PC (polycarbonate) plate. By monitoring the power intensity and number of laser shots, depth of the holes drilled by the excimer laser can be well controlled. Fig. 1(a) shows the resultant PC plate with micro holes that serves as the pedestal in the next step.

II. Then, a thin liquid PMMA film is coated on the PC plate and is provided the reasonable thickness through spin coating. As the liquid PMMA is rapidly spreading out, due to its own weight and viscosity. The PMMA film suspended with special curvature on the pedestals is formed on the hole. The schematic diagram is shown in Fig. 1(b). The effect of the liquid surface tension can maintain high-quality surface. After baking at 60 °C for 5 min, the liquid film is solidified and stuck fixedly on the PC plate.

III. A soft PDMS mold with convex patterns is formed by pouring liquid PDMS that mixes PDMS-Sylgard silicone elastomer and curing agent with the weight ratio of 10–1 onto the PMMA film and baked at 60 °C for 20 min. The solidified PDMS mold can be easily stripped from the solid PMMA film, due to low surface energy. The resulting convex PDMS mold is shown in Fig. 1(c).

IV. A concave soft mold can be fabricated by pouring the PDMS liquid mixture on the surface of convex PDMS mold in Fig. 1(d). To make sure both of the concave and convex PDMS mold can be separated after baking, the weight ratio of the silicone elastomer and the curing agent for the concave mold should be different from that for the convex mold. In this study, the ratio for the concave mold is set as 5–1.

V. As shown in Fig. 1(e), both of the concave and convex polymeric structures can be fabricated by casting the polymeric liquid in the corresponding convex and concave molds, respectively.

3. Results and discussion

Pulsed eximer laser through metallic mask can easily creates a simple two-dimension holes, such as circular or square pattern. Therefore, these depths of holes also can be controlled through number of laser shots. As the depth of the hole is deeper than concave surface that is formed through concave surface forming. Complete structures were not limited by the contours on treated substrate. Hence, the array of circular curved relief structures with the diameter of 200 μm is shown in Fig. 2(a). These circular structures can regard as micro-optical elements, microlenses. The profile of a single structure by α-step is shown in Fig. 2(b). This profile seems to be non-spherical shape. After measuring by atomic force microscopy, the root mean square surface roughness was less than 10 nm. Hence, a high-quality, non-spherical profile can easily be fabricated through this method. However, the depth of a hole is shallower than concave surface. Concave structures on the bottom were limited by the contours on treated substrate. And the bottom of the spin-coated liquid film is able to touch the bottom of hole. Hence, a 4×4 convex relief structures with platform structures on the top array is shown in Fig. 3(a). The height of this structure is about 8 μm and the width of a platform is about 100 μm that is shown in Fig. 3(b). This structure connects with refractive and one-order diffractive microoptical element, applied in

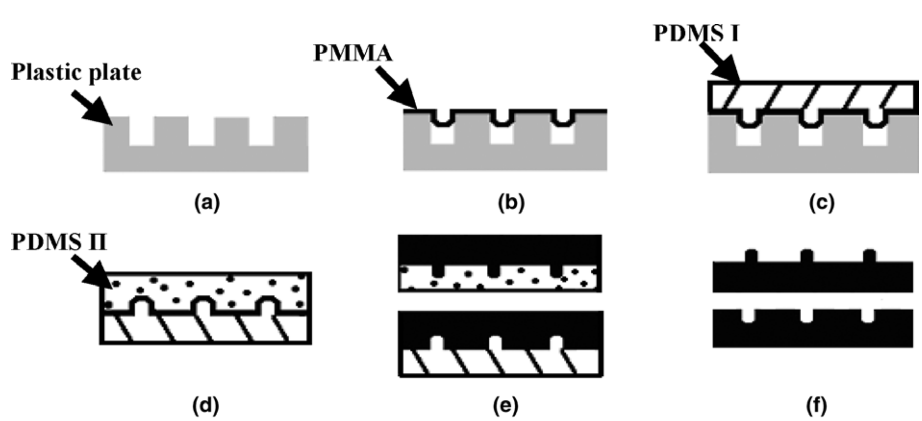


Fig. 1. Schematic showing the steps in fabrication of various curved relief structures.

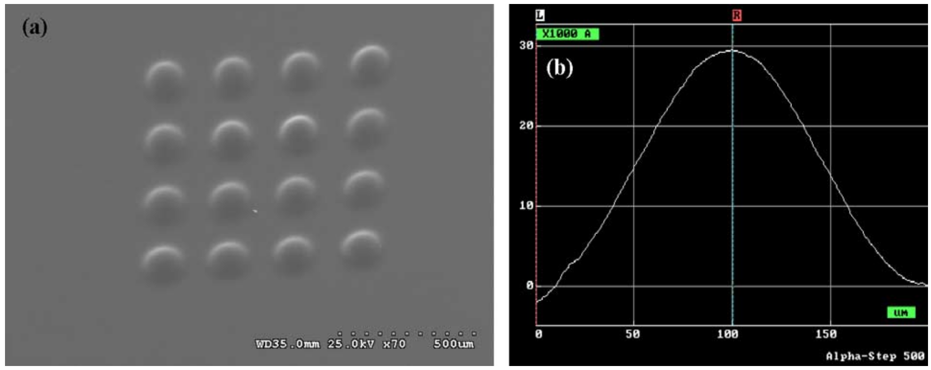


Fig. 2. (a) An SEM image of a circular curved relief structures array and (b) the profile of a single circular curved relief structure by α-step.

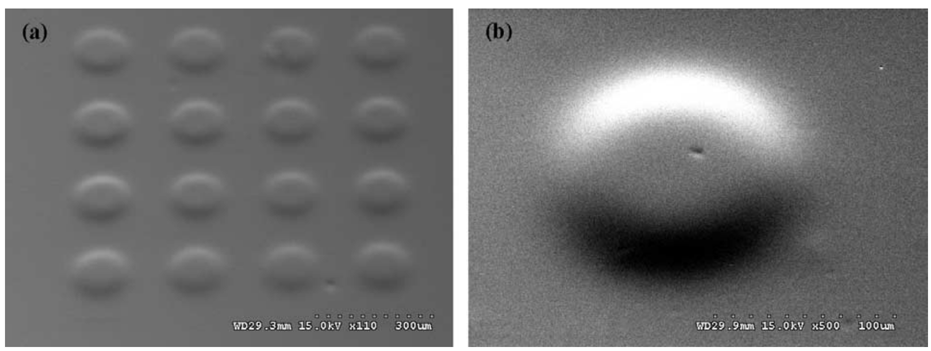


Fig. 3. An SEM image of a platform structure on the top with convex relief structure (a) a patterned array and (b) a single pattern.

optical sensors. Controlled the width of the platform, the size of a focused spot can be easily determined.

The depth of the concave surface depends mainly on both factors: the thickness of a liquid film and the width of a hole. The reasonable thickness of a film can be adjusted through spin coating. As the thickness of a film is gradually becoming thinner, the depth of a concave surface reduces. As the width of a hole is gradually decreasing, the depth of concave surface also reduces. Hence, characters of the curved relief structures can be controlled.

In order to create some particular micro-optical elements, the contours on treated substrate can be used. The contours are fabricated through a mask with a simple pattern by eximer laser. A refractive beam-shaping element, a microlens with dual curvatures and the asymmetric structures were considered. Usually, a refractive beam-shaping element with a moth eye pattern is used for antireflection on top [5]. For the popular fabrication technologies this is challenging because it has to generate a global surface profile of small spatial frequency but relatively large depth superposed with a profile of high spatial frequency but small depth [5]. However, for the new method this is simple because the beam-shaping element can easily be fabricated with a simple two-dimension hole. A mask with a circular pattern is only used. First, a circular hole was fabricated on the plastic plate. Then, moved the reasonable distance from the original location and bombarded again the plastic plate. The reasonable distance is approximately the diameter of a circular pattern. Finally, the contours on treated substrate are created. Hence, the resulting structure is shown in Fig. 4(a). Although the SEM image was shown that both of the curved structures were separated. An optical photography with a defocus image can find this face that they were connected with each other and regard as a beam-shaping element. The resulting image is presented in Fig. 4(b). The phenomenon of Rayleigh criterion is similar to this optical photography. The Rayleigh criterion is the generally accepted criterion for the minimum resolvable detail. In order to fabricate another structure with dual curvatures, the contours with concentric squares composed of the outer square and the inter square on treated substrate were considered. The sided length of an outer square is bigger than the inter square. And the depth of an outer square is shallower than the inter square. Hence, both different widths of these holes can produce the structure with dual curvatures. Hence, the resulting structure is shown in Fig. 5(a). This structure should have the bifocal lengths, applied in focusing laser light onto two separate planes on dual-layer disks or for multiple-layer optical tweezers configurations [6]. Besides, the asymmetric structures, including both of meniscus and circular structures, also were fabricated through the presented method. The resulting structure is shown in Fig. 5(b). The asymmetric structures are very difficult to fabricate by using traditional photolithography. Usually, an expensive gray scale mask is used to fabricate such a three-dimensional structure.

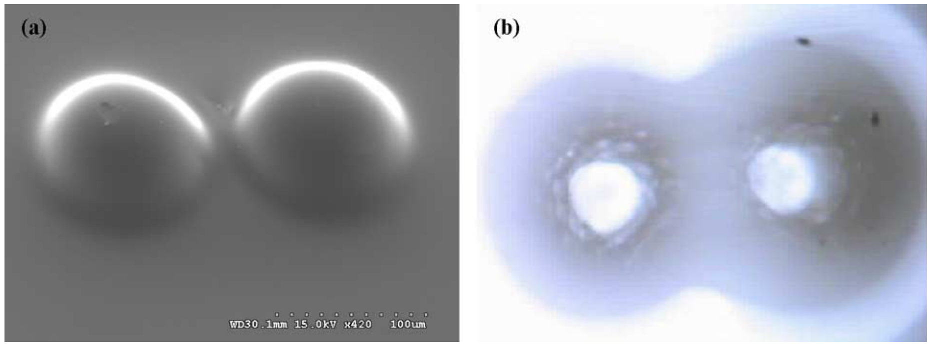


Fig. 4. (a) An SEM image of a refractive beam-shaping element and (b) an optical photography with a defocus distance for the beam-shaping element.

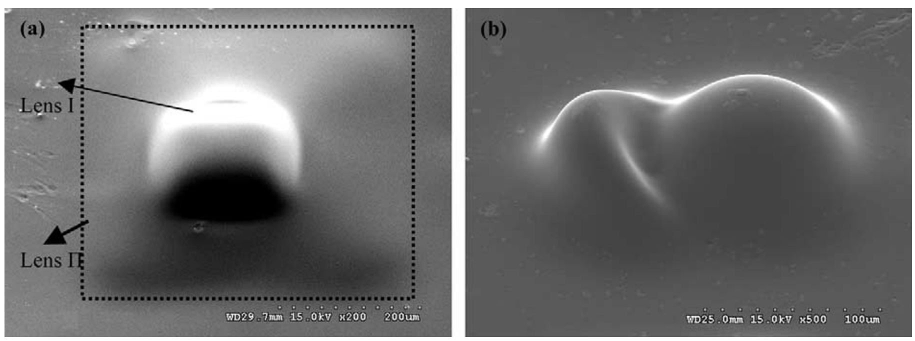
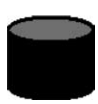
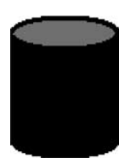


Fig. 5. The SEM image (a) the structure with dual curvatures and (b) an asymmetric structure.

Table 1
The summary of different optical elements and the contours on treated substrate

	A convex relief structure with the platform structure on the top	The circular curved relief structure	The beam-shaping structure	The structure with dual curvatures	The asymmetric structure
The contours on treated substrate					
Different optical elements					

For this case, the contours were also created through a mask with a circular pattern. First, a circular hole was still fabricated on the plastic plate. Then, moved the distance within a quarter of the diameter of a circular pattern from the original location and bombarded again the plastic plate. Finally, the contours on treated substrate were created.

In this paper, our groups presented various optical structures through the presented method. To give a summary of these structures, Table 1 is shown.

4. Conclusion

A fabricated method, connecting with soft replica molding and concave surface forming, was presented. Five kinds of microoptical elements can be presented in this case, inducing circular curved relief structures, convex relief structures with platform structures on the top, refractive beam-shaping elements, these structures with dual curvatures and asymmetric structures. On the contrary, these concave structures can be also fabricated. But our groups were not presented them in this paper. These curved relief structures have good surface and non-spherical shape. All processes of manufacture are in several simple steps without multistep optical lithography and complex masks. Further research is underway creating more and more complex optical element through the ideal contours on treated substrate.

Acknowledgements

This work was supported by the National Science Council (series no. NSC 94-2216-E-009-014) of Taiwan.

References

[1] H. Yang, C.K. Chao, C.P. Lin, S.C. Shen, J. Micromech. Microeng. 14 (2004) 277–282.
[2] J. Yao, J. Su, J. Du, Z. Hang, F. Gao, Y. Guo, Z. Cui, Microelectronic Eng. 53 (2000) 531–534.
[3] W. Daschner, P. Long, R. Stein, C. Wu, S.H. Lee, Appl. Opt. 36 (1997) 4675–4680.
[4] Y. Xia, G.M. Whitesides, Angew. Chem., Int. Ed. 37 (1998) 550–575.
[5] L.C. Witting, T. Clausnitzer, E.B. Kley, A. Tünnermann, Proc. of SPIE 5183 (2003) 109–115.
[6] H.W. Choi, E. Gu, C. Liu, J.M. Girkin, M.D. Dawson, J. Appl. Phys. 97 (2005) 063101.