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Investigation of microlens mold fabricated by focused ion beam technology

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Abstract

A novel fabrication method of microlens mold, focused ion beam (FIB) milling, is presented in this paper. Substrates with different materials, copper, nickel, and bulk silicon, were used in order to compare their milling quality. Two-dimensional profiles and surface roughness of the fabricated molds were measured using a laser interferometer. Finally, the mold was used for hot embossing replication. The surface roughness (R_a value) of the replica is about 8 nm, and the profile is neat and symmetric. Measured sizes of the replica coincide well with that of the design.

Keywords: Microlens mold; FIB milling; Hot embossing; Replication

1. Introduction

Conventional fabrication methods of molding for microlens and optical components are lithography patterning and electroplating [1–6]. Fabrication error is large due to accumulated error during many procedures. A novel micromachining method for microlens molding, focused ion beam milling, is presented in this paper. Compared with conventional methods, it has the following advantages:

- it is a one-step machining, and no other procedures are needed, therefore manufacturing error is less than that of the conventional methods;
- the material of the mold can be glass, silicon, metal or other non-metal;
- machining accuracy can be controlled easier using computer programming during the milling process.

Substrates with different materials, copper, nickel and bulk silicon, were used to compare their milling

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quality. Experimental results of the replication by hot embossing for the microlens are presented in this paper.

2. Mold microfabrication using FIB milling

The milling experiments were carried out using our focused ion beam (FIB) machine (Micrion 9500EX) with the liquid gallium ion source integrated with scanning electron microscopy (SEM), energy dispersion X-ray spectrometry (EDX) facilities and gas-assisted etching (GAE) functions. This equipment uses a focused Ga^+ ion beam with energy between 5 and 50 keV, a probe current between 4 pA and 19.7 nA and a beam-limiting aperture size between 25 and 350 μm. For the smallest beam currents, the beam can be focused down to 7 nm in diameter at full width and half magnitude (FWHM).

The microlens mold is designed with diameter of 70 μm, a depth of 3.45 μm, a radius curvature of 180 μm and spherical form. The mold milling process is controlled by a computer program, in which the parameters of machining and the mold were set. Fabrication process was introduced in detail in Refs. [7–10]. In order to study the mold milling performance for different materials, substrates of nickel, copper and bulk silicon were used for trials.

After finishing the mold, hot embossing was carried out using a pressure machine with a heating and thermal control system, with Polycarbonate 2800 (Bayer). The molding was completed under the following conditions: temperature, 340°F; pressure, 2000 lb (~8.8 kN).

3. Experimental results and discussion

Designed microlens parameters are as follows: diameter, 70 μm; sag height, 3.45 μm; NA value, 0.1; working under wavelength of 633 μm.

Fig. 1 shows the microlens mold manufactured by FIB milling on the substrate with copper. Fig. 2 shows the two-dimensional profile of the mold measured using the WYKO NT 2000 laser interferometer. It can be seen that the surface of the mold is not smooth, with some defects on one side of the mold. The two-dimensional profile shows that the surface of the mold is very rough, and

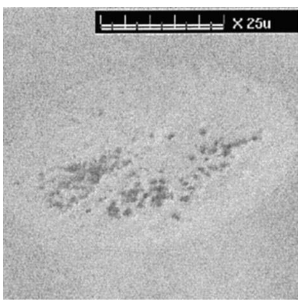

Fig. 1. Microlens mold with copper material, milled by FIB.

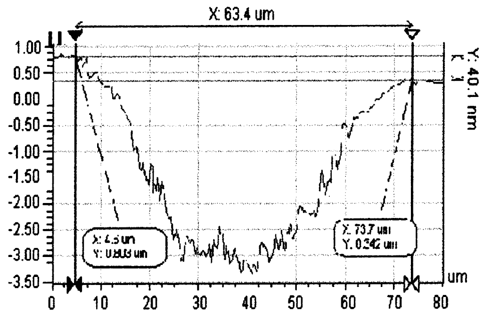

Fig. 2. Copper mold profile measured by the WYKO NT 2000 laser interferometer.

the form is irregular. Figs. 3 and 4 show milling and measuring results for the mold with nickel material. As can be seen, the results are not ideal, and similar to the previous case.

Figs. 5 and 6 show milling and measuring results for the mold with bulk silicon. It can be seen that the milling result is ideal with a smooth surface, and a neat and symmetric profile. The measured surface roughness R_a value is 2.5 nm. Fig. 7 shows a scanning electron microscope (SEM) micrograph of a 6×6 microlens mold array milled by FIB on bulk silicon. Its two-dimensional profile data measured by the interferometer is transferred in order to compare with the designed profile, as shown in Fig. 8. As can be seen, these two profiles coincide well.

It can be seen that the mold quality for bulk silicon is better than the metal materials. The possible reason is that the milling process is a pure physical collision process between positive ions and metal

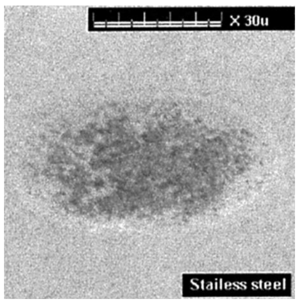

Fig. 3. Microlens mold with nickel material milled by FIB.

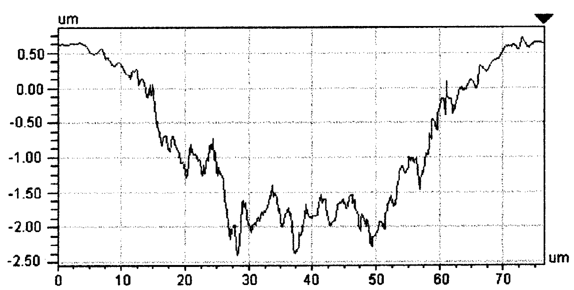

Fig. 4. Nickel microlens mold profile measured by the WYKO NT 2000 laser interferometer.

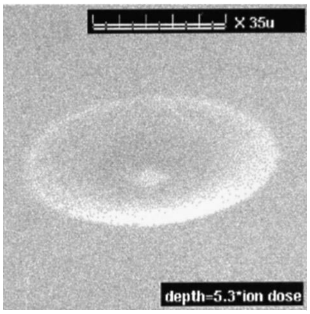

Fig. 5. Microlens mold milled by FIB on bulk silicon material.

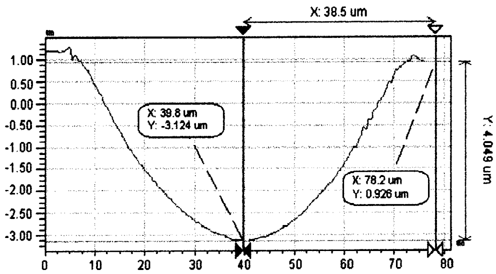

Fig. 6. Profile of the microlens mold milled by FIB on bulk silicon material measured by the WYKO NT 2000 laser interferometer.

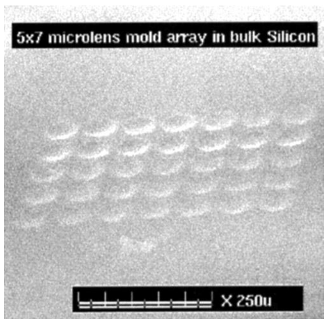

Fig. 7. Microlens mold array milled by FIB on bulk silicon material.

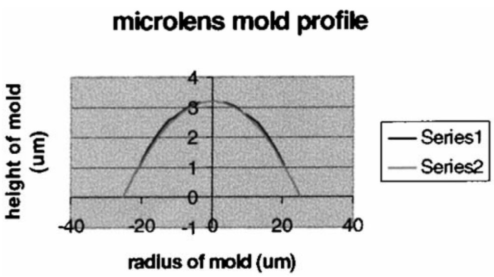

Fig. 8. Comparison of profiles for designed mold and machined mold using FIB.

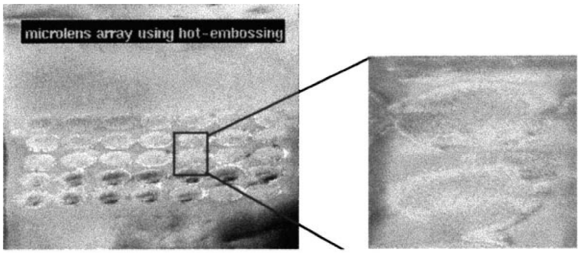

Fig. 9. Please supply a caption for here if one is necessary — ICPC.

atoms. Because of the difference of crystalline structure between metal and silicon, the crystalline grain size for metal is larger than silicon. For metal material, large bulk material is removed under the ion collision with high energy. For silicon, the dimension of deprived material in the role of ion collision is less than that of the metal due to its loose crystalline structure and fragile characteristics. Because of working principle of FIB, it is more suitable for materials with brittle fracture, and not suitable for metal with ductility. However, the silicon mold is a short-lifetime material due to its low wear-resistance. Further study should focus on searching for a new material with good milling performance and high wear-resistance.

Figs. 9 and 10 show the replicated microlens array using the bulk silicon mold and two-dimensional profile measurement using the laser interferometer. Measured surface roughness (R_a value), diameter and sag height of the replica are 8 nm, and 69.56 and 3.48 μm, respectively, which is acceptable for practical application. Focused spot size of the replicated microlens is about 7.5 μm, which is measured using our beam scanner (model BeamScope-5P™). The wavelength of the beam scanner light source is 0.633 μm.

4. Summary

In summary, fabrication of a microlens mold using focused ion beam is practical. The surface roughness of the mold is acceptable. Because it is a one-step direct machining, there is no accumulated fabrication error in the process. The replication results show that the mold is available for microlens replication using hot embossing.

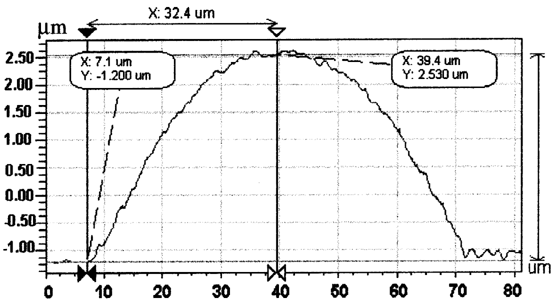

Fig. 10. Two-dimensional profile of the replicated microlens measured by the WYKO NT2000 laser interferometer.

Further study will focus on looking for new materials with good milling performance and high wear-resistance in order to improve the lifetime of the mold.

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References

[1] I.K. Pasco, J.H. Everest, Plastics optics for opto-electronics, Optics Laser Technol. 10 (1978) 71–76.
[2] M.T. Gale, L.D. Baraldi, R.E. Kunz, Replicated microstructures for integrated optics, Proc. SPIE 2213 (1994a) 2–10.
[3] S. Kaleram, M. Gross, A. Neyer, Injection molded 2×8 couplers for optical communications, in: Proc. 7th European Conf. on Integrated Optics ECIO'95 Delft, The Netherlands, 3–6 April, 1995, pp. 77–80.
[4] M. Popall, J. Kappel, J. Schulz, H. Wolter, ORMOCERs, inorganic polymer materials for applications in micro systems technology, in: H. Reichl, A. Heuberger (Eds.), Microsystem Technologies, VDE Verlag, Berlin, 1994, pp. 271–279.
[5] K. Tiefenthaler, V. Briguit, E. Buser, M. Horisberger, L. Lukosz, Preparation of planar optical SiO_2–TiO_2 and $LiNbO_3$ waveguides with a dip coating method and an embossing technique for fabricating grating couplers and channel waveguides, Proc. SPIE 401 (1983) 165–173.
[6] H.P. Herzig, in: MICRO-OPTICS Elements, Systems and Applications, Tayler & Francis, Oxford, 1997, pp. 153–178.
[7] Y. Fu et al., Experimental study of 3D microfabrication by focused ion beam, Rev. Sci. Instrum. 71 (2) (2000) 1006–1009.
[8] Y. Fu et al., Diffractive optical elements with continuous relief fabricated by focused ion beam for monomode fiber coupling, Optics Express 7 (3) (2000) 141–147.
[9] Y. Fu, N. Kok, A. Bryan, Microfabrication of diffractive optical element with continuous relief by focused ion beam, Microelectronic Eng. 54 (3-4) (2000) 287–293.
[10] Y. Fu, N. Kok, A. Bryan, Microfabrication of microlens array by focused ion beam technology, Microelectronic Eng. 54 (3-4) (2000) 211–221.