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Fabrication Method of Microlens Array Using Oxidized Porous Silicon Bulk Micromachining and PDMS Replication Molding

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1. Introduction

In recent years, micro-optic devices have gone through significant development and rapid growth [1]. Also, these optical elements have become successful in miniaturization, such as optical micro-switch, coupler and microlens. Among them, microlens has a variety of applications in optical communication and interconnection [2]. Also, these microlens arrays are likely to be combined with other optical devices to play key roles in optical sensor system, optical interconnection system, biomedical system and high-definition display system.

Many different lens fabrication methods have been extensively investigated, including the photoresist reflow method [3], ultraviolet curing of polymer technique, micro-jet technique and lithographie galvanoformung abformetechnik (LIGA) method [4]. Among these methods, the photoresist reflow method has been widely used because of the easy and simple fabrication process. However, due to the unreliability and instability of the photoresist reflow, this method is not yet accepted as a commercial fabrication method. In addition, the photoresist reflow condition must be exactly controlled for the process uniformity and reproducibility requirements [5]. And other techniques are not yet suitable for the commercial fabrication of the low-cost and high performance microlens.

Polydimethylsiloxane (PDMS) is commonly used for micro-scale plastic systems and replica molding processes. This material has characteristics which are very attractive in micro-fabrication, including biocompatibility, chemical inertness, optical transparency and flexibility [6]. In addition, PDMS replica molding process is relatively simple to work with and fabrication costs are low in comparison to other materials (e.g., glass or silicon).

In this paper, we propose a new fabrication method of microlens with PDMS replication molding and porous silicon bulk micromachining techniques. This new method is made by utilizing isotropic oxide membrane shaping of selectively oxidized porous silicon.

2. Experiments

Oxidized porous silicon (OPS) has been researched for applications in optoelectronic modules and good sacrificial layers for MEMS [7]. OPS is obtained by oxidizing the porous silicon layer (PSL) formed on p-type silicon substrate. Thickness and morphology of the OPS depend on experimental conditions, such as anodization current density, anodization time and resistivity of silicon wafer. Fig. 1 shows conceptual process steps for microlens using selective OPS layer, silicon mold and PDMS. This fabrication method combines silicon mold using porous silicon bulk micromachining with PDMS replica molding using soft-lithography.

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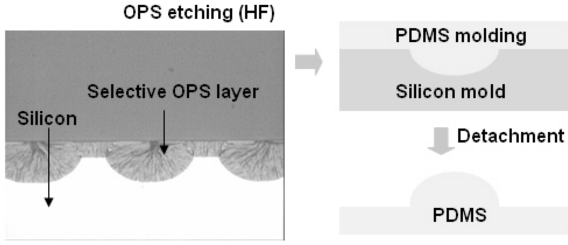

Fig. 1 Conceptual process schematic for microlens using selective OPS layer, silicon mold and PDMS

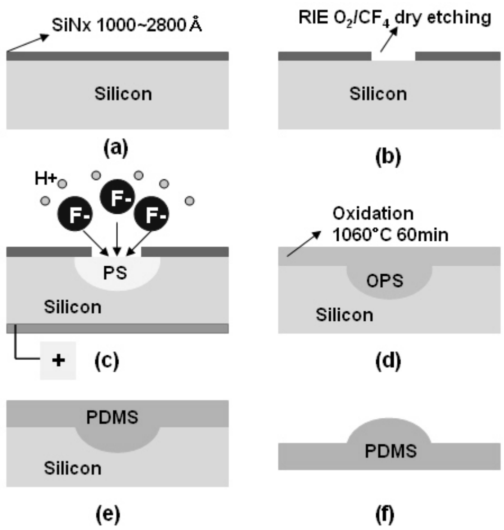

Fig. 2 Process flow steps for microlens
(a) LPCVD SiNx deposition, (b) Selective SiNx dry etching, (c) Anodization with SiNx dissolution, (d) Oxidation, (e) OPS etching and PDMS molding, (f) PDMS membrane detachment

First of all, silicon nitride layer (1000~2800 Å thick) was deposited for the selective anodization process by using LPCVD (fig. 2(b)). Then, photoresist (AZ4330) layer was coated for microlens array patterns and SiNx layer was selectively etched by using RIE O_2/CF_4 plasma. Fig. 2(c) shows selective anodization process. The reaction mechanism is simply that F- ions attack silicon bondings and make porous layer on silicon surface. Anodization process is controlled by current density, time, chemical composition of solution and resistivity of silicon wafer as shown in table I.

Table I
Anodization conditions and surface roughness of Fig. 3

Index in Fig.3	Resistivity Of silicon (Ω·cm)	HF: EtOH	Current density (mA/cm^2)	Time (min)	Rough-ness (rms)
(c)	8-10	50:20	7	60	512 Å
(d)	0.01	20:50	7	60	84 Å

These conditions affect surface morphology of the silicon mold. Root mean square roughness of silicon mold is from 84 to 512 Å. After anodization process, porous silicon layer was oxidized at 1060°C in wet O_2 for 30min. Oxidized porous silicon layer was etched by HF solution for 60min. Then a liquid PDMS mixture (Sylgard 184 (DOW Corning silicone elastomer): curing agent = 10:1) was coated on the silicon mold. After baking at 90°C for 2hours, PDMS layer could be easily stripped from the silicon mold. Finally, PDMS molding with microlens patterns was formed by the replica molding method.

3. Results and Discussion

Fig. 3 shows CCD and SEM photographs of the fabricated microlenses and cross sectional profiles using surface profiler. The diameter of the fabricated microlens is from 20um to 120um and the height of the fabricated microlens is from 6um to 50um, measured by surface profiler. The focal length was calculated by the measurement of diameter of hemi-spherically shaped microlens using the equation

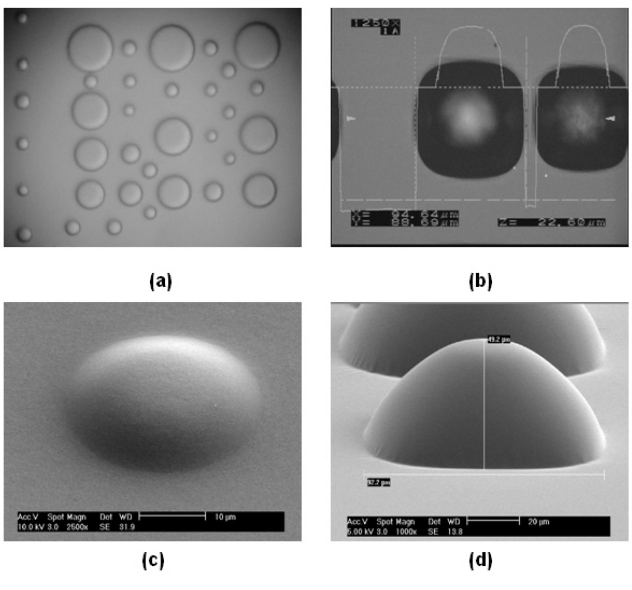

Fig. 3 CCD and SEM photographs of the fabricated microlenses (a) CCD picture of microlens array, (b) cross-sectional profile of microlens using surface profiler, (c) SEM picture of microlens (radius=30um), (d) SEM picture of microlens (radius=95um)

given by

$$f = \frac{D}{2(n-1)} = \frac{r}{n-1} \qquad (1)$$

where D and r are the diameter and radius of microlens, respectively, and n is the refractive index of the PDMS layer with the value of 1.45. Fig. 4 shows that the focal length of the fabricated microlens is from 22um to 90um.

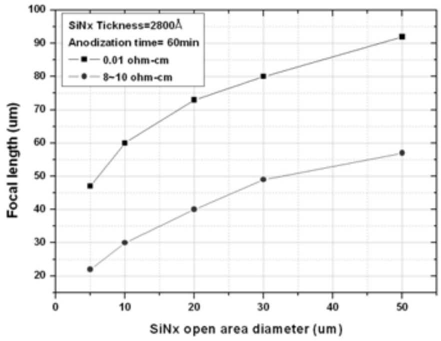

Fig. 4 Focal lengths as functions of SiNx open window area and silicon resistivity

The configuration of microlenses depends on parameters, such as SiNx thickness, anodization time and SiNx open window area. The focal length of microlens shows a tendency of increasing with decrease of silicon wafer resistivity. Also, the focal length of microlens increases with respect to the SiNx open window area. Fig. 4 shows the dependency of the focal length of fabricated microlens on SiNx open window area and silicon wafer resistivity.

4. Conclusions

In this paper, a novel fabrication method of microlens array has been proposed by using oxidized porous silicon bulk micromachining and PDMS replication molding technique. The focal length of the fabricated microlens is between 6um and 50um while lens diameter ranges from 20um to 120um. It is possible to shape microlens reliably by controlling selective OPS process conditions.

Comparing with photoresist reflow method, this fabrication method has some advantages like good durability of silicon bulk mold for batch process and low-cost fabrication for mass production. This fabrication process can be used to manufacture micro-optical components and low-cost integrated optical devices.

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