유리 리플로를 이용한 실리콘-관통형 마이크로렌즈 어레이의 구현

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Implementation of a through-silicon microlens array using glass reflow

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Abstract - Through-silicon microlens array has been implemented using glass thermal reflow process. Design, numerical analysis, fabrication, and measurement results are discussed. Microlenses with six different volumetric dimensions were successfully fabricated and characterized. Radius of curvature of each microlenses were measured with less than 1 % deviation compared to calculated value. Measured average roughness of the microlens surface was 16.5 nm.

1. Introduction

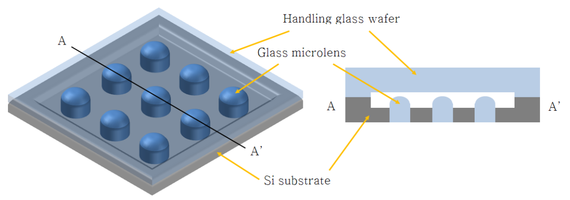
Ever since the development of the concept of micro-opto-electro-mechanical systems (MOEMS), micro-optics and resulting micro-optical devices have gained increasing attention from the related industry. It has emerged as one of the viable means to realize various optical components and to propose solutions to bottlenecks in conventional microelectronics.

Microlens is one of the most widely used and indispensable component in micro-optics. It has various applications in the line of optical communication, microscopy, image processing, sensors for precise measurement, optoelectronics, and photonics. In many applications, performance of the optical device is determined by the quality and characteristics of the microlens used. Moreover, the fabrication method of the microlens could potentially limit overall fabrication process of the optical device with integrated microlens.

Up to the present, many research groups have come up with microlens-integrated devices with lateral, vertical, or rotational micro actuators. Since most of them utilized thermally unstable polymer as lens material, they suffered from compatibility and scalability issues with consecutive fabrication processes or a complicated manual assembly process with the actuator could not be avoided.

Thermally stable glass material could be a solution to these issues. Moreover, chemical stability, optical transparency, and mechanical robustness are some of other advantages over other potential lens materials. Several research groups have developed glass microlens array via thermal reflow in vacuum cavity[1] or wet-etch followed by thermal reflow process[2]. However, it is still very challenging to precisely control the profile of a glass microlens, mainly due to relatively high process temperature.

In this paper, a through-silicon microlens array has been proposed to address above-mentioned technological issues. Figure 1 depicts the proposed microlens-assembled-substrate concept. As with a silicon-on-insulator (SOI) substrate, it can be utilized as the base substrate for implementing various microlens-integrated micro-optical components including actuators and collimator arrays. Numerical analysis, fabrication method, and results will be discussed in the following sections.

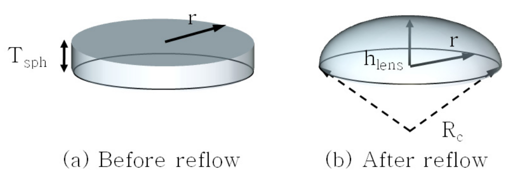


<Fig. 1> Schematic diagram of the proposed design

2. Design and Fabrication

2.1 Thermal reflow modeling

Since the microlens is fabricated basically using thermal reflow, fundamental numerical modeling has been carried out based on two assumptions; i) before and after the reflow, volume of the glass cylinder and the spherical microlens are equal, ii) viscous glass has an infinite surface tension, which means other factors such as gravity and characteristics of the substrate are negligible. Schematic diagram of the microlens fabrication and variables are illustrated in Fig. 2.



<Fig. 2> Thermal reflow of a spherical microlens

Equation (1) could be derived from the equivalent volume of the cylinder and microlens

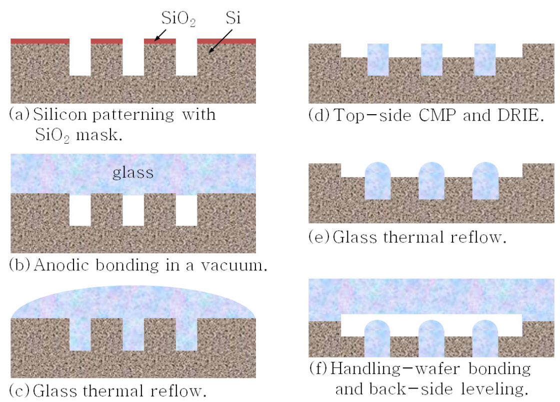
$$\pi r^2 T_{sph} = \frac{1}{3}\pi h_{lens}^2 (3R_c - h_{lens}) \tag{1}$$

From the geometry of the spherical microlens, the radius of curvature (R_c) could be represented with the radius and the height of microlens.

$$R_c = \frac{r^2 + h_{lens}^2}{2h_{lens}} \tag{2}$$

By combining eq.(1) and eq.(2), the height and radius of curvature of the microlens could be derived from the radius and thickness of the cylinder.

2.2 Fabrication



<Fig. 3> Schematic diagram of the fabrication process

Schematic diagram of the fabrication process is depicted in Fig. 3. Silicon wafer was patterned via a deep reactive ion etching (DRIE) with an oxide mask (Fig. 3(a)), then anodically bonded with a glass wafer in a vacuum (Fig. 3(b)). Thermal reflow at 850℃ in a furnace (Fig. 3(c)), and top-side polishing were followed by DRIE (Fig. 3(d)) to make glass cylinders with desired volumetric dimension. Second thermal reflow (Fig. 3(e)) and bottom-side leveling with the assistance of a handling glass wafer (Fig. 3(f)) were performed to accomplish the plano-convex microlens array.

3. Measurement and Discussion

Microlenses with six different volumetric dimensions (L1 to L6) were designed and fabricated, as summarized in Table 1. Expected value of the R_c was calculated from the measured radius and thickness of the glass cylinder. The actual R_c of the fabricated microlens was derived from the surface profile measured with 3D Surface Profiler (NanoFocus Usurf). Figure 4 shows the profile comparison between the calculated and measured values, illustrated in solid lines and scattered dots, respectively. As shown in Table 1, a precise consistency between calculated and measured values of R_c has been observed with less than 1 % deviation. Average roughness of the microlens surface was 16.5 nm. Since the value is less then 1/20 of the wavelength of visible light, proposed concept could be utilized in various applications requiring high performance glass microlenses.

SEM (scanning electron microscope) images taken before and after the second reflow process are depicted in Fig. 5 and 6. Figure 7 is a cross-sectional SEM image of the fabricated through-silicon microlens array. The glass successfully filled the silicon cavity without void. The cross-sectional view of the microlens also validates the measured profile which indicates near perfect spherical lens shape.

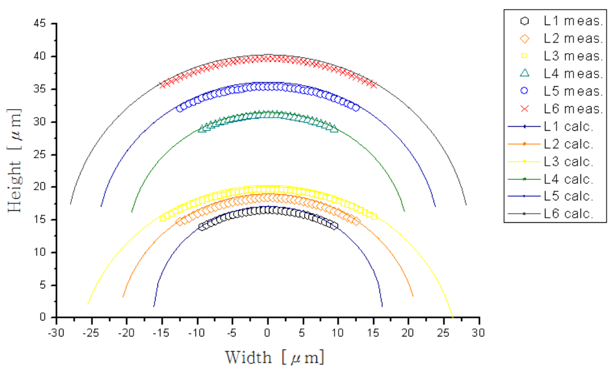
4. Conclusion

Through-silicon microlens array has been implemented through glass thermal reflow process. Microlenses with six different volumetric dimensions were successfully fabricated. Radius of curvature of each microlens has been measured with less than 1% deviation from the calculated value. Measured average roughness of the microlens surface was 16.5 nm. Pre-assembled microlens array proposed in this research could be utilized in various micro-optical component applications requiring high performance glass microlenses.

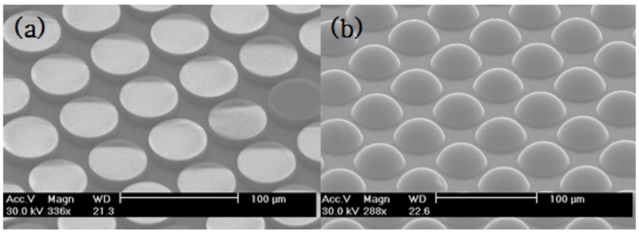
<Table 1> Summary of the microlens characteristics

Design	T_{sph}	r	R_c (calculated)	R_c (measured)	Error [%]
L1	11.69	16.25	16.27	16.26	0.108
L2	12.04	21.25	21.38	21.47	0.394
L3	12.19	26.25	27.11	27.30	0.675
L4	35.48	16.25	19.94	19.80	0.737
L5	35.49	21.25	24.32	24.08	0.987
L6	36.01	26.25	28.70	28.53	0.601

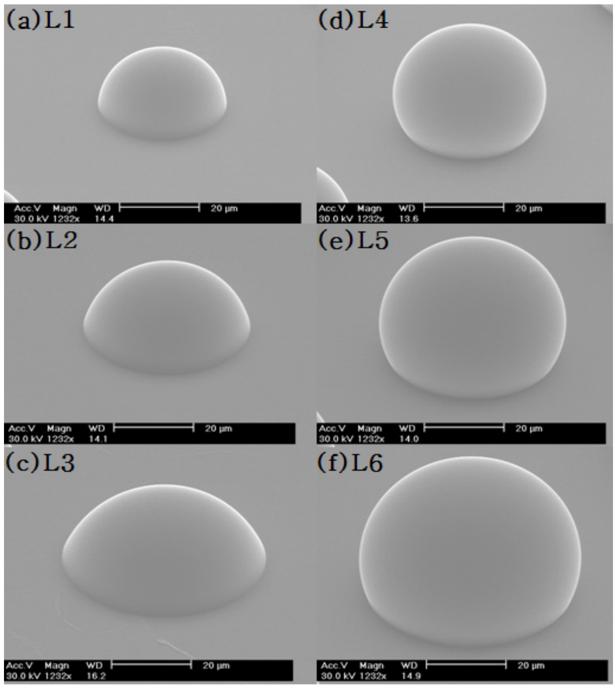
unit: [μm]



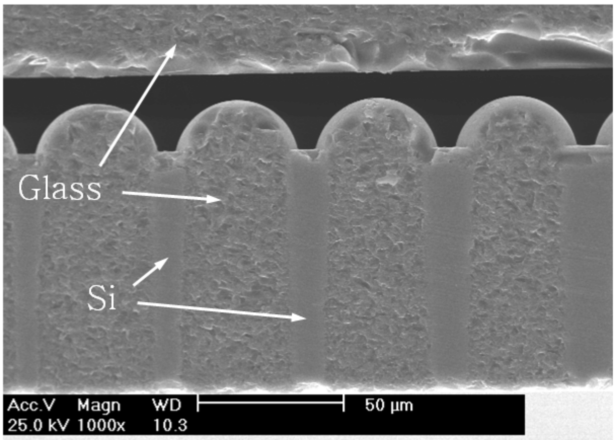
<Fig. 4> Microlens profile comparison between the calculated and measured values



<Fig. 5> SEM image of the fabricated (a) glass cylinder and (b) microlens array of design L3



<Fig. 6> SEM images of the fabricated microlens



<Fig. 7> Cross-sectional SEM image of the fabricated through-silicon microlens array (L2)

[Reference]

[1] P. Merz, H. J. Quenzer, H. Bernt, B. Wagner, and M. Zoberbier, "A novel micromachining technology for structuring borosilicate glass substrates", *in The 12th International Conference on Solid-State Sensors, Actuators and Microsystems*, 2003, pp. 258-261.

[2] Sung-Kil Lee, Man-GeunKim, Kyoung-Woo Jo, Sang-Mo Shin and Jong-Hyun Lee, "A glass reflowed microlens array on a Si substrate with rectangular through-holes", *J. Opt. A: Pure Appl. Opt.* 10, 2008, 044003 (7pp).