OPTOELECTRONICS LETTERS Vol.9 No.2, 1 March 2013

Microlens fabricated in silicon on insulator using porous silicon*

ZHONG Fu-ru (钟福如)[1], **LÜ Xiao-yi** (吕小毅)[2], **JIA Zhen-hong** (贾振红)[2]**, and **TIAN Min** (田敏)[1]
1. College of Information Science and Technology, Shihezi University, Shihezi 832003, China
2. College of Information Science and Engineering, Xinjiang University, Urumqi 830046, China

(Received 12 September 2012)

In order to realize the planar gradient refractive index (GRIN) microlens which is based upon porous silicon (PSi) and fabricated on silicon on insulator (SOI), a novel anodization method is used by applying lateral electric field. The microlens with smooth variation of the effective optical thickness is achieved. The lens is transparent in the infrared region, including the optical communication window (1.3 μm$<\lambda<$1.6 μm). This approach also allows the fabrication of an array of such lenses on SOI, and the GRIN microlens can be used as potential components in future silicon-based integrated optical circuits.

Document code: A **Article ID:** 1673-1905(2013)02-0105-3
DOI 10.1007/s11801-013-2352-8

Several methods have been developed for the preparation of microlens in various materials, such as photopolymers[1], microporous polymer[2], metal[3], glass[4], liquid crystal[5], semiconductor, even silicon on insulator (SOI) substrate[6-9]. Microlens fabricated in silicon seems more promising for its compatibility with standard integrated circuit processes. Unfortunately, most of them are expensive or complicated. Because the refractive indices of porous silicon (PSi) can be tuned ranging from 1.2 to 2.3, and the actual refractive index is controlled by the current density, many researchers have yielded gradient PSi films according to the factors[10-15]. This is not only because of their unusual optical properties, but also because simpler and cheaper electrochemical etching methods have been developed for preparing reproducible porosity and thickness at the same key parameters. S. Ilyas and M. Gal[8] have successfully fabricated planar microlens in silicon using porous silicon technology. In this paper, we investigate another approach for the fabrication of microlens based on a double-tank electrochemical etching method.

In general, there are two main approaches to synthesize PSi, which are single-tank and double-tank electrochemical etching methods[16, 17]. But the traditional single-tank electrochemical etching method is not suitable for SOI substrate for the insulator between upper and lower layers. The double-tank electrochemical etching method may be an alternative method. Indeed, the gradient refractive index (GRIN) can be fabricated by electrochemical etching methods using gradient lateral field. And none of the double-tank electrochemical etching methods developed can provide PSi on SOI wafers. Herein, we present a simple and highly adaptable method to yield planar microlens on SOI substrate.

PSi samples were prepared from SOI silicon wafers with 60 μm-thick N-type (100) orientation silicon epitaxial layer with a resistivity of 0.02 Ω•cm grown on a 2 μm-thick SiO_2 layer on silicon substrates. Samples were prepared in a novel double-tank setup. Briefly, surfaces were etched by placing the electrode parallel to the surface on one end of the substrate in a 1:1 (v/v) solution of 49 % aqueous HF/ethanol for 300 s at a current density of 40 mA·cm^{-2} over a surface area of about 0.785 cm^2. The anodization time is 5 min. After etching, the samples were rinsed with ethanol, and dried in a vacuum tank.

As mentioned above, microlens described in this paper is not made by single-tank method, but synthesized via a novel double-tank electrochemical etching method as shown in Fig.1. In conventional double-tank etching methods, the positive electrode links to the backside of the samples. In our present method, a lateral potential field is applied at the same side of the sample, that is, the hole which is necessary for electrochemical etching method can be provided through the PSi.

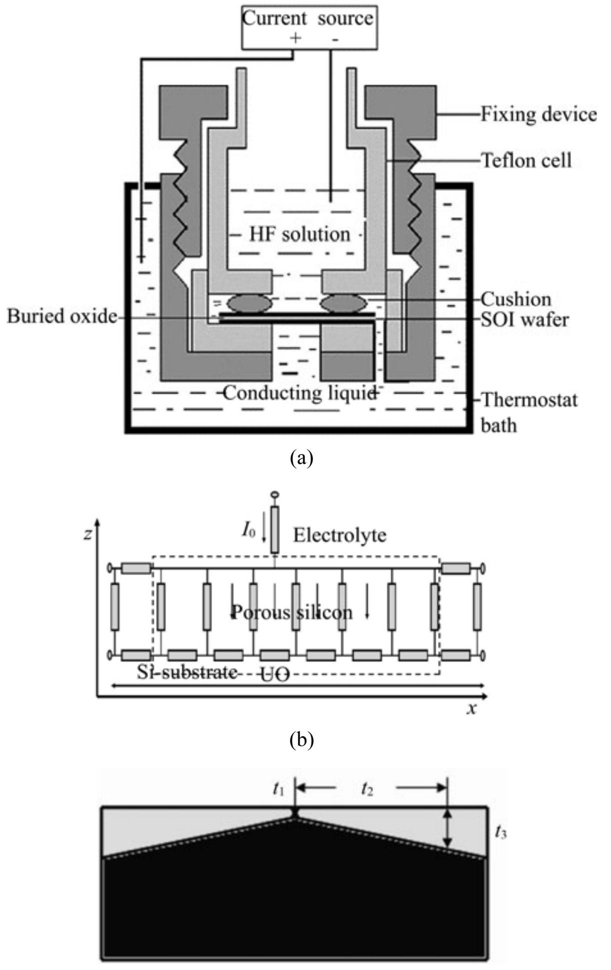
We used scanning electron microscopy (SEM) (leo-1430) to directly observe the surface morphology and thickness distribution. Then we used Fourier transform infrared (FTIR) spectroscopy to investigate the optical properties of the lenses. Fig.2 shows the cross-sectional SEM images of PSi samples formed by this method. Because of the presence of a lateral potential field, the obtained PSi columns appear to have suffered considerable

---

* This work has been supported by the National Natural Science Foundation of China (No.60968002), and the Excellent Youth Foundation of Shihezi University (No.2012ZRKXYQ-YD20).

** E-mail:jzhh@xju.edu.cn

lateral etching, as compared with the straight columns of uniform thickness obtained without a lateral field. There are good reasons to believe that lateral potential field drive force the holes from the column walls to the center, thus leading to the observed morphology.



(a)

(b)

(c)

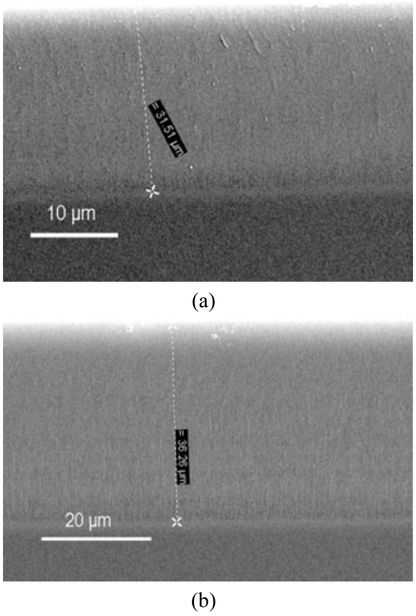
Fig.1 (a) Schematic diagram of experimental setup for preparing microlens; (b) Equivalent circuit model describing the current distribution in setup (a); (c) Cross-sectional view of the thickness of the PSi

As can be seen from FTIR spectra in Fig.3, the novel electrochemical etching method can prepare PSi whose effective optical thickness (EOT) distribution has a very good approximation equivalent to that of GRIN lens. The EOT depends on the position from the centre of the microlens, which can be shown as

$$N_{\mathrm{ot}}(x) = [n(x)L(x)] \approx N_0-0.5N_0Ax^2, \qquad (1)$$

where x represents the radial distance from the optical axis, N_0 is the maximum EOT in the centre on the optical axis of the lens, and A is the gradient constant of the lens. Since the lower porosity, the reflectance is higher in the central part.

We also study the effects of applied voltage on the formation of planar microlens in this process.



(a)

(b)

Fig.2 Cross-section images at (a) centre position and (b) edge position

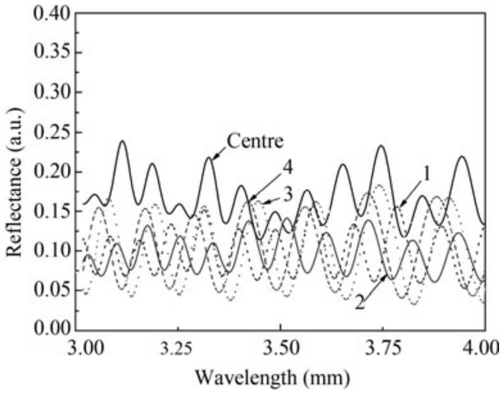


Fig.3 FTIR reflectance spectra at different positions (1 to 4 are from centre to rim, respectively.)

Why emerges this phenomenon? We can find the results from the equivalent circuit model of the PSi as shown in Fig.1(b). During the formation of PSi, the porosity and the thickness of the PSi films at any point are intimately related to the magnitude of the etching current flowing through that point. At the very beginning etching process, intensity of electric field even changes with position. But in the etching process, there is not only longitudinal current, but also transverse current. During the etching, the longitudinal current and transverse current also change. In addition, the etching rate is not linear with the local etching current density, so there is not a completely quadratic distribution. The measured distribution of the EOT for a 10 mm-diameter sample is shown in Fig.4. As can be seen, there is the approximately quadratic relationship between EOT and position as expected for this GRIN lens. The decrease of EOT is attributed to the increasing porosity of the PSi layer due to the increase of current density with decreasing distance from the electrode.

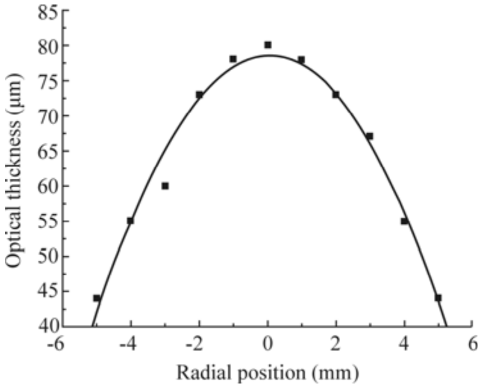


Fig.4 EOT profile of the microlens

In conclusion, we fabricate planar GRIN lenses in SOI silicon with the aid of a lateral electrical field applied in the sample during etching in HF solution. With the high level of design flexibility of PSi and low-loss dielectric medium, this modified double-tank electrochemical etching process is appropriate for rapid prototyping of GRIN lenses.

References

[1] C. F. Ye and R. R. McLeod, Opt. Lett. **33**, 2575 (2008).

[2] A. Verma and A. Sharma, Advanced Materials **22**, 5306 (2010).

[3] G. M. Lerman, M. Grajower, A. Yanai and U. Levy, Opt. Lett. **36**, 3972 (2011).

[4] JIANG Xiao-ping, LIU De-sen, ZHANG Feng-jun, ZHOU Su-mei, ZHAO Zhi-fang and CHEN Xiao-mei, Journal of Optoelectronics·Laser **22**, 1143 (2011). (in Chinese)

[5] C.-T. Lee, Y. Li, H.-Y. Lin and S.-T. Wu, Opt. Express **19**, 17402 (2011).

[6] B. D. F. Casse, W. T. Lu, Y. J. Huang and S. Sridhar, Applied Physics Letters **93**, 053111 (2008).

[7] C. F. Chen, S. D. Tzeng, H. Y. Chen and S. Gwo, Opt. Lett. **30**, 652 (2005).

[8] S. Ilyas and M. Gal, Applied Physics Letters **89**, 211123 (2006).

[9] J. Tian, M. Yan, M. Qiu, C. G. Ribbing, Y.-Z. Liu, D.-Z. Zhang and Z. Y. Li, Applied Physics Letters **93**, 191114 (2008).

[10] C. C. Striemer and P. M. Fauchet, Applied Physics Letters **81**, 2980 (2002).

[11] J. D. Hwang, S. B. Hwang, C. H. Chou and Y. H. Chen, Thin Solid Films **519**, 2313 (2011).

[12] L. L. Ma, Y. C. Zhou, N. Jiang, X. Lu, J. Shao, W. Lu, J. Ge, X. M. Ding and X. Y. Hou, Applied Physics Letters **88**, 171907 (2006).

[13] C. M. Thompson, A. M. Ruminski, A. G. Sega, M. J. Sailor and G. M. Miskelly, Langmuir **27**, 8967 (2011).

[14] Y. L. Khung and N. H. Voelcker, Optical Materials **32**, 234 (2009).

[15] K. Hwang, S. Kim, Y. Park, H. Jeon and J. Jeong, Appl. Opt. **47**, 1628 (2008).

[16] P. Sun, M. Hu, M. D. Li and S. Y. Ma, Acta Physico-Chimica Sinica **28**, 489 (2012).

[17] ZHONG Fu-ru, LÜ Xiao-yi and JIA Zhen-hong, Optoelectronics Letters **7**, 0133 (2011).