Fabrication of concave spherical microlenses on silicon by femtosecond laser irradiation and mixed acid etching

An Pan,[1] Bo Gao,[1] Tao Chen,[1,*] Jinhai Si,[1] Cunxia Li,[2] Feng Chen,[1] and Xun Hou[1]

[1]*Key Laboratory for Physical Electronics and Devices of the Ministry of Education & Collaborative Innovation Center of Suzhou Nano Science and Technology, School of Electronics & Information Engineering, Xi'an Jiaotong University, No. 28, Xianning West Road, Xi'an, 710049, China*

[2]*Department of Applied Physics, Xi'an University of Technology, Yanxiang Road 58, Xi'an, 710054, China*

[*]*tchen@mail.xjtu.edu.cn*

Abstract: All-silicon plano-concave microlens arrays with spherical profiles and good image performance were obtained using femtosecond laser direct irradiation and mixed acid etching. A femtosecond laser was employed to produce microhole arrays on silicon, and the microholes were expanded and smoothed by the mixed acid to form concave microlenses. The effects of the etching time, laser power, and pulse number on the microlens morphology were investigated. This method has potential applications in the fabrication of all-silicon plano-concave microlenses for use in infrared devices.

OCIS codes: (230.4000) Microstructure fabrication; (350.3950) Micro-optics; (160.6000) Semiconductor materials; (140.7090) Ultrafast lasers.

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1. Introduction

Microlenses have drawn much attention in recent years because of their applications in optical or biochemical sensors [1], optical interconnection [2], and multi-aperture imaging (compound eyes) [3]. Although many researchers have investigated the fabrication of convex or concave microlenses using different materials, such as polydimethylsiloxane [4], glasses [5], liquids or liquid crystals [6], and silicone [7], there are few studies of all-silicon microlenses, especially concave ones. Microlenses on silicon are more compatible with mature micro-electro-mechanical-systems or electron manufacturing techniques that could be applied in integrated optical circuits [2]. Compared with glasses and polymers, silicon is a type of visible-light-omitted material that is transparent in the optical communication window (1.3–1.6 μm). Silicon microlenses have been used in infrared devices such as detector arrays [8], microcameras, and fiber-optic couplers [3,9], as well as terahertz emitting and detecting devices [10]. As one type of microlenses, concave microlenses have important applications in optical scanners [11] and diffusers [12]. Furthermore, they are often combined with convex microlenses in micro-optical systems to achieve optical functions such as achromaticity [13]. Silicon concave microlens arrays (MLAs) are suitable for infrared scanners [11] and infrared diffusers [14] and can be applied in combined lens. Note that in addition to their use as concave microlenses, silicon concave structures can also be used as micro-mirrors that focus incoming light in front of the mirror, which have applications in free-space light coupling, optical trapping, and quantum information processing [15–17]. In addition, silicon concave structures have also been widely used as molds for replication of plastic microlenses [18,19].

To date, many methods of fabricating microlenses have been proposed, such as resist reflow [20], reactive-ion etching (RIE) [21], reversal replication [22], the moving mask method [23], and direct writing [24]. Further, laser patterning combined with wet etching has been attractive because of its relatively simple devices, high fill factor of the lenses, and flexibility for regulating the curvature [25,26]. Silicon microlenses are generally fabricated by transferring resist lenses or an etching mask via RIE. Although RIE is effective for high-precision anisotropic etching, it is hard to obtain the ideal spherical surface. In addition, the surface roughness problem needed to be considered [21,27]. In the last decade, the fabrication of silicon concave structures or microlenses has been studied. A scanning-probe gray-scale oxidation method was adopted to fabricate silicon microlenses [24]; this direct-writing method has good controllability and flexibility, except for a slightly low efficiency for fabricating arrays. Coated by an RIE-processed hard mask, silicon concave structures were also created via isotropic wet etching to form molds [19]. Femtosecond laser direct writing, alone or combined with wet etching, has been applied recently to fabricate MLAs on glass [25,28]. However, although many works have examined the microprocessing of silicon by femtosecond direct writing [29,30], no studies have reported the fabrication of all-silicon concave microlenses by femtosecond laser patterning combined with wet etching.

In this study, femtosecond laser direct irradiation combined with mixed acid etching was adopted to pattern concave MLAs on silicon. A femtosecond laser was employed to produce microhole arrays, and the microholes were expanded and smoothed by the mixed acid to form concave MLAs. The initial laser patterning on silicon can enhance the etching process to realize spherical profiles [31]. The mixed acid, which has an isotropic etching and polishing effect, can oxidize silicon and remove the silicon oxides as well [32]. The microlens morphology could be controlled by changing the laser irradiation and etching conditions. In the study, the diameter of the microlens varied from 21.4 μm to 116 μm, and the radius of curvature varied from about 31 μm to 190 μm. Arrays with fill factors of up to 96.6% were realized. An image array formed by the hundred-micron-sized microlens array was demonstrated. This method has potential applications in the fabrication of all-silicon plano-concave microlenses of specified sizes for optical and photoelectron applications.

2. Experimental setup

A two-step process combining femtosecond laser irradiation and mixed acid etching was adopted to fabricate the plano-concave MLA on silicon. Figure 1 shows the procedures.

As the first step, microhole arrays with diameters of less than 20 μm were produced by femtosecond laser irradiation of silicon. The silicon wafer was fixed on a 3D translation stage and irradiated by a femtosecond laser at room temperature. The stage was controlled by a computer program and had a precision of 40 nm in the x, y, and z directions. The regeneratively amplified Ti:sapphire laser system could generate 120 fs Gaussian laser pulses with a central wavelength of 800 nm and repetition rate of 1 kHz. The femtosecond laser beam was focused on the upper surface of the silicon wafer by a 10 × microscope objective lens (N.A. = 0.30), and the focal position in the z direction was not changed in the experiment. Subsequently, microholes in a square array were fabricated by laser pulses. In front of the microscope system, a variable optical attenuator helped to adjust the laser power continuously, and a mechanical shutter was used to control the laser pulse number.

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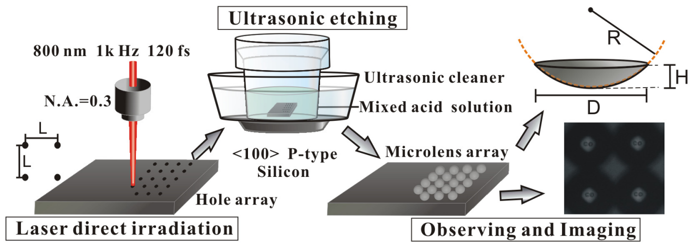

Fig. 1. Schematic diagram of microlens fabrication.

After laser patterning, the specimen with microhole arrays was ultrasonically cleaned by acetone, alcohol, and deionized water for 15 min each. Next, the specimen was etched by a mixed acid solution of hydrofluoric acid (HF, 40 wt%), nitric acid (HNO_3, 69 wt%), and acetic acid (HAC, 99 wt%) at ambient temperature. The volume ratio of the three acids was 3:12:10. The nitric acid could oxidize the silicon, and the hydrofluoric acid could remove the silicon oxides [32]. The acid transformed the laser-irradiation-induced microholes into concave structures. The height (*H*), diameter (*D*), and radius of curvature (*R*) of the microlenses are indicated in Fig. 1. The 2D and 3D morphologies of the microlenses were characterized by scanning electron microscopy (SEM) and confocal microscopy (OLS4000 Olympus), respectively. The optical image array formed by the MLA was observed by a high-sensitivity CCD camera fixed on the optical microscope imaging system.

3. Experimental results and discussion

3.1 Microlens formation in etching process

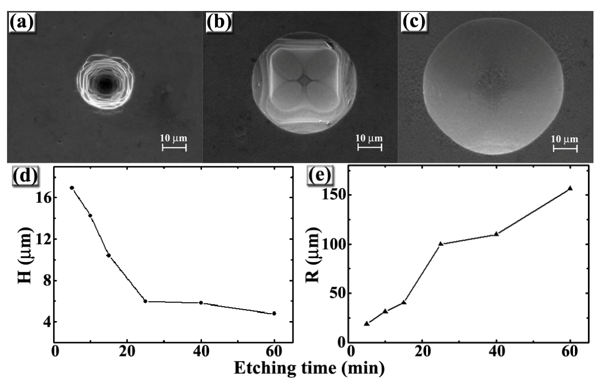

Fig. 2. SEM images of microlenses with laser power of 7 mW and pulse number of 50 at etching times of (a) 1 min, (b) 5 min, and (c) 10 min. (d) Heights and (e) radii of curvature at successive times during etching.

First, the effect of the etching time on the microlens formation was studied. Figures 2(a), 2(b), and 2(c) illustrate the etching process of structures at different times. At the beginning of the ultrasonic-assisted etching process, a short time was clearly required for the acid to expand and smooth the laser-irradiation-induced microholes to form concave structures. The etching enlarged the microholes and reduced *H*, which increased the *R* values of the structures. In addition, the inner surfaces of the microholes became smoother as time increased. Detailed data for *H* and *R* during the etching process are shown in Figs. 2(d) and 2(e), respectively. The etching process is greatly influenced by the flow of acid to the surface by diffusion. It is relatively hard for the acid to diffuse into the laser-induced microholes. Thus, the etching rate of silicon outside the microholes was higher than that inside in the *z* direction, which caused *H* to decrease over time. Then the MLA was observed by SEM and confocal microscopy. Figures 3(a) and 3(b) show the uniform all-silicon MLA and its partial 3D morphology, respectively.

The microlenses with $D = 57.814$ μm and $H = 12.073$ μm were fabricated at a laser power of 7 mW and pulse number of 50. The fill factor is estimated to be 78.0%, and it can reach nearly 100% when square microlenses are fabricated. In Fig. 3(c), the dashed line represents the profile of a theoretical sphere ($R = 40.403$ μm), and the solid line shows the measured profile of the microlenses. The deviation between the actual and ideal profiles was smaller than 0.46% in the radial direction, with a root-mean-square deviation of about 85.1 nm. Microlenses with good spherical profiles were fabricated.

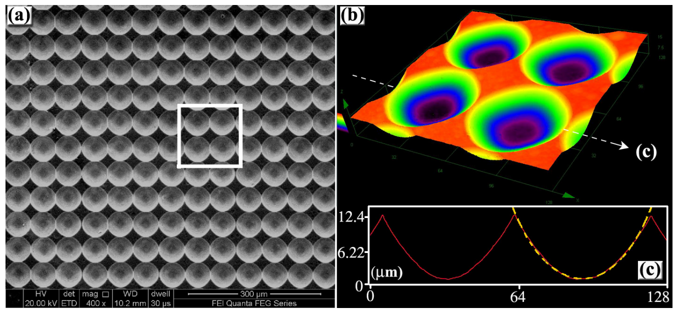

Fig. 3. Morphological observation of MLA with a fill factor of 78.0%. (a) SEM image of uniform MLA. (b) 3D-confocal analysis of marked region in (a). (c) Cross-sectional profile analysis of marked position in (b); *y* axis (etch depth) was stretched relative to *x* axis to show the profile more clearly.

3.2 Effects of laser power and pulse number on microlens morphologies

To study how the laser irradiation conditions affected the dimensions of the microlenses, we fabricated microlenses at different laser powers and pulse numbers. The results are shown in Fig. 4. In Figs. 4(a)–4(c), the pulse number was set to 50. When the laser power was below 20 mW, the *D* and *H* values of the microlenses were positively correlated with the laser power, and higher powers yielded smaller *R* values.

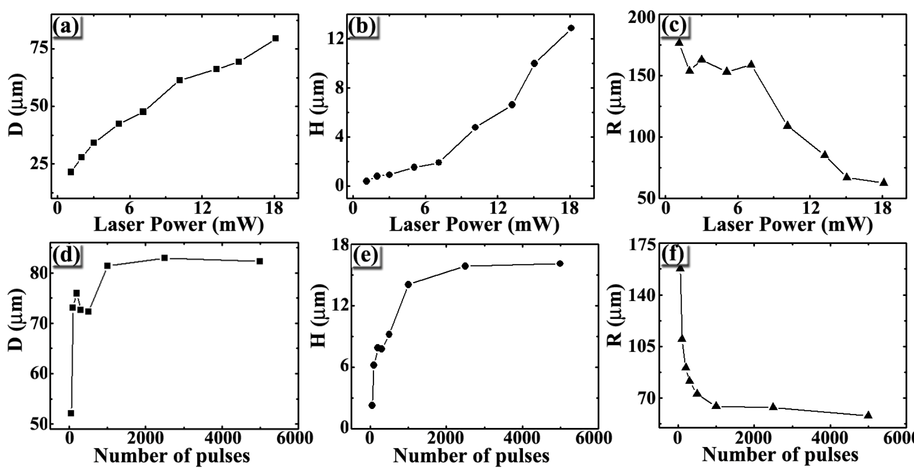

Fig. 4. Dependences of *D*, *H*, and *R* values of microlenses on (a), (b), and (c) femtosecond laser power and (d), (e), and (f) number of pulses. Etching time was 40 min. *D*, *H*, and *R* were measured by confocal microscopy.

Figures 4(d)–4(f) show the effect of the pulse number on the microlenses at a laser power of 7 mW. *D* and *H* increased sharply with increasing pulse number and then increased much more slowly when the pulse number was above 1000. *R* decreased and reached saturation when the pulse number was above 1000. The results indicated that with increasing pulse number, the *D*, *H*, and *R* values of the fabricated microlenses would ultimately be almost constant. To control

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the dimensions of the microlenses, a relatively high pulse number could be applied to reduce the fluctuation of the laser pulses and increase the uniformity. The *D*, *H*, and *R* values of the microlenses were associated with those of the laser-irradiation-induced microholes, which depended on the pulse parameters. For microholes, a higher laser power or pulse number increased *D* and *H*. The *D* and *H* values of the microholes reached saturation as the pulse number increased further. The saturation value of *D* was determined by the spot size, and that of *H* depended on the focal position in the *z* direction.

3.3 Optical performance of silicon concave spherical microlens array

To measure the focal length *f* and obtain an image array formed by the MLA with a fill factor of about 96.6%, an optical microscopy imaging system was adopted, as shown in Fig. 5(a). Light with a central wavelength of 600 nm was used. The focal length was measured by moving the translation stage along the *z* axis to successively image the front surface and focal plane of the MLA. The distance between these two planes was recorded. Further, the height of the MLA needed to be considered. For microlenses with *D* = 116.7 µm, *H* = 21.6 µm, and *R* = 87.3 µm, the measured focal length was about 41.3 µm. In Fig. 5(a), the object distance was set to 6500 µm. According to the geometrical optics, the image magnification of one microlens was calculated as 0.006394. Figure 5(b) shows the image array formed by the MLA. The images were erect and shrunken, and the measured image magnification was 0.006549. The experimental results agreed well with the theoretical calculation. In addition, the magnification could be regulated by controlling the object and image distance.

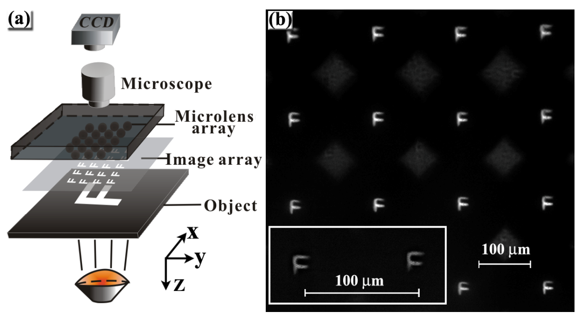

Fig. 5. Process of imaging MLA with a fill factor of 96.6%. (a) Imaging device. (b) Image array made by the MLA.

4. Conclusion

We fabricated plano-concave spherical microlenses on silicon by femtosecond direct irradiation combined with mixed acid etching. By changing the laser power, pulse number, and etching time, we fabricated microlenses with diameters ranging from 20 µm to 120 µm. The microlens array showed high uniformity and good image performance. This method could help us to obtain all-silicon plano-concave microlenses, which have potential applications in infrared devices. In addition, these concave structures could also be used as silicon micro-mirrors or molds for polymer microlenses.

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