

High Numerical-Aperture Microlens Fabricated by Focused Ion Beam Milling

Yi Chiu, Chien-Hsun Huang, and Ying-Chien Hsu
Department of Electrical and Control Engineering, National Chiao Tung University
1001 Ta Hsueh Road, Hsinchu, Taiwan 300, ROC
Tel: +886-3-5731838, Fax: +886-3-5715998, E-mail: yichiu@mail.nctu.edu.tw

ABSTRACT

The focusing objective lens is a key component in the optical pick-up head. In this paper, focused ion beam milling is used to fabricate a NA 0.65 microlens in the silicon nitride film suspended on a silicon substrate. The measured NA is 0.64 and the focused spot size is 0.64 μm .

Keywords: numerical aperture, microlens, focused ion beam, silicon nitride

1. INTRODUCTION

The focusing objective lens is a key component in the optical pick-up head. In micro fabricated pickups or other micro optical systems, several methods have been proposed to fabricate the microlens, including thermal reflow of photoresist or polymer [1], binary photolithography on thin film materials [2], gray-scale photolithography [3], and micro milling by focused ion beam (FIB) systems [4]. Among them, the profile and focal length of the microlens fabricated by the thermal reflow process is hard to control; the binary photolithography method becomes complicated as the number of mask levels increases for high diffraction efficiency. In processes employing gray-scale masks, the half-tone mask method needs a projection stepper for high resolution [5] and the high-energy beam-sensitive (HEBS) masks [6] are expensive.

Focused ion beam milling has been used widely in the preparation of TEM samples. It is also used to fabricate micro optical components such as cylindrical lenses, gratings, and Fresnel lenses by direct milling or deposition of dielectric thin films [4]. In this paper, FIB is used to mill the microlens pattern into the silicon nitride deposited on a silicon substrate to form the microlens. The silicon substrate under the lens pattern is etched so that the lens can be readily used in a stacked type [7] or a free-space type [2, 8] micro optical pickup. The lens design, fabrication processes, surface profile measurement, and focused spot measurement of the FIB-milled microlens are presented.

2. LENS DESIGN

Silicon nitride is used as the material of the microlens due to its chemical stability and compatibility with micro fabrication processes. Since the depth of the milled patterns is usually less than 1 μm , the lens is designed by treating it as a phase object, i.e. the phase front after the lens is calculated by assuming straight propagation of light through the lens. As shown in Fig. 1, the optical path length from a point A on the planar incident wavefront to the focal point is

$$\ell = d - h(r) + n \cdot h(r) + \sqrt{r^2 + f^2}, \quad (1)$$

where $h(r)$ is the profile of the lens as a function of the diameter r , $d = h(0)$ is the thickness of the lens, $n = 2.23$ is the measured refractive index of silicon nitride, and f is the focal length. The focal length and diameter R of the lens are related by the numerical aperture $\text{NA} = \sin(\theta) = \sin(\tan^{-1}(R/f))$. For a focusing lens, the wavefront becomes a focusing spherical one after the incident planar wave passes through the lens. The lens profile $h(r)$ can be obtained from Eq. (1) by assuming equal optical path length ℓ for all radius r ,

$$h(r) = \left(-\sqrt{r^2 + f^2} + \sqrt{R^2 + f^2} \right) / (n-1), \quad (2)$$

Microlenses with various diameters were designed. However, due to the limitation of the process time in the FIB system, a microlens with a diameter 20 μm is designed as a demonstration of this technique. For a NA 0.65 lens, the focal length

and maximum thickness of the nitride film can be determined as $f = 11.7 \mu\text{m}$, and $d = 3.0 \mu\text{m}$, respectively. The thickness is too large for a deposited silicon nitride film so the profile needs to be sliced. For a 650 nm light source, the reduced thickness, and thus the FIB-milled depth, of the microlens can be calculated as $\lambda/(n-1) = 528 \text{ nm}$. After the slicing, the width of the outmost ring is $0.7 \mu\text{m}$. The design of various microlenses are summarized in Table 1. Fig. 2 shows the designed lens profile of the 20- μm lens coded as a bitmap figure with 256 gray levels to be fed into a FEI Nova Nanolab FIB system.

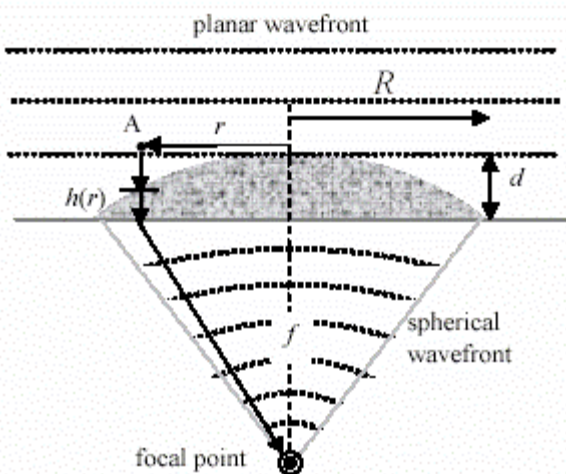


Fig. 1 Schematic diagram of microlens design

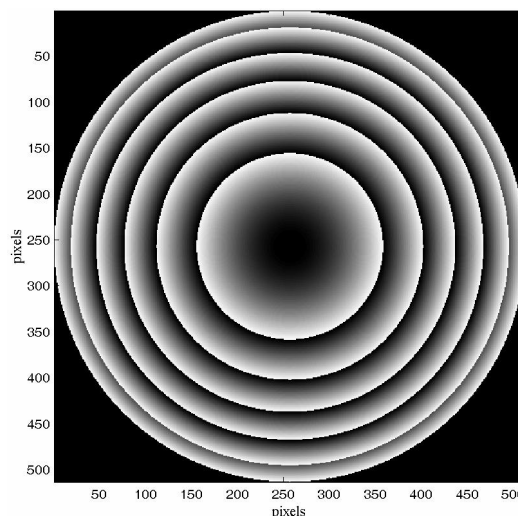


Fig. 2 Bitmap pattern of nitride microlens.

Table 1 Design parameters of micro lenses

Material	Diameter (μm)	Focal length (μm)	Thickness (nm)	Min. linewidth (μm)
silicon nitride	50	29	528	0.21
	30	18	528	0.53
	20	12	528	0.70

3. FABRICATION PROCESS

The fabrication process of the microlens is shown in Fig. 3. A (100)-orientated silicon wafer was used for the substrate. After the RCA cleaning, a 1- μm -thick silicon nitride layer was deposited on both sides of the wafer by low pressure chemical vapor deposition (LPCVD). Then the bulk etching window on the back side was opened by photolithography and reactive ion etching (RIE). After KOH etching of the silicon substrate from the back side, a suspended silicon nitride was formed covering the etched pit. FIB milling was then used to write the microlens pattern in the suspended nitride film according to the input bitmap file. The size of the lens was set in the operation menu. The maximum dwell time and ion current were 1 ms and 0.5 nA, respectively. The total milling time was 20 min. To avoid charge accumulation and its effect on the milling accuracy, a thin layer of gold or platinum was sputtered on the both side of the specimen before the FIB process.

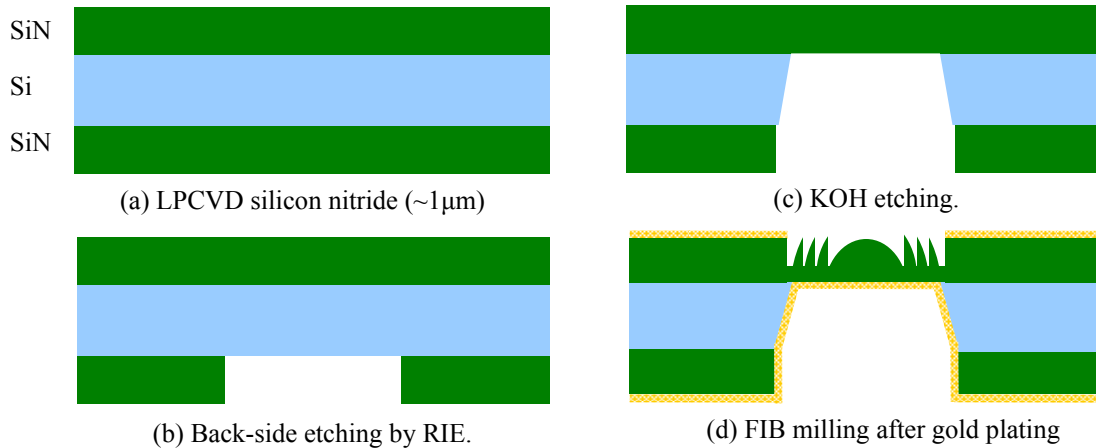


Fig. 3: Fabrication process of the microlens.

4. MEASUREMENT

The SEM micrograph of a fabricated lens is shown in Fig. 4. The surface profile was measured by an atomic force microscope, as shown in Fig. 5. The surface roughness is less than 5 nm. A line scan of the profile is shown in Fig. 6, which is compared to the original design. It can be seen that the center part of the microlens matched well with the desired profile, whereas the fine outer rings did not fully resolve in this device. From measurement of various milled microlens, it is observed that the minimum resolvable zone profile is about 1 μm wide under current beam parameters. However, the step height between zones is generally smaller than the desired value. Without changing the ion beam parameters such as current, dwell time and magnification, we are currently in the process of fine tuning the design profiles near the steps to compensate for the reduced height.

The focal length and focused spot size were measured using a 633-nm HeNe laser, as shown in Fig. 7. After the laser light passed through the microlens, a microscope objective was placed behind the lens. The collected images were captured by a CCD camera. The focal length was measured as the difference in the microlens positions for a clear image and a minimum spot on the CCD image, as shown in Fig. 7. The measured focal length of the 20- μm microlens was 12 μm ; therefore the numerical aperture was 0.64. In addition, the focused spot size at the focal point was measured by comparing the CCD images of spot and the lens image with a known diameter. The two-dimensional spot profile captured by the CCD camera and the full width at half maximum (FWHM) spot size measurement are shown in Figs. 8 and 9, respectively. Due to the reduced step height in the outer rings shown in Fig. 6, the focused spot size was 0.64 μm , larger than the diffraction limit of a NA 0.65 lens, $s = 0.5 \lambda/\text{NA} = 0.49 \mu\text{m}$. Conversely, the FIB-milled microlens has an effective NA of 0.5.

5. CONCLUSION

Focused ion beam milling is used to fabricate microlenses in silicon nitride films. The minimum resolvable zone profile is about 1 μm wide. The measured NA of a 20- μm microlens is 0.64, closed to the design specification of 0.65. However, the focused spot size of 0.64 μm is larger than the diffraction limit of 0.49 μm due to the fabrication errors in the outer rings. The refinement of design and fabrication parameters is in progress. This work is partially supported by the Ministry of Economic Affairs by the grand No. 95-EC-17-A-07-S1-011. The authors are grateful to the National Nano Device Laboratory and Nano Facility Center of National Chiao Tung University for the use of their facilities.

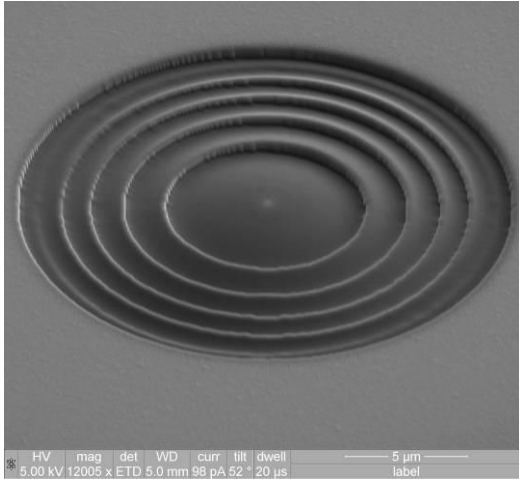


Fig. 4 SEM micrograph of the microlens

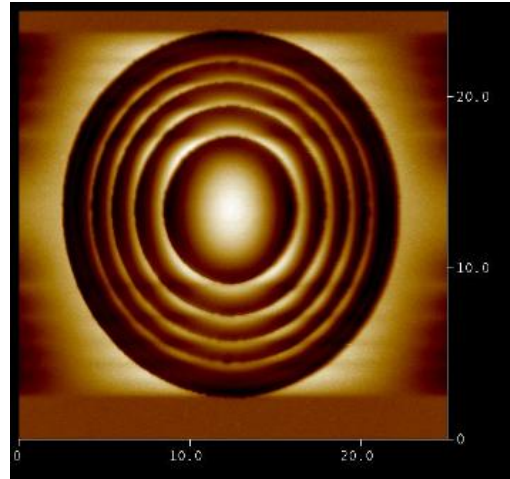


Fig. 5 AFM measurement of the microlens.

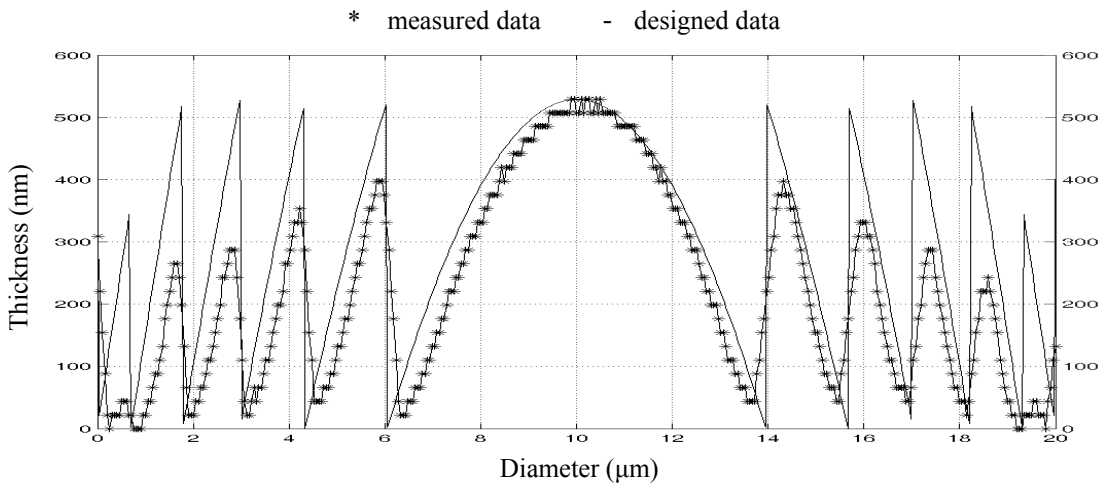


Fig. 6: AFM line-scan profile of the microlens as compared to the design.

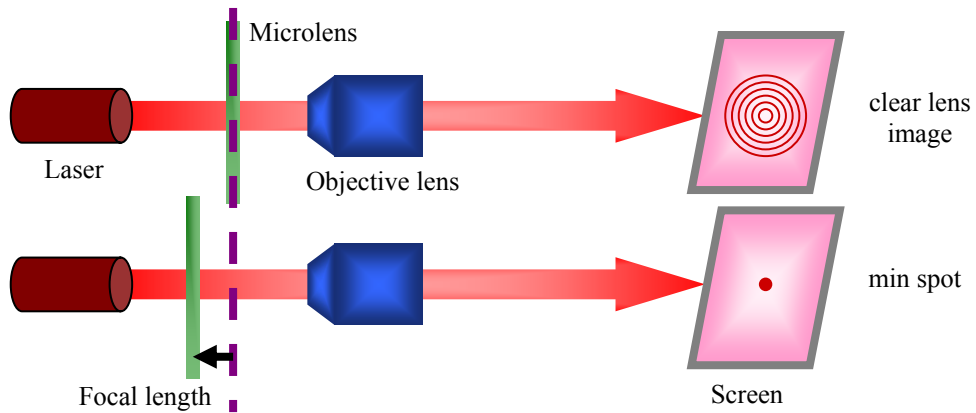


Fig 7 Optical measurement setup

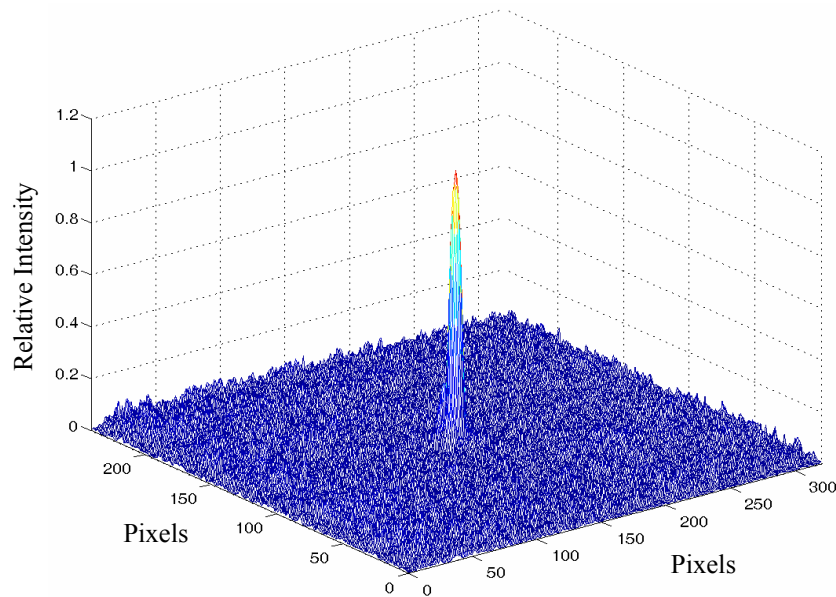


Fig. 8 Profile of the focused spot.

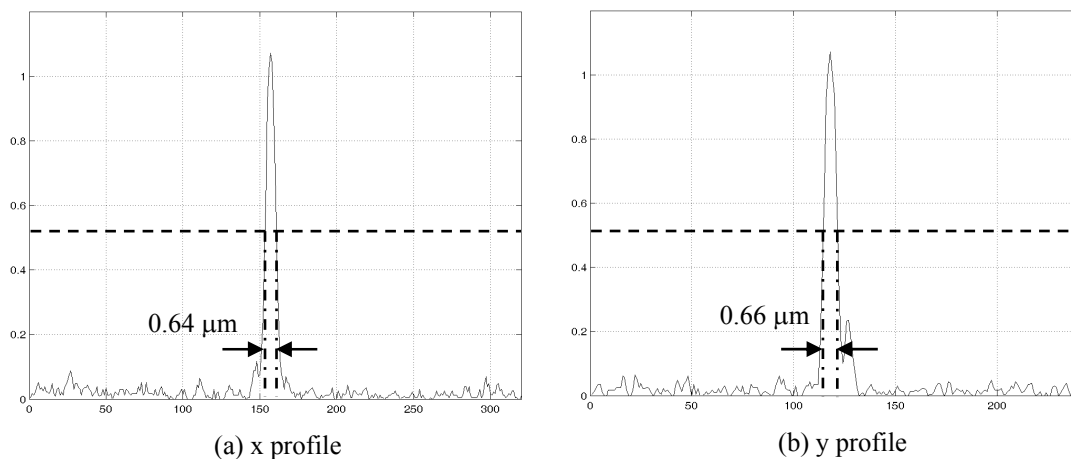


Fig. 9 FWHM of the focused spot

REFERENCE

- [1] Daly D, Steven RF, Hutley MC, and Davis N, "The manufacture of microlenses by melting photoresist," *Measurement Science & Technology*, Vol. 1, No. 8, pp. 759-66 (1990).
- [2] Wu MC, "Micromachining for optical and optoelectronic systems," *Proceedings of the IEEE*, Vol. 85, No. 11, pp. 1833-56 (1997).
- [3] Wang MR, Su H, "Laser direct-write gray-level mask and one-step etching for diffractive microlens fabrication," *Applied Optics*, Vol. 37, No. 32, pp. 7568-76 (1998).
- [4] Fu Y and Ngoi B KA, "Investigation of direct milling of micro-optical elements with continuous relief on a substrate by focused ion beam technology," *Applied Optics*, Vol. 37, No. 32, pp. 7568-7576 (1998).
- [5] Waits CM, Modafe A, and Ghodssi R, "Investigation of gray-scale technology for large area 3D silicon MEMS structures," *Journal of Micromechanics and Microengineering*, Vol. 13, No. 2, pp. 170-7 (2003).
- [6] Daschner W, Long P, Stein R, Wu C, and Lee SH, "Cost-effective mass fabrication of multilevel diffractive optical

elements by use of a single optical exposure with a gray-scale mask on high-energy beam-sensitive glass,” *Applied Optics*, Vol. 36, No. 20, pp. 4675-80 (1997).

- [7] Chang JY, Wang CM, Lee CC, Shih HF, and Wu ML, “Realization of free-space optical pickup head with stacked Si-based phase elements,” *IEEE Photonic Technology Letters*, Vol. 17, No. 1, pp. 214-216 (2005).
- [8] Chiu Y. Chen CH, Chiou JC, Fang W, and Shieh HP D, “MEMS-based miniature optical pickup,” *IEEE Transaction on Magnetics*, Vol. 41, No. 2, pp. 967-970 (2005).