IOP PUBLISHING JOURNAL OF MICROMECHANICS AND MICROENGINEERING

J. Micromech. Microeng. **17** (2007) 1593–1597 doi:10.1088/0960-1317/17/8/023

Smoothing dry-etched microstructure sidewalls using focused ion beam milling for optical applications

In-Hyouk Song, Yves-Alain Peter and Michel Meunier

Department of Engineering Physics, École Polytechnique de Montréal, CP 6079, Succ. Centre-ville, Montréal, Québec H3C 3A7, Canada

Received 1 May 2007
Published 13 July 2007
Online at stacks.iop.org/JMM/17/1593

Abstract
This paper presents a new sidewall smoothing process for Si micro-optical components using focused ion beam (FIB) milling. First, the deep reactive ion etching (DRIE) Bosch process is employed to form a microstructure on a Si substrate. However, scalloping which is induced on the sidewall by the repetition of etching and passivation steps is a major source of light scattering, reducing surface reflectivity in optical applications. In this research, FIB is used to smooth the rough sidewall surface and obtain polished mirror surface. After the DRIE Bosch process, the values of sidewall roughness as measured by atomic force microscopy were 153.0 ± 13.5 nm with an rms value of 28.1 ± 6.4 nm. The FIB smoothing process tremendously improved the surface roughness of etched sidewalls resulting in a maximum peak-to-valley roughness and an rms roughness of 5.7 ± 1.8 nm and 1.6 ± 0.7 nm, respectively. In this paper, the DRIE Bosch process and the FIB smoothing process are described in detail and applications using this technique are discussed.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Microelectromechanical systems (MEMS) that include optical components are often referred to as micro-opto-electro-mechanical systems (MOEMS). Recently, Si MEMS have been employed for optical components such as optical switches, micro-mirrors, projection displays, adaptive optics and variable optical attenuator [1–8]. Smoothing the sidewall of microstructures is technologically important for producing optical components. Hence, the smoothing process has been extensively investigated and proposed using wet etching or dry etching techniques to fabricate Si microstructures for optical applications. Yun reported a KOH wet etching process after the deep reactive ion etching (DRIE) process to devise a Si micro-mirror with an rms roughness down to 9.6 nm [7]. However, this technique requires a precise alignment to achieve desired angles since the etching angle is dependent on crystal orientation. In contrast, dry etching methods are more flexible for designing and fabricating micro-optical components, but usually lead to rougher surfaces.

Deep reactive ion etching (DRIE) is one of the most used techniques to fabricate Si optical components with nano-scaled roughness. DRIE based on electron cyclotron resonance (ECR) source followed by thermal oxidation or boron diffusion has been used to fabricate high aspect ratio vertical Si micro-mirrors with good optical properties [9]. The additional oxidation and diffusion process after dry etching was reported to help sidewall roughness reducing down to 5 nm. However, this process could only be applied on samples that can be exposed to high temperature (over 1100 °C). In this paper, the DRIE Bosch process based on an inductively coupled plasma (ICP) source was used to form microstructures [10]. The DRIE Bosch process is useful in Si micromachining to fabricate high aspect ratio structures [11, 12]. It has been also reported to fabricate vertical mirrors with several tens of nanometers of rms value of surface roughness [2, 6]. However, it is still necessary to reduce roughness in order to increase reflectivity of optical components since roughness of the order of $\lambda/10$ results in significant light scattering for optical surfaces.

This paper introduces an alternative method to enhance surface smoothness combining the DRIE Bosch process with the focused ion beam (FIB) milling process. FIB has been widely employed in semiconductor research and processing environments for highly precise milling and deposition of conductors or insulators [13–15]. The FIB technique has also been reported in Si micromachining applications for performing unique and highly precise process on a relatively low scale, where the inherent slow FIB processing time is not an issue [16, 17]. This paper presents the use of FIB milling as a means of smoothing Si sidewall to improve surface roughness quality for optical applications.

2. Experimental details

A one-mask process shown in figure 1 is used to fabricate a prototype microstructure consisting of a vertical micro-mirror. A brief overview of the fabrication process is given as follows. First, a 7 μm thick photoresist is spin-coated as a mask layer for the DRIE Bosch process on a Si substrate. It is then patterned with UV lithography, thus creating an opening window for Si etching (figure 1(*a*)). The opened Si area is etched down to 67 μm by the DRIE Bosch process (figure 1(*b*)). Then, the passivation layer due to the DRIE Bosch process and the photoresist mask layer are simultaneously stripped away by an O_2 plasma etching process. Finally, a vertically standing microstructure is obtained. The etched sidewall is not smooth, but scalloped. The scalloping of the microstructure sidewall is then smoothened using the FIB milling process (figure 1(*c*)). The dimension of polished optical mirror is 100 μm wide and 67 μm high. Details of the DRIE Bosch and FIB smoothing processes are given below.

2.1. Microstructure patterning

Deep reactive ion etching (DRIE) allows large and vertical structures to be created that are used in micro-optical applications. The DRIE Bosch process is useful to fabricate vertical sidewall microstructures with a relatively high etch rate. Another advantage of the DRIE Bosch process is to allow the use of a photoresist as a mask material which simplifies the process. In this experiment, a 7 μm thick SPR 220 photoresist is used. Figure 2 schematically illustrates the DRIE Bosch process after the photoresist mask patterning. The DRIE Bosch process is based on alternating Si etching steps using SF_6 as reacting gas and passivation steps by fluorocarbon polymer layer deposition from C_4F_8. Table 1 shows the DRIE Bosch process parameters used in this experiment. The DRIE Bosch process is followed by an O_2 plasma etching to remove the passivation layer resulting from deposition steps. As a consequence of repeated isotropic etching and passivating steps, etched sidewalls are scalloped, as seen in the scanning electron microscopy (SEM) photograph of the Si sidewall (figure 3). The scalloping produces shadows during metal deposition using evaporation, further contributing to a non-uniform thickness. The roughness due to scalloping could be reduced by adjusting the etching and deposition step efficiencies or the frequency of the two steps [18]. Whatever the approaches, scalloping cannot be completely removed in the DRIE Bosch process.

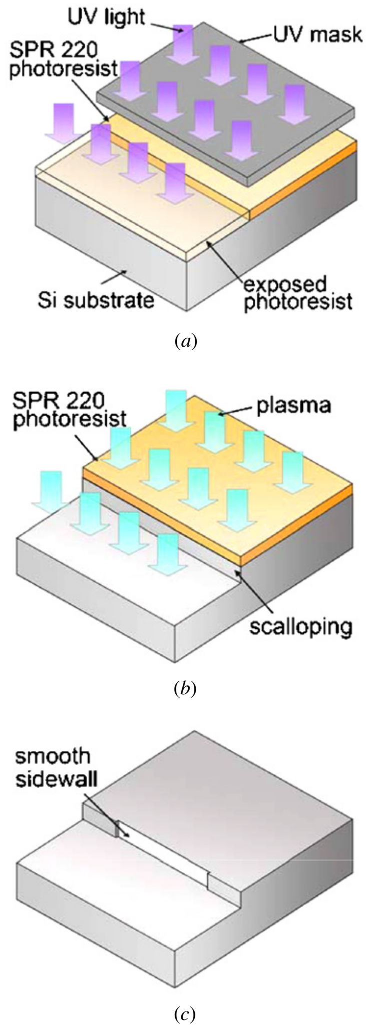


Figure 1. Schematic diagrams of smoothing procedures using the FIB milling technique. (*a*) 7 μm thick SPR 220 photoresist mask patterning using UV lithography. (*b*) 67 μm deep Si etching using the DRIE Bosch process. (*c*) Smoothing process on the sidewall using the FIB milling technique. The size of the polished area is 100 μm wide and 67 μm high.

Table 1. DRIE Bosch process parameters for silicon etching.

Cycle step	Etching	Deposition
Gas flow rate (sccm)	SF_6: 50 C_4F_8: 1	SF_6: 1 C_4F_8: 50
Active time (s)	8	8
Pressure (mTorr)	20	20
Substrate temperature (°C)	20	20
ICP power (W)	450	450
Platen RF power (W)	26	0
Bias (V)	110–126	0

2.2. Focused ion beam (FIB) smoothing

In order to limit the fabrication imperfections for micro-optical components due to scalloping in the DRIE Bosch process, additional smoothing process is introduced using a FIB milling technique. One of the main features of a FIB is to locally mill the target material by physical sputtering. The milling is achieved using a high current ion beam and by scanning it

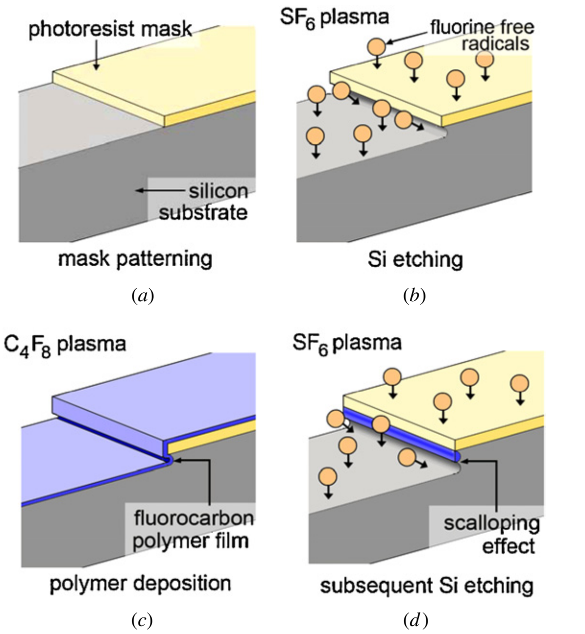


Figure 2. Schematic diagrams of the DRIE Bosch process. (*a*) 7 μm thick SPR 220 photoresist mask patterning using UV lithography. (*b*) The first isotropic etching in SF_6 plasma. The fluorine-free radicals in the SF_6 plasma etch the exposed silicon. (*c*) The first cycle of passivation in the C_4F_8 plasma. Fluorocarbon polymer film is deposited. (*d*) The subsequent isotropic etching in SF_6 plasma. Etching and deposition steps result in scalloping on the sidewall.

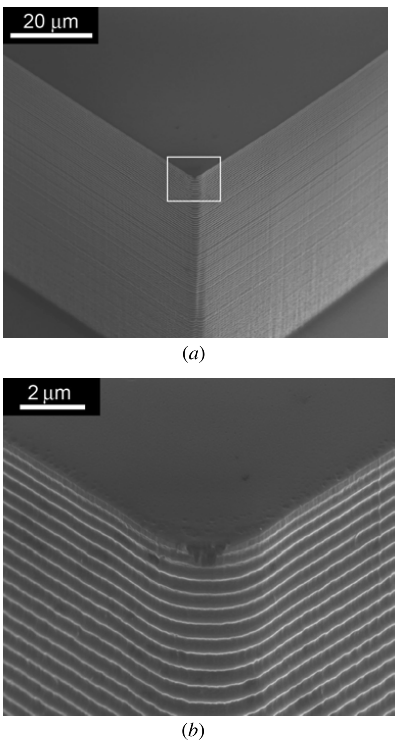


Figure 3. (*a*) SEM photograph of a Si sidewall after the DRIE Bosch process. The structure height is 67 μm. (*b*) Inset details of scalloping due to the DRIE Bosch process.

over the substrate. The technique presents the advantage that any arbitrary designed shape can be patterned.

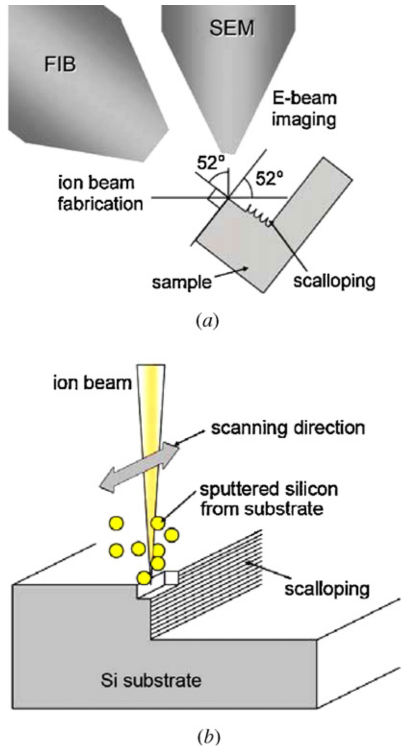
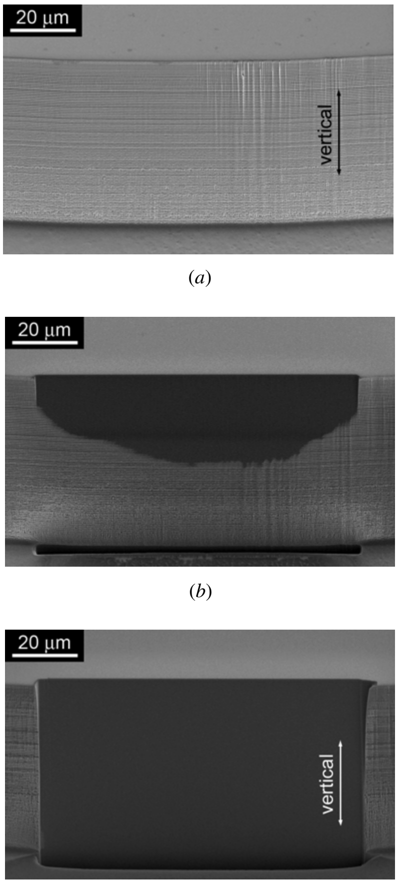


Figure 4. (*a*) A schematic diagram of the FEI™ dual-beam DB235 FIB workstation. The sample is tilted 52° offset for the smoothing sidewall process. (*b*) A schematic diagram of the principle of the FIB milling process. Milling is carried out over 100 μm along the scanning direction.

In this research, smoothing the Si sidewall is carried out using a commercially available FEI™ dual-beam DB235 FIB. Figure 4(*a*) illustrates the schematic diagram of the workstation equipped with a focused ion beam column and a scanning electron microscope column tilted to each other at an angle of 52°. The ion beam and the electron beam are used for microfabrication and imaging, respectively. The ion beam is generated from liquid gallium. The workstation provides beam currents varying between 1 pA and 20 nA. The high beam current is suitable for fast milling process while the lower beam current is for fine structures with high resolution.

In this experiment, the ion beam energy is operated at 30 keV, with 10 nA of beam current. First, the FIB chamber is pumped down to an operating vacuum below 3×10^{-6} mbar. The electron beam is then focused at a point on the sidewall edge which is used as an eucentric point. Due to the 52° offset between the ion beam column and the vertical electron beam column of the system, the stage is tilted 52° so that the sample plane is normal to the ion beam column during the smoothing process. By scanning the beam over the designed area on the sample, the scalloping on the sidewall of microstructure can be polished with high precision as illustrated schematically in figure 4(*b*). The dwell time is left at default value to 1 μs. To mill a sidewall surface with high smoothness, the ion flux with respect to the scanning direction has to be constant. As proposed by Tseng [19], good ion flux uniformity should be obtained when the beam overlap as controlled by the distance between the centers of two adjacent pixels is larger than 36.3%. In order to have a uniform scanning ion flux, a 50% overlap



(*a*)

(*b*)

(*c*)

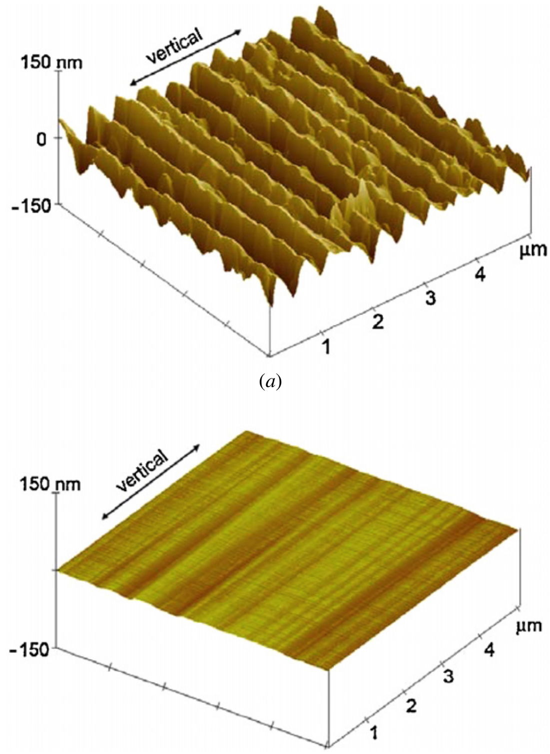
Figure 5. Si sidewall smoothing process on a 67 μm thick microstructure using FIB. (*a*) SEM photograph after DRIE Bosch microstructure patterning. (*b*) SEM photograph during sidewall smoothing using FIB. (*c*) SEM photograph after the sidewall smoothing process using FIB. The opening size is 100 μm in width and 67 μm in height.

of beams is used as the default value. In this process, careful monitoring is necessary in order to avoid under-etching and over-etching during the smoothing process.

3. Experimental results

The SEM photographs are taken along a 52° tilted angle with the sidewall surface prepared by FIB milling. The smoothing steps are shown in figure 5. Figure 5(*a*) shows the sidewall of a 67 μm thick microstructure formed with the DRIE Bosch process. The same sidewall is observed during the FIB milling process (figure 5(*b*)). In figure 5(*c*), the sidewall scalloping is completely removed by the FIB over the 100 μm $\times$ 67 μm surface.

The surface profiles were measured on the vertical sidewalls using a MultiMode V atomic force microscopy (AFM) in contact mode. Five samples of the post-DRIE Bosch process and five samples of the post-FIB milling process were prepared for AFM scanning. The AFM measurements performed on a 5 μm $\times$ 5 μm area were averaged to give a statistical estimation of the true surface roughness. According to the measurements given in table 2, for the post-DRIE Bosch process, the average maximum peak-to-valley roughness was measured to be 153.0 $\pm$ 13.5 nm and the average rms roughness value was 28.1 $\pm$ 6.4 nm. Figure 6(*a*) shows a representative AFM surface image of the sidewall of figure 5(*a*) prior to the FIB smoothing process with 168.6 nm maximum peak-to-valley roughness and 21.6 nm rms value. Note that this surface cannot be an effective micro-mirror in the visible because this roughness is much larger than the usual criteria of $\lambda/10$. In contrast, the surface roughness was tremendously reduced after the FIB smoothing process. The average maximum peak-to-valley roughness and the average rms roughness were brought down to 5.7 $\pm$ 1.8 nm and 1.6 $\pm$ 0.7 nm, respectively. Figure 6(*b*) shows an AFM scanning image of the smooth area of figure 5(*c*). Measured values of the maximum peak-to-valley roughness and the rms roughness are 6.9 nm and 1.4 nm, respectively. This surface is smooth enough to act as an effective reflective micro-mirror.



(*a*)

(*b*)

Figure 6. (*a*) AFM 3D scan image of the etched sidewall of figure 5(*a*). The measured maximum peak-to-valley roughness and rms roughness are 168.6 nm and 21.6 nm, respectively. The scan area is 5 μm $\times$ 5 μm. (*b*) AFM 3D scan image of the sidewall surface of figure 5(*c*). The measured maximum peak-to-valley roughness and rms roughness are 6.9 nm and 1.4 nm, respectively. The scan area is 5 μm $\times$ 5 μm.

Table 2. Roughness for the sidewall surface of microstructures as measured by AFM.

Process	Roughness	Average roughness (nm)
Post-DRIE Bosch	RMS	28.1 $\pm$ 6.4
	Peak-to-valley	153.0 $\pm$ 13.5
Post-FIB milling	RMS	1.6 $\pm$ 0.7
	Peak-to-valley	5.7 $\pm$ 1.8

4. Conclusion

We demonstrated a new, powerful smoothing process to achieve high optical quality surface roughness for MOEMS structures combining the techniques of FIB milling following the DRIE Bosch process. Roughness is an important factor for evaluating optical qualities since reflectivity strongly depends on the surface roughness of optical components. The proposed technique overcomes roughness limitations experienced with the Si DRIE Bosch process. This paper demonstrated the capability of the FIB milling process for smoothing sidewalls of micro-optical components. Using the proposed technique, the rms roughness of the sidewall was measured to be as low as 1.6 nm with a standard deviation of 0.7 nm. The process developed in this research can be used in the fabrication of micro-optical devices since it enables vertical sidewalls with a smooth surface while retaining the design flexibility of the silicon DRIE Bosch process.

Acknowledgments

The authors thank Mr Phillippe Vasseur of the Microfabrication Laboratory (LMF) at École Polytechnique de Montréal for assistance in this project. The financial contribution of the Canadian Institute for Photonics Innovations (CIPI) is acknowledged.

References

[1] Uenishi Y, Masahiro T and Mehregany M 1995 Micro-opto-mechanical devices fabricated by anisotropic etching of (110) silicon *J. Micromech. Microeng.* **5** 305–12

[2] Syms R R A, Zou H, Stagg J and Moore D F 2004 Multistate latching MEMS variable optical attenuator *IEEE Photon. Technol. Lett.* **16** 191–3

[3] Rosengren L, Smith L and Backlund Y 1994 Micromachined optical planes and reflectors in silicon *Sensors Actuators* A **41–42** 330–3

[4] Smith L, Tenerz L and Hok B 1990 Silicon micromachined (2×2) optocoupler *Proc. SPIE* **1281** 91–5

[5] Klaassen E H, Petersen K, Noworolski J M, Logan J, Malu N I, Brown J, Storment C, McCulley W and Kovacs G T A 1996 Silicon fusion bonding and deep reactive ion etching: a new technology for microstructures *Sensors Actuators* A **52** 132–9

[6] Marxer C, Thio C, Gretillat M-A, de Rooij N F, Battig R, Anthamatten O, Valk B and Vogel P 1997 Vertical mirrors fabricated by deep reactive ion etching for fiber-optic switching applications *J. Microelectromech. Syst.* **6** 277–85

[7] Yun S-S, You S-K and Lee J-H 2006 Fabrication of vertical optical plane using DRIE and KOH crystalline etching of (1 1 0) silicon wafer *Sensors Actuators* A **128** 387–94

[8] Jung I W, Peter Y-A, Carr E, Wang J-S and Solgaard O 2007 Single-crystal-silicon continuous membrane deformable mirror array for adaptive optics in space-based telescopes *IEEE J. Sel. Top. Quantum Electron.* **13** 162–7

[9] Juan W H and Pang S W 1996 Controlling sidewall smoothness for micromachined Si mirrors and lenses *J. Vac. Sci. Technol.* B **14** 4080–4

[10] Larmer F and Schilp A 1996 Method of anisotropically etching silicon *US Patent* US5501893, March 26. Applicant: Robert Bosch GmbH, Stuttgart, Germany

[11] Milanovic V, Kwon S and Lee L P 2004 High aspect ratio micromirrors with large static rotation and piston actuation *IEEE Photon. Technol. Lett.* **16** 1891–3

[12] Carlen E T, Heng K-H, Bakshi S, Pareek A and Mastrangelo C H 2005 High-aspect ratio vertical comb-drive actuator with small self-aligned finger gaps *J. Microelectromech. Syst.* **14** 1144–55

[13] Youn S, Takahashi M, Goto H and Maeda R 2006 A study on focused ion beam milling of glassy carbon molds for the thermal imprinting of quartz and borosilicate glasses *J. Micromech. Microeng.* **16** 2576–84

[14] Stewart D K, Doyle A F and Casey Jr J D 1995 Focused ion beam deposition of new materials: dielectric films for device modification and mask repair, and Ta films for x-ray mask repair *Proc. SPIE* **2437** 276–83

[15] Smith S, Walton A J, Bond S, Ross A W S, Stevenson J T M and Gundlach A M 2003 Electrical characterization of platinum deposited by focused ion beam *IEEE Trans. Semicond. Manuf.* **16** 199–206

[16] Daniel J H and Moore D F 1999 A microaccelerometer structure fabricated in silicon-on-insulator using a focused ion beam process *Sensors Actuators* A **73** 201–9

[17] Brugger J, Beljakovic G, Despont M, de Rooij N F and Vettiger P 1997 Silicon micro/nanomechanical device fabrication based on focused ion beam surface modification and KOH etching *Microelectron. Eng.* **35** 401–4

[18] Chang C, Wang Y-F, Kanamori Y, Shih J-J, Kawai Y, Lee C-K, Wu K-C and Esashi M 2005 Etching submicrometer trenches by using the Bosch process and its application to the fabrication of antireflection structures *J. Micromech. Microeng.* **15** 580–5

[19] Tseng A A 2004 Recent developments in micromilling using focused ion beam technology *J. Micromech. Microeng.* **14** R15–34