

Roughness Treatment of Silicon Surface after Deep Reactive Ion Etching

Hoa T.M. Pham, Charles R. de Boer, Pasqualina M. Sarro

Abstract— In this paper, the roughness of the silicon surface after dry etching, in both vertical and horizontal direction, is studied. Structures with different shape (circular, square) and size (from 0.5 μm to 50 μm) are etched using the Bosch process. The etch depth varies between 5 and 100 μm . The surface roughness depends on the etching parameters and on the aspect ratio of the structures. To reduce the roughness of the sidewall, exposure to NH_3 plasma is performed in a PECVD system. The experiment is carried out at pressure of 3.5Torr, power of 700W, temperature of 400°C and NH_3 flow rate of 2400sccm. The obtained results will be discussed and compared to oxidation method.

Index Terms— Deep Reactive Ion Etching (DRIE), plasma, surface roughness, wet etching.

I. INTRODUCTION

THE fabrication of precisely dimensioned 3D microstructures with well controlled surfaces is of great importance for improving the optical and electro-mechanical performance of micro/nanoelectromechanical systems (MEMS/NEMS). Etching processes play a key role in the fabrication of silicon-based 3D microstructures. A wide variety of wet anisotropic etchants such as potassium hydroxide (KOH), sodium hydroxide (NaOH) and ammonium hydroxide (NH_4OH), tetramethylammonium hydroxide (TMAH), etc. and dry reactive ions, including CF_4 , SF_6 , CHF_3 , BCl_3 , etc. for etching Si have been employed [1-3].

The control of the roughness, for both the bottom and the vertical sidewalls of the etched structures, is quite relevant for a large number of applications. In fact, smooth sidewall morphology and vertical profile are necessary to minimize light scattering and maintain collimated light beam when the etched sidewall is used as mirror surface [4]. The roughening of the surfaces can also affect the nanotribological (friction and wear) behavior as well as other mechanical properties of the etched

microstructures. Liquid distribution in a static microfluidic device is influenced by the capillary force and

surface tension which, in turn, largely depend on the surface roughness. In a flowing channel, surface roughness results in unsteady secondary flow [5]. Another application which is strongly affected by the roughness of the surface is wafer to wafer bonding. The mechanism of direct wafer bonding at room temperature has been attributed to the short range intermolecular and interatomic attraction forces, such as van der Waals forces. Consequently, the wafer surface smoothness becomes one of the most critical parameters in this process. High surface roughness will result in small real area of contact, and therefore yield voids at the bonding interface. When the surface roughness exceeds a critical value, the wafers will not bond at all [6].

As often reported in literature, wet etching of Si generally results in very high surface roughness as compared to dry etching. In order to improve the smoothness of the surface after wet etching, several methods such as adding metallic elements such as magnesium (Mg) into KOH solution to create a hydroxide complex to collect impurities in the solution or adding isopropyl alcohol (IPA) to hinder the access of reactive OH^- ions when it adsorbs on the etched surface.

Dry etching processes are also not exempted from surface roughness, though of a different type [2,7]. Methods to smoothen the etched surfaces dry etching processes produce are also being investigated.

In this paper, after a brief overview of recently presented methods used to reduce the roughness of the etched Si surface after deep reactive ion etching (DRIE), a new method which uses NH_3 plasma to smoothen the surface of Si after DRIE is presented.

II. SURFACE ROUGHNESS AFTER DRIE AND SMOOTHEN TREATMENTS

Deep Reactive Ion Etching (DRIE) has become one of the most important processes in MEMS fabrication and is a potentially competitive technology for high volume fabrication. For DRIE of silicon the well established and widely applied Bosch process is used [8,9]. Nevertheless, the Bosch process still shows some defects, especially the surface roughness of the vertically etched sidewall. This process employs cyclic etching and deposition steps to achieve high aspect silicon

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structures and sidewall scalloping is observed. This scalloping is clearly visible in the SEM images shown in Fig.1.

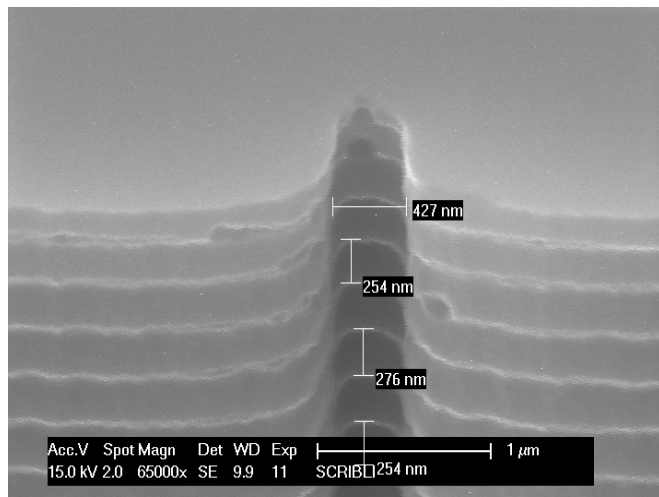
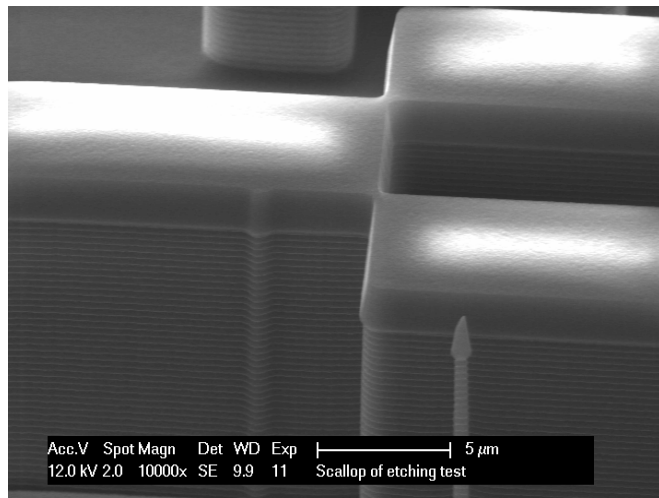


Figure 1. The scalloping effect on the sidewall of a silicon structure etched using the Bosch-process. A close-up indicates the height and depth of the observed roughness.

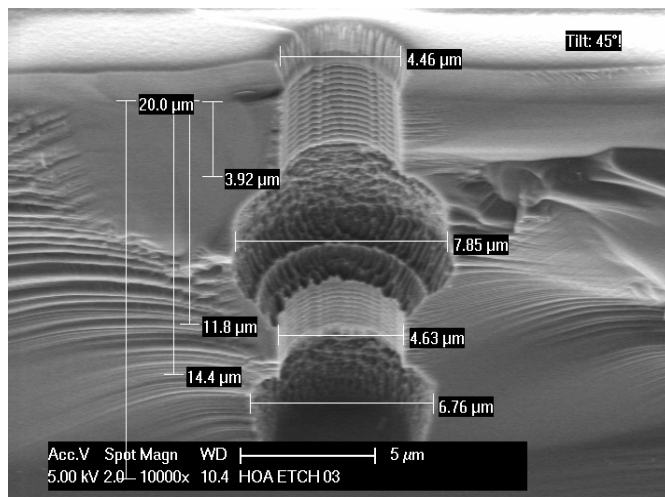


Figure 2. Cross section of a 4.5μm wide circular hole after two cycles of alternating anisotropic and isotropic etching steps.

Surface roughness, although of a different type is observed also with isotropic dry etching processes. This can be seen when a combination of in-situ isotropic and anisotropic etching steps, using an ICP reactor and without interruption of vacuum (in-situ), are performed [10]. The anisotropically etched regions suffer from scalloping while the isotropically etched ones show a different type of roughness (see Fig. 2).

It has been reported that the smoothening of the scalloping on the sidewalls can be achieved by controlling the etching parameters. The concentration of O₂ in the gas flow and the electrode bias are found to be important in controlling via features. The pressure and the electrode bias can have a dominant effect on the sidewall morphology. The smoother surface is achieved at higher rf power. It is also reported that the more directional ion are present, the fewer collisions with Si sidewalls occur resulting in a smoother surface [11-13].

Several post treatments including wet and dry methods have been reported to improve the roughness of etch silicon surface. For example, Nilsson et al. [14] used chemical wet etching with an aqueous KOH + IPA solution after the DRIE on a (100) silicon wafer, followed by thermal oxidation to improve the smoothness of the vertical sidewall on a (110) surface. Yun et al [15] proposed a new method using KOH crystalline etching at low concentration and low temperature to smoothen the vertical etched sidewall of (110) SOI wafer after DRIE.

To provide design flexibility and smooth vertical sidewall, Juan [13] suggested to use thermal oxidation and subsequent removal of the oxide layer after the DRIE process. A higher oxidation temperature appears to be more effective in smoothening the silicon sidewalls. The dependence of sidewall smoothness on oxidation temperature could be related to the temperature dependent viscous stress for two dimensional oxide growth. By employing hydrogen annealing, M.M. Lee et al. [16] demonstrated that sidewall scalloping can be dramatically reduced. The root-mean-square (rms) surface roughness is estimated to be 100nm at the sidewall. The wafer was then annealed in pure hydrogen at 1100°C, 10 torr for 10 min. The surface roughness on both the sidewall and the substrate was dramatically reduced. Sacrificial thermal oxidation has been utilized to improve sidewall quality [17]. However, this process consumes too much silicon and builds up residual stress in the microstructure, effects that are often detrimental to the proper working of the final device.

III. NH₃ PLASMA FOR ROUGHNESS REDUCTION

Most of the methods used so far to smoothen the rough surfaces resulting from DRIE of silicon use high temperature steps or are very complex or time consuming. The process we developed is fully IC compatible as it only requires a temperature of 400°C. Several test structures with different shape (circular, square) and size (from 0.5μm to 50μm) are patterned and etched using the Bosch process. The in-situ isotropic and anisotropic etching of Si is carried out in an

Adixen (AMS100 I-speeder) reactor. Each single stage of the process consists of the following steps: (a) anisotropic etching Bosch process, (b) sidewall passivation using C_4F_8 chemistry, (c) isotropic etching using SF_6 chemistry and finally (d) passivation removal by O_2 plasma. The etching parameters employed are summarized in Table I.

Table I: The main parameters used for the in-situ isotropic and anisotropic etching steps

Parameters	Value	
	<i>Isotropic etching</i>	<i>Anisotropic etching</i>
SF_6 (sccm)	400	400
C_4F_8 (sccm)	-	280
Power(W)	1500	1500
Pressure(mbar)	2.3×10^{-2}	2.3×10^{-2}
Temperature ($^{\circ}C$)	$-10^{\circ}C$	$-10^{\circ}C$

The etch depth varies between 5 and 100 μm . The surface roughness depends on the etching parameters and the aspect ratio of the structures. After etching, the silicon wafers are first placed in oxygen plasma (Tepla stripper) for one hour to remove the passivation layer, and then in a HF 40% solution for 5 minutes to remove the SiO_2 mask. After rinsing and drying the plasma treatment is applied. The parameters setting of the NH_3 treatment can be seen in Table II.

Table II: NH_3 plasma treatment condition after DRIE step

Parameters	Value
Pressure (Torr)	3.5
NH_3 flow rate (sccm)	2400
Power (W)	700
Time (sec)	1800
Temperature ($^{\circ}C$)	400
Mode	Uniformity

The surface roughness of silicon after a DRIE step depends on the etching parameters. Figure 3 shows the silicon sidewall (high magnification image) of a 5 μm diameter hole, after isotropic etching and after treatment in NH_3 plasma, respectively. The results show that NH_3 plasma can be indeed used to reduce the roughness of the Si surface produced by the isotropic etching step.

In a NH_3 plasma environment, the incident hydrogen ion flux is fixed at constant plasma parameters. The substrate temperature determines the subsurface hydrogen concentration. When the NH_3 plasma is in contact with a rough Si surface, the surface is bombarded with energetic hydrogen ion in plasma, especially at the hillocks. Hydrogen plasma etches Si and the etching reaction may be explained by the classical nucleation theory [19].

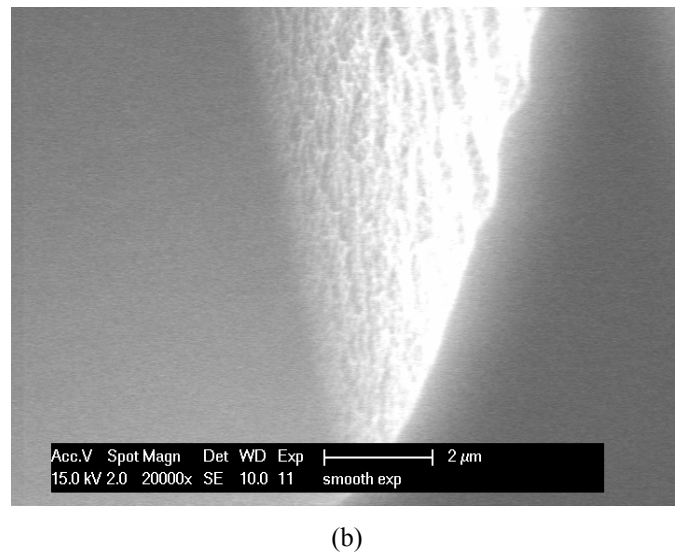
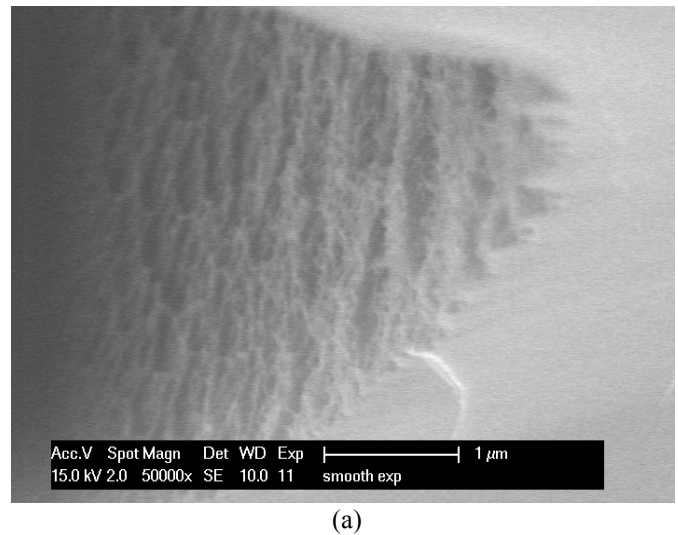


Figure 3. The etched sidewall before (a) and after (b) treatment in NH_3 plasma.

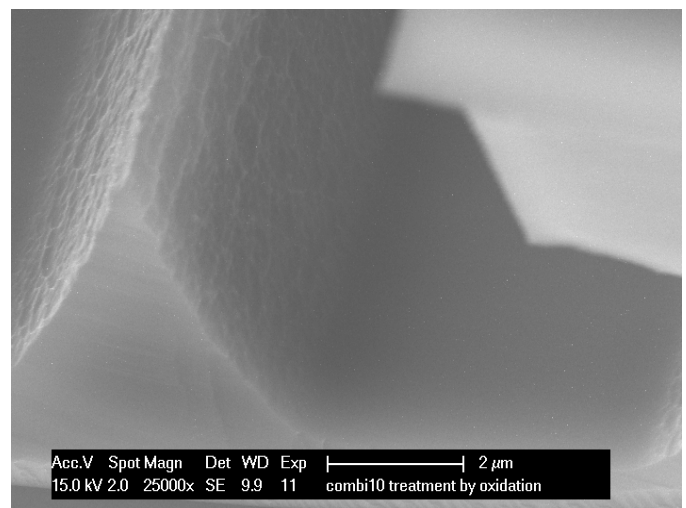


Figure 4. The etched surface after the oxidation treatment.

To compare the effect of the NH₃ plasma treatment to the thermal oxidation, the traditionally used method to smoothen the etched surface, we have applied the thermal oxidation method to the same structure (see Fig. 4).

By comparing Fig. 4 with fig 3b it can be observed that the here proposed plasma treatment gives similar results without the high temperature the oxidation method requires.

IV. CONCLUSION

In this paper, a new method to smoothen the surface of silicon after etching is presented. By exposing the silicon surface to a NH₃ plasma a clear reduction of the surface roughness is observed. The results are comparable to the ones achieved with thermal oxidation methods without the need of high temperature steps. Moreover, by avoiding oxidation unwanted consumption of silicon or building up of residual stress, effects that are often detrimental to the proper working of the final device, are prevented. More work is in progress to fine tune the plasma process and to establish a relationship between the specific dry etching process and the optimum plasma condition for roughness reduction.

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