# High-aspect-ratio deep Si etching of micro/nano scale features with $SF_6$ /$H_2$/ $O_2$ plasma, in a low plasma density reactive ion etching system

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## ABSTRACT

Using three gasese of $SF_6$, $O_2$ and $H_2$, deep vertical etching of silicon substrates in a low plasma density environment is reported. A reactive ion etching (RIE) unit with an operating frequency of 13.56 MHz has been used with plasma power densities below 1 W/cm$^2$. The vertical etching process is based on a sequential method with two sub-sequenes, etching and passivation. High etch rates of the order of 0.7 to 1.5 µm/min for deep sub-micrometer features, and aspect ratios about 100 for nano-rods have been achieved.

***Keywords***: deep etching, silicon, reactive ion etch

## 1 INRODUCTION

Deep etching of high-aspect-ratio structures in Si is needed in modern fields as micro/nano electromechanical systems, through-silicon via structures, and super junction power devices. A time-multiplexed etching technique called as "Bosch" process is one of the most established methods to realize complex features with high aspect ratio structures. Despite its strong capabilities, this technique suffers from the formation of scalloped structures on sidewalls, the complexity of the equipment and the expense of the gases (e.g. $C_4F_8$). Cryogenic etching processes, on the other hand, are based on the mixtures of $SF_6$ and $O_2$ gases, as alternative candidates for the Bosch process. They are, however, based on cryogenic coolings and certain limitation on the masking layer[1-3]. The formation of high aspect ratio features has been reported using Bosch process, whereas high etch rates more than 10 µm/min have been achieved using the latter method.

It is worth mentioning that the reported etch rates on nanometric patterns using such techniques have been well below 1 µm/min. A value of 0.3 µm/min has been reported using a magnetron RIE tool with a high horizontal magnetic field [4]. Also, etch rates up to 0.25 µm/min (Bosch process), 0.6 (ferromagnetic-inserted RIE reactor) and 0.2 µm/min using ICP and a mixture of $SF_6/C_4F_8/O_2$/Ar gases have been obtained by several groups [5-7].

In an attempt to realize submicrometer and nanometric featues, we have recently developed a sequential reactive ion etching process based on using $SF_6$, $H_2$ and $O_2$ gases as the main constituents. This technique enjoys the use of low-density capacitive-coupled plasma in a regular RIE machine with a sequential etching and passivation fashion. We have been able to achieve high aspect ratio features at both micro and nano-scales with etch-rates about 1 µm/min. The plasma power density is varying between 0.5-1 W/cm$^2$ while the sample is kept at an ambient temperature without a need to rapid gas management, cryogenic cooling, or ICP incorporation. This cyclic RIE process was used to fabricate features below 300 nm width and high aspect ratios of etched depths over 100.

## 2 EXPERIMENTAL DETAILS

Figure 1 shows, schematically, the etching procedure in this paper. Three gases of $SF_6$, $H_2$ and $O_2$ could be used in the etching and passivation sub-cycles of this process. While mere $SF_6$ plasma results in an isotropic profile, anisotropic vertical features are achieved both with a $SF_6/O_2$ system or a $SF_6/H_2$ etching system. Using $O_2$ in the passivation step with a small trace of $SF_6$ leads to highly anisotropic features in a process, even with short passivation times compared to the etching period.

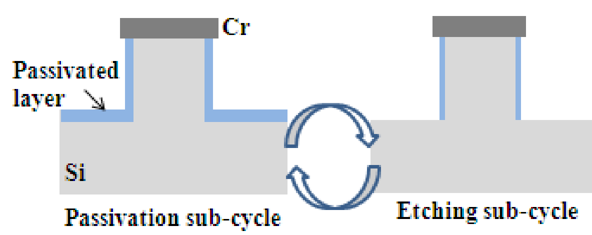


Figure 1: Schematic viewgraph of our DRIE process. In both etching and passivation sub-cycles $SF_6$, $O_2$ and $H_2$ can be used.

## 3 RESULTS

Figures 2 to 7 collect the SEM images of several etched samples. Etching parameters such as flow of gases, plasma time and power should be properly adjusted to achive the desired etched profile. Figure 2 depicts the result of an improper passivation leading to an isotropic etching of silicon, showing round regular plates which are almost suspended.

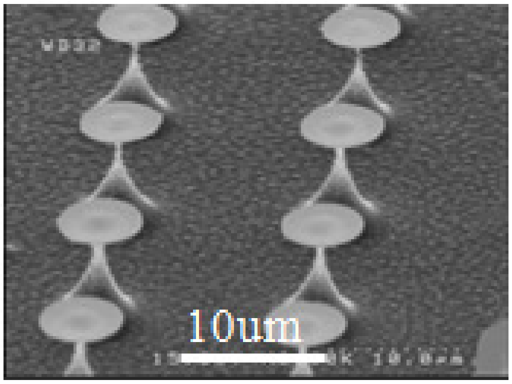


Figure 2: Isotropic etching of silicon using improper passivation during the etching process. A heavy mask undercut is observed.

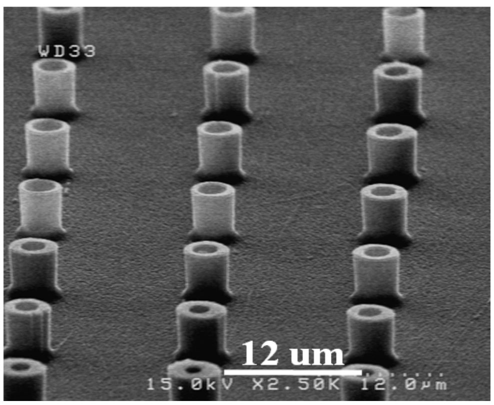


Figure 3: Anisotropic etching of silicon when in the passivation sub-cycle, both $O_2$ and $SF_6$ gases are used.

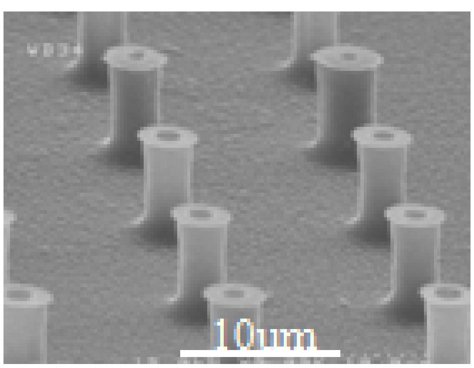


Figure 4: Anisotropic etching while in the passivation sub-cycle, a mixture of $H_2$ and $SF_6$ gases are used. By adjusting the passivation parameters, it has been possible to achieve near-vertical features.

Fig.3 shows the etching results when both $O_2$ and $SF_6$ gases with flow rates of 240 and 6 sccm, plasma power of 250 W and a duration of 4 sec are used during the passivation sub-cycle. The etching step is perfomed using 7 sec of $SF_6$ plasma with a power of 130 W and a gas flow rate of 34 sccm which yields highly vertical features. Similar experiments have been repeated with replacing the oxygen constituent with hydrogen during the passivation sub-cycle and the result is shown in figure 3. To achieve highly anisotropic etching, passivation sub-cycle should be longer in comparison with previouse experiment, 50 sec for this case. It has been observed that by using two-gas systems, either a mixture of $O_2/SF_6$ or $H_2/SF_6$ it has been possible to achieve high aspect ratio features. However, the formation of highly complex features with extended heights has faced severe obstacles which enforces a more sophisticated three-gas etching procedure as described in the following sections.

## 4 THREE-GAS PROCEDURE

As stated before, highly vertical etching of complex features could be obtained using proper selection of three gases, $SF_6$, $O_2$ and $H_2$. Figs 5 collects some SEM images of vertical micro-cylinders with heights up to 18 µm. During the etching sub-cycle, $SF_6$ plasma with a power of 130 W and duration of 10 sec. is used, while the passivation sub-cycle has been carried out in a plasma of $H_2$, $O_2$ and $SF_6$ gases with respective gas flows of 200, 170 and 4 sccm. The plasma power was set at 150 W while the length of this step was adjusted to be 50 sec. This extended passivation step has been suitable to achieve proper passivation of the sidewalls so that during the etching sub-cycle no sign of mask undercut is observed. Figure 6 collects the results of etching sub-micrometric-wall cylinders with a height of 8µm and wall width about 300 nm. Arrows in this figure, show the verticality of etching.

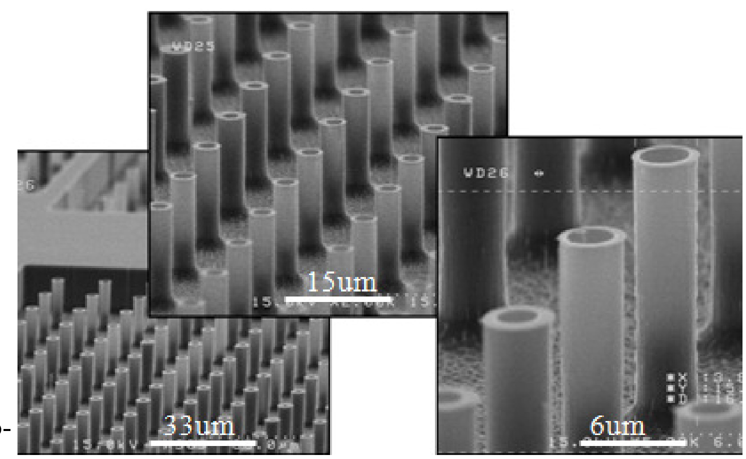


Figure 5: The evolution of high vertical features using mixture of $H_2$, $O_2$ and $SF_6$ in passivation sub-cycle. 18µm height hollow micro cylinders with no sign of sample bowing are observed for this sample.


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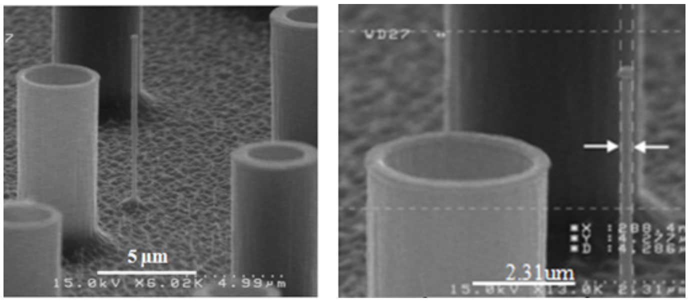
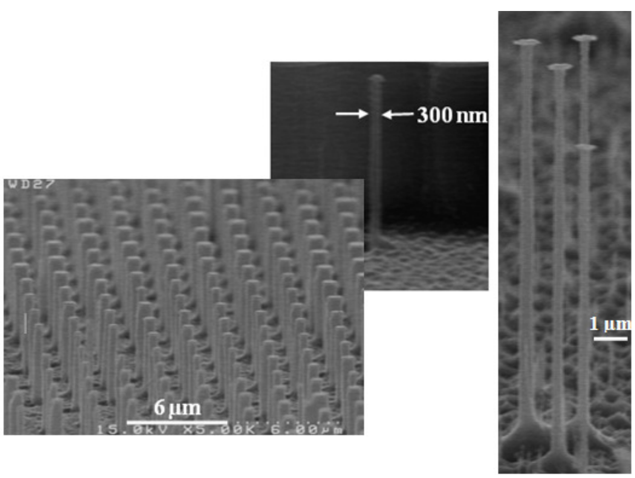



Figure 6: A vertical rod with a width of 280 nm and 8 µm height, pointed by the arrows. This image shows the verticality and the ability of the etching method to realize ultra-fine, high aspect ratio features.

Once the effect of both hydrogen and oxygen gases have been studied, a mixture of three gases have been investigated to obtain high aspect ratio features with high rates. Figure 7 collects the results of sub-micrometer silicon rod fabrication. Part (a) in this figure refers to rods with height of 5 µm, while in the part (b), one can see features with 200 nm width and 11 µm height, formed with an etch rate about 0.5 µm/min. The formation of the original pattern has been possible using a precision projection lithography. The value of mask undercut has been measured to be around 200 nm, which allows the realization of ultra high aspect ratio features. By extending the passivation time, it is possible to minimize this value to achieve structures below 100 nm in width.




(a) (b)

Figure 7: SEM images of silicon rods. (a) Two left images refer to 5 µm silicon rods. (b) 200 nm rods with height of 11 µm. These structures with aspect ratio of 55 were etched with an etch rate about 0.5 µm/min.

The effect of various parameters on etching rate have been summarized in Figure 8, where the etch-rate has been plotted against the flow-rate of $SF_6$ and the plasma time and power during the passivation and etching sub-cycles. As it can be seen in parts (a)-(c), increasing the gas flow of $SF_6$, etching time and power leads to higher etch rate. Changes in the passivation time and passivatio plasma power also affect the etch rate. Etch rate will decrease with increasing passivation time as seen in part (d), whereas the etching process seems to be less sensitive to plasma power during the passivation step. Part (e) in this figure shows the effect of plasma power during the passivation step showing a less varying curve.

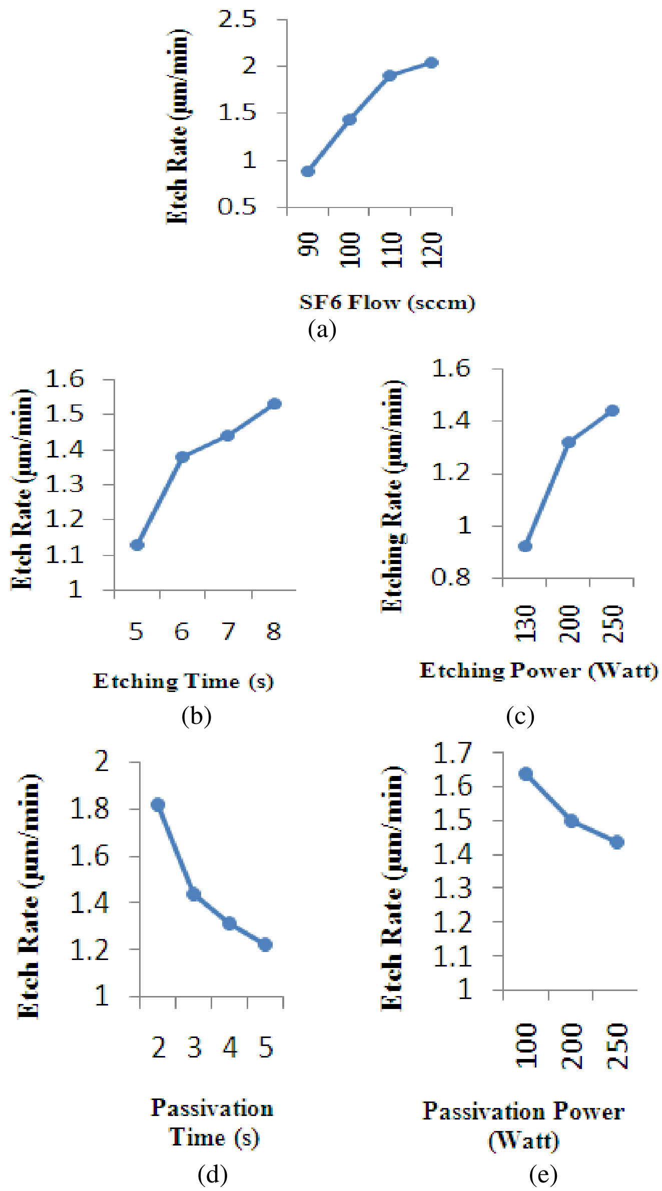



Figure 8: Silicon etch rate as a function of several parameters in etching and passivation sub-cycles. (a), (b) and (c) etch rate versus $SF_6$ flow, eching time and power. increasing these parameters increase the etching rate. (d) and (e) etch rate versus passivation time and power.

By increasing the passivation time it is possible to achieve higher aspec ratio features although the etch rate drops in a monotonic fashion. An optimum condition for the etching process can be arrived at by simultaneously adjusting the etch-rate as well as the verticality of the features.

## 5 CONCLUSION

In this paper, we have developed a high aspect ratio vertical etching of silicon substrates by means of a low-density reactive ion etching process. A time-multiplexed sequential procedure has been used to engineer the etching process and to achieve high aspect ratio features while the etch rate is maintained at moderate or high values. Using this method, we have arrived at a high etch rate of 0.7 to 1.5 µm/min for deep sub-micrometer features with no need to high density plasma while achieving aspect ratios over 50 and features below 0.5 µm. In addition features of the order of 100-200 nm have been obtained where the height has been around 8-11 µm. Higher aspect ratio features seem feasible by further adjusting the etching parameters. This work has been supported by the research council of the University of Tehran.

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