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Ultra high aspect ratio sub-micron silicon micromachining by double-passivation deep reactive ion etching

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1. Introduction

Deep reactive ion etching (DRIE) process by time multiplexed etching has been widely used in diverse applications ranging from micro-electro mechanical systems (MEMS), opto-electronics to wafer level 3D packaging. Extremely vertical silicon microstructures have been formed by alternately repeating etching and passivation steps several times until the required depth is achieved [1]. This approach is also known as BOSCH process which is named after its inventor [2]. Though this technology is capable of etching through sub-micron gaps, after etching a depth of ~ 6-8 micron the profile starts to taper and limits further etching by forming a self-stopping V-shaped profile [3]. This happens due to excessive polymer usage for getting a smooth sidewall and vertical profile. As a result it leads to the accumulation of passivation polymer at the bottom of the etched patterns where the ion energy shows a decreasing trend due to increasing depth. Another factor that limits the performance of the deep reactive ion etch process is the excessive reaction that takes place at the top of the structures compared to bottom of the micro structures. This puts greater demand on the passivation chemistry in the etching process to prevent undercut at the top.

In this work, we focus on developing and characterizing a novel double passivation deep reactive ion etch process for realizing sub-micron to deep sub-micron high aspect ratio nano-structures (HARNS) like trenches and pillars, for emerging silicon device applications like photonic crystals, RF resonators, nano electromechanical systems (NEMS) and nano-filtration systems. All such applications demand a high degree of profile verticality and aspect ratios of >25-30 for sub-micron trenches.

2. Experimental

Etch Concept

A standard BOSCH process consists of a single C_4F_8 based sidewall passivation cycle (~5-6 seconds) followed by a SF_6 based isotropic silicon etch cycle (~8-9 seconds). To improve the sidewall passivation and achieve greater penetration of incoming reactive ions, excess of oxygen gas is made to flow during the etch cycle along with SF_6 which helps in clearing the polymer build-up at the bottom of the fine trenches while at the same time oxidizing the sidewall during the etch process cycle. This results in silicon sidewall oxidation during etch cycle and followed by C_4F_8 based Teflon deposition during passivation cycle. This is resulting in a double sidewall passivation layers which prevents excessive sidewall bowing due to reactive F-radicals in fine trenches. This concept has been schematically explained in Figure 1(a) and is supported by the SEM image in Figure 1(b) below.

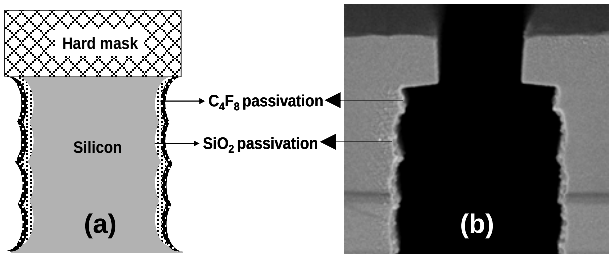


Fig-1: Fig-1(a) Illustrates double passivation etch concept. (b) SEM image showing double passivation layers after etch.

Process and Characterization

8-inch diameter, p-type silicon wafers were deposited with 1.0μm thickness of silicon dioxide by plasma enhanced chemical vapor deposition. The oxide layer was patterned for long trenches with openings ranging from 250nm up to 8.0μm. After opening the 1.0μm silicon dioxide hard mask, the photo resist was removed in O_2 plasma and subsequently wet-cleaned in Piranha clean mixture at 100°C. The wafers were then used in developing the novel double passivation DRIE silicon etch process based on the experimental matrix summarized in Table-1 below.

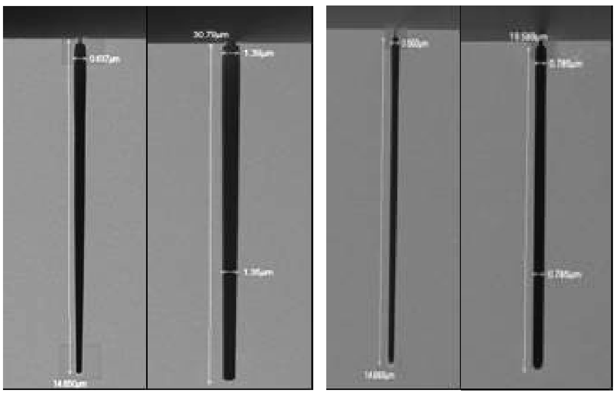
Table-1: Summary of process conditions with single and double passivation silicon etch process:

Recipe Name	Cycle name	Cycle Time (seconds)	Pressure (mtorr)	Gas flows in sccm.			Coil RF (Watts)	Platen RF (watts)
				C_4F_8	SF_6	O_2		
Single Pass	Etch	9	30	0	100	10	600	20
	Pass	6		140	0	0	600	0
Double-Pass1	Etch	8	30	0	100	50	600	14
	Pass	5		100	0	0	600	5
Double-Pass2	Etch	8	30	0	100	60	600	20
	Pass	5		100	0	0	600	5
Double-Pass3	Etch	8	21	0	100	50	600	20
	Pass	5		100	0	0	600	5
Double-Pass4	Etch	8	21	0	100	50	600	30
	Pass	5		100	0	0	600	5
Double-Pass5	Etch	8	19	0	100	50	600	30
	Pass	5		100	0	0	600	5

3. Results and Discussion

Initially the etch process that used standard single-passivation etch chemistry was evaluated. This process contains high concentration of C_4F_8 based Teflon-like sidewall passivation to achieve smooth sidewalls and vertical profile. Rest of the etch processes have been varied to evaluate the double pasivation etch concept. The main contributing factors were found to be pressure, platen power and Oxygen gas flow. The etched wafers are later cut through the trenches of different sizes and analyzed using SEM for profile microloading or verticality (measured by difference in top and bottom width) and etch rate microloading effect (measured by maximum minus minimum etch rate expressed in percentage with respect to its mean value).

Figure-2(a) and (b) shows the cross-section SEM images after etching with standard single passivation BOSCH process that was shown in Table-1. It shows that a self-limiting V-shape is being formed which clearly reveals the limitations of single passivation chemistry. It further confirms that even for a larger trenches of >2µm width, the profile continues to be tapered due to sidewall polymer build-up with increasing depth. Figure-2(c) and (d) on the other hand shows the cross-section of the optimum double passivation etch process (Double-Pass5). It can be seen that the profile is highly vertical for trenches of 0.56µm and 0.76µm width. This demonstrates that the double passivation process approach gives minimum profile microloading effect compared to single passivation etch process which shows a significant profile dependency from sub-micron gap size to above 2 µm.



(a) **(b)** **(c)** **(d)**

Fig-2: (a) & (b) are SEM images of 0.59µm and 2.44µm trenches resulting in V-shape due to Single-Passivation etch process. **(c) & (d)** are SEM images of 0.56µm and 0.78µm trenches resulting in improved vertical profile due to Double-Passivation etch process.

Figure-3 below shows the trend-chart of silicon etch rate versus critical dimensions (CD) of trenches. It can be seen that the etch rate microloading effect is more pronounced in single passivation process (88.4%) than the double passivation etch process (55.1%). Figure-4 shows the plot of silicon to silicon dioxide etch selectivity as a function of trench size. It can be seen that the double passivation etch process shows very little variation over a wide range compared to single passivation etch process. From Figure-5 we can see the trend of profile microloading effect as a function of trench width. It shows that the double passivation etch process exhibits minimum profile microloading effect compared to single passivation etch process.

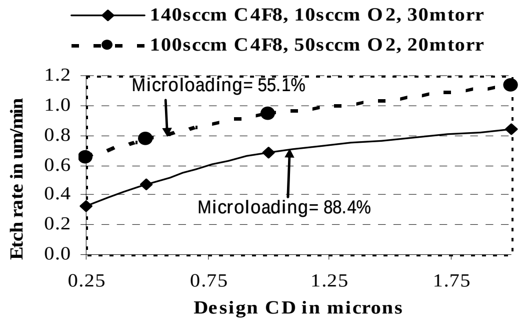


Fig-3: Trend of Si-etch rate with different gap sizes

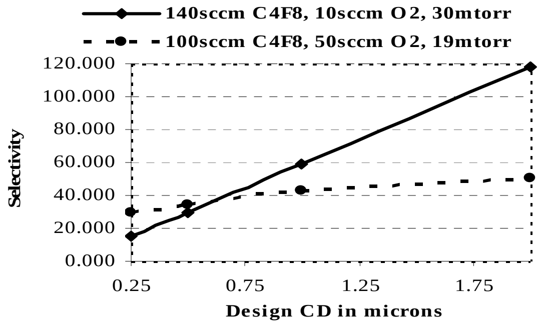


Fig-4: Sensitivity of Si/Oxide etch selectivity with gap sizes

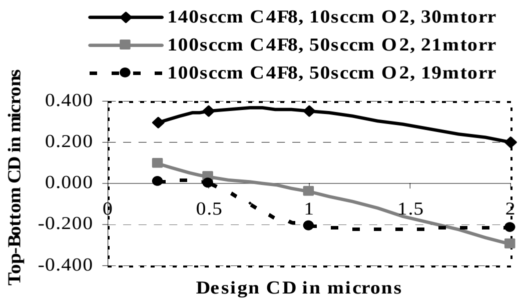


Fig-5: Trend of Profile verticality with different gap sizes.

4. Conclusions

The double passivation silicon etch process showed the capability to achieve aspect ratios of > 30. It has been further demonstrated that it can achieve 33% higher etch rates, minimum variation in etch selectivity and minimum profile microloading effect compared to standard BOSCH process.

Acknowledgements

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