STSetch2 Profile Characterization - Undercut Investigation for Silicon Trench Etching in STSetch2

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1. Introduction

The technology, today widely known as the BOSCH process, is a plasma etching procedure dedicated to the structuring of silicon, invented by Lärmer and Schilp [1]. A more refined process, called Advanced Silicon Etch process (ASE^{TM}), is based on the BOSCH process to address the limit and inability of BOSCH process for future MEMS dry etch applications. The deposition of passivation layer and etching take turns in the silicon etch process. SF_6 and C_4F_8 are used as the etching and deposition gases, respectively. The SF_6 plasma supplies fluorine radicals for spontaneous etching of exposed silicon. The C_4F_8 deposits a $(C_xF_y)_n$ polymeric layer on all substrate surface. The sequence is repeated to the desired depth. and is shown schematically in **Figure 1** [2].

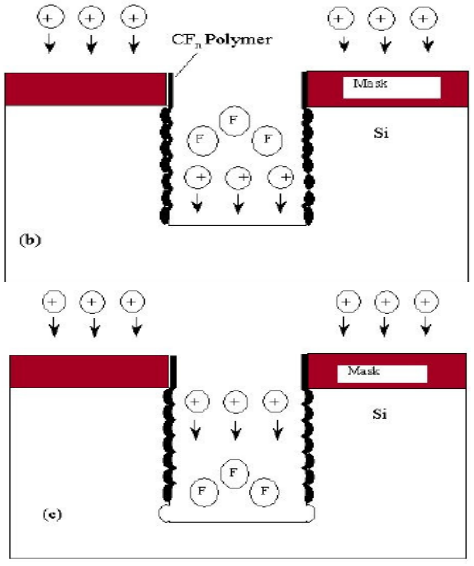


Figure 1. Bosch process.

The principle of the ASE process can be described as a simple reaction model as the following scheme 1 [3]. The deposition gas, octaflurocyclobutane (C_4F_8) is dissociated by the plasma to form ions and radicals (equation 1), which then undergo polymerization reactions (equation 2) to result in the deposition of the protection layer.

$$CF_4 + e^- \rightarrow CF_x + CF_x^{\bullet} + F^{\bullet} + e^- \quad \text{[eq 1]}$$
$$nCF_x^{\bullet} \rightarrow nCF_{2\,(ads)} \rightarrow nCF_{2\,(f)} \quad \text{[eq 2]}$$
$$nCF_{2\,(f)} + F^{\bullet} \rightarrow \text{ion energy} \rightarrow CF_{x\,(ads)} \rightarrow CF_{x\,(g)}$$

Scheme 1. Mechanism for formation of passivation layer and its removal

The gases are then switched to allow etching. Sulfur hexafluoride (SF_6) is used as the etching gas to deliver fluorine radicals after excitation of SF_6 gas molecules by electron impact from the plasma. The etching rate of silicon has three components: physical sputtering, spontaneous thermal etching, and ion-enhanced chemical reaction. The Silicon is primarily etched by the atomic fluorine radicals assisted by ion bombardment [5]. The ion bombardment only serves to remove polymer layer from the bottom of the trenches and then to enhance the etching process by continuing to improve the reactivity of the silicon by damaging the surface making it more susceptible to reacting with fluorine radicals. The spontaneous isotropic etching mechanisms of exposed silicon is illustrated in **Scheme 2** [3].

$$SF_6 + e^- \rightarrow S_xF_x^+ + S_xF_y^{\bullet} + F^{\bullet} + e^{\bullet}$$
$$Si + F^{\bullet} \rightarrow Si\text{-}nF$$
$$Si\text{-}nF \rightarrow Si\text{-}F_{x\,(ads)}$$
$$Si\text{-}F_{x\,(ads)} \rightarrow Si\text{-}F_{x\,(gas)}$$

Scheme 2. Mechanism for etching silicon in an SF_6 plasma.

2. Objective and Rationale

Due to incomplete sidewall protection, if the polymeric layer on the sidewall is removed before each etching cycle finishes, there will be lateral etching. Figure 2 shows one example of the dependence of vertical and lateral etching rate, aspect ratio of the etched trench on the etching time [6].

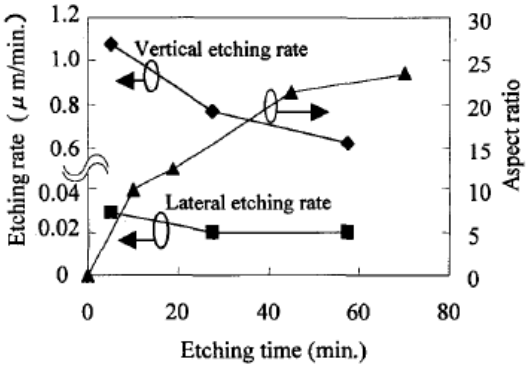


Figure 2. Etching time dependence of the etch rate (vertical and lateral), the aspect ratio obtained by the normal ASE process

We can see from this figure that there is a constant lateral etching rate and decreasing vertical etching rate as the etching time increases, which limits the etch anisotropy and aspect ratio. The decreasing vertical etching rate is due to the decreasing density of fluorine radicals that reaches the bottom of the trench as the trench becomes deeper. The lateral etching is due to insufficient sidewall passivation which could contribute to undercut at the mask and silicon interface as shown in Figure 3.

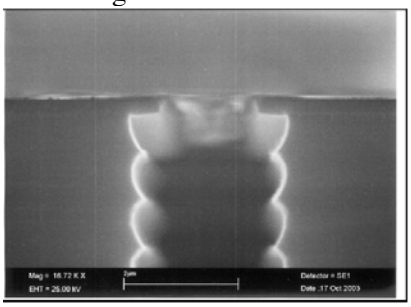


Figure 3. Undercut problem in ASE process

The possible reasons for the undercut problem is the diffusion of active species at the mask and silicon interface; and the isotropic chemical etching mainly at the beginning of the process [7].

Our objective for this course is to characterize the parameters that controls undercut and adjust the parameters to minimize the undercut problem. The parameters that are most relevant to the undercut problem are pressure, etching and passivation gas flows, source power and platen temperature. Their effects on the undercut are discussed as follows.

Etch and Passivation time

The ratio of etch time to passivation time have a large influence on the etching profile and etch rate. Reducing the passivation cycle reduces the amount of passivation which is deposited on the sidewall and base of the features. Therefore, a greater portion of the etch cycle is spent on etching silicon, resulting in a longer effective etch cycle and higher etch rate. But if the etch to deposition ratio is too large then the sidewall will not be well protected by polymer. Generally speaking, the larger the etch cycle, the larger the scallops and roughness on the sidewall, and the undercut will be probably larger. While if the etch to deposition ratio is too small, excess passivation can lead to grass on the base of the trench or even stop the etch cycle completely. The optimum etch to deposition ratio depends on application. Our objective is to obtain a smaller sidewall roughness and undercut, the etch to deposition cycle time ratio is typically 4:2[2].

Etch and Passivation Gas Flows

Generally speaking, increasing the etch gas flow (SF_6) to a certain point will increase the etch rate and undercut. Beyond that point, the power becomes the limiting factor and more power is required to ionize the SF_6 gas. If the power is not supplied, the additional gas will not be ionized into reactive species. On the other hand, with increasing passivation gas flow (C_4F_8), the deposition rate will increase to a particular level. Therefore, the sidewall is better protected by polymer with larger passivation gas flow and the undercut is expected to be smaller.

Source Power

The source power is the power that generates plasma. Source power and gas flow are closely related in determining the etch rate. Generally the higher the source power, the higher the etch rate. So combined with other parameters, source power may have a direct or indirect effect on undercut.

Pressure

The pressure helps to increase the etch rate by increasing the number of reactive species. Sometimes it also helps to prevent passivation breakdown by decreasing the ion energy. In the following analysis part, we also explored the effect of pressure on undercut.

Platen Temperature

The deposition step is strongly dependent on temperature. When temperature is reduced, the deposition rate increases. Sometimes during processing, higher source powers tend to elevate wafer temperature. Therefore, platen temperature could have an effect on undercut by affecting deposition. In our experiment, platen temperature was varied to explore its effect on the undercut problem. In order to reduce undercut, it is better to over passivate at the beginning of the etching process and to add passivation gas during etching cycle. In order to keep undercut to minimum, generally, we need to keep etch and deposition cycle to minimum; reduce etch gas pressure; reduce etch gas flow; increase deposition component by increase deposition time, power or deposition gas flow. As it appears to be the first few cycles of the process that generate an undercut, add passivation gas to the etch gas and gradually ramp out over time could also help to reduce undercut [2].

3. Experimental Setup and Results

All the processing is carried out in an STS2 Multiplex inductively coupled plasma system. A schematic of the process chamber is shown in Figure 4. The source plasma is generated by an inductively coupled coil generator (3 kW, 13.56 MHz). The wafer is mechanically clamped to the platen electrode and the temperature is generally maintained at 10 □. After performing the dry silicon etching, the etch profile of the trench is evaluated by a scanning electron microscope (SEM). It is also noted that STS2 has several improvement over its predecessor STS1, which includes faster etch rate up to 10 μm/min, better oxide selectivity to 500:1 and photoresist selectivity to 200:1, dual bias power, electromagnet to enhance selectivity, and a funnel to increase both etch rate and selectivity.

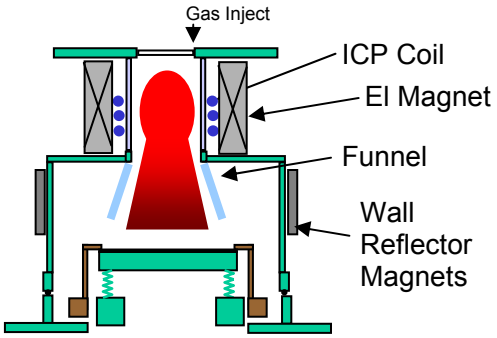


Figure 4. Schematic of STS2 chamber.

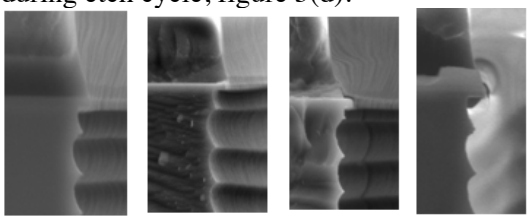
The samples are silicon substrates with 100 nm thermal oxide on top as etching mask. We use 1.6µm 3612 as photoresist mask, and use UV light and 110°C oven bake to harden the photoresist. With oxide, it is more accurate to measure the size of undercut because erosion of photoresist. After photolithography, the oxide was removed in AMT etcher. Generally, to reduce undercut, the etch components should be reduced and passivation components should be increased. We varied single parameter or two parameters at the same time such as etch and passivation time, pressure, gas flow to invest into the effects of the most relevant parameters on the undercut problem. We started with a standard recipe for high aspect ratio etch as shown in Table 1.

Table 1. Standard HAR Recipe Gas Flow

Parameter	Dep	Etch
Time	2 sec	3.5 sec
APC manual setting	16 %	16 % (ob
C4F8 flow	200 sccm	0 sccm
SF6	0 sccm	450 sccm
O2	0 sccm	45 sccm
Coil power	2 kW	2.5 kW
HF platen	0 W	40 W

Gas Flow

In the experiment, we reduced the etch gas from the standard 450 sccm to 250 sccm, figure 5(a); ramped the etch gas from 250 sccm to 450 sccm, figure 5(c); added passivation gas from 10 sccm to 2 sccm during etch cycle, figure 5(d).



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

Figure 5. SEM (a) Etch gas 250 sccm (b) Etch gas 450 sccm (c) Ramp etch gas from 250 sccm to 450 sccm (d) Ramp passivation gas from 10 sccm to 2 sccm during etch cycle.

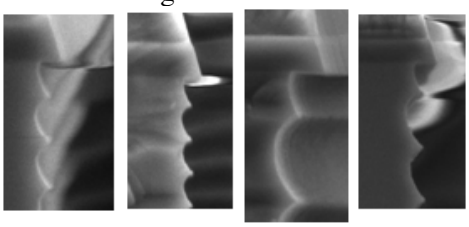
The measured results are summarized in Table 2. We can see from the table that both reducing etch gas flow and ramping parameters helps to reduce undercut. The ratio of undercut to scallop size is almost constant, which means undercut is directional proportional to etch rate.

Table 2. Undercut dependence on Gas Flow

	250 Etch	450 Etch	Ramp Etch (250-450)	450 Etch Ramp Pas (10-2) in Etch
Undercut	243.5nm	468nm	299.5nm	306.5nm
Scallop	470nm	755nm	498nm	655nm
Ratio	0.52	0.62	0.6	0.458

Etch time & Pressure

The standard recipe mentioned in Table 1 has an undercut of about 451 nm. In the experiment, we changed the etch time and pressure together: etch time was changed to 2.5 and 4.5; the automatic pressure control (APC) of pressure was changed from 14% to 18%. The SEMs of the etching samples are presented in Figure 6.



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

Figure 6. SEM (a) Etch cycle 2.5s APC 14% (b) Etch cycle 2.5s APC 18% (c) Etch cycle 4.5s APC 14% (d) Etch cycle 4.5s APC 18%

The results of undercut are summarized in Table 3. We can see from the table that as etch cycle time decreases from 4.5s to 2.5s, the undercut and scallop size nearly reduces to half of the original value. As the APC increases from 14% to 18%, the undercut and scallop decreases, but not much.

Table 3. Undercut dependence on etch time and APC

Etch time	2.5s	4.5s
APC14%		
UC	266.5nm	635nm
Scallop	426nm	1080nm
APC18%		
UC	243.5nm	574nm
Scallop	425nm	984nm

We also added O_2 into the etching gas SF_6 and tried to change the O_2/SF_6 ratio at 5%, 10% and 20%. The resulted undercut and etching profile looks similar. The undercut as a function of O_2/SF_6 ratio is shown in Figure 7. Although adding O_2 ranges from 5% to 20% during etch cycle does not have much effect on undercut and general trench profile, the role of O_2 in Bosch process is: increase free fluorine species, thus increase the etch rate; reduce deposition in the turbo pump, resulting in longer pump life time.

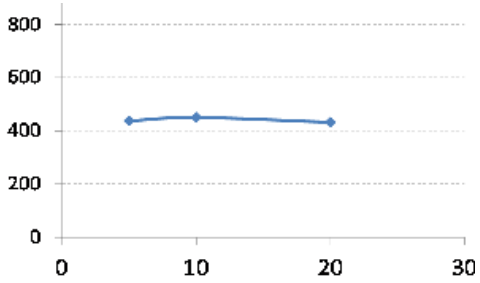


Figure 7. Undercut vs. O_2/SF_6 ratio

Trench Width

Figure 8 shows that the undercut increases with trench width and saturates at widths beyond 5um.

By measuring the depth of the first scallop in each trench, we can get the initial vertical etch rate for different widths of trenches. We found that the trend of this vertical etching rate has the similar trend with that of

undercut. And the ratio of this two quatites is a constant (Figure 9).

Undercut is caused by the lateral etching of the fluorine gas during each cycle.

The vertical etching is enhanced by ion bombarment and is faster compared to the lateral etching. The ratio of the etching rates of these two directions, which is also the ratio of undercut and depth of the first scallop, keeps a constant for trenches with different widths(Figure 9).

Larger trench width allows more etching gas reacting with the same of exposed areas, so the etching rates are faster for large trenches. As trench width goes beyond 5um, this effect become less affective and undercut saturates.

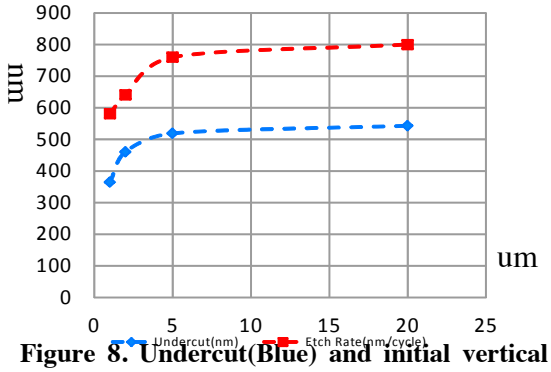


Figure 8. Undercut(Blue) and initial vertical etch rate(Red)(nm) vs. Trench width(um)

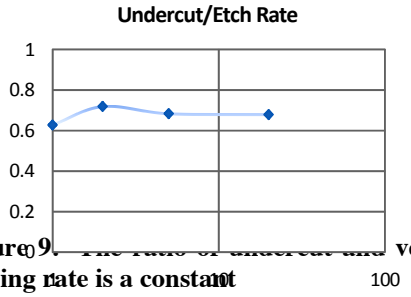


Figure 9. The ratio of undercut and vertical etching rate is a constant

Overall Trench Depth

The undercut does not depend on the number of cycles(trench depth) with the etch/dep ratio of 3.5s/2s(Figure10). This means that at this ratio, during each cycle, the scalloped above are well protected and not affected by the etching gas. Increasing etch/dep ratio may increase undercut and cause barrel shape profile. Decreasing this ratio may cause V-shape profile. For example the profile of trenches foretch/dep ratio of 3s/3.5s are shown in Figure 11.

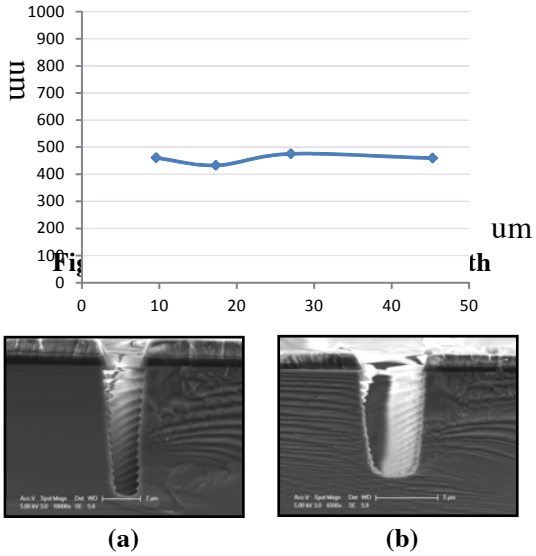


Figure 11. V-shapes at etch/dep ratio of 3s/3.5s. (a)2um trench (b)5um trench

Plasma Source Power

Undercut is reduced by decreasing source power. However, low source power affects the overall profile. Reduced ion energy can not knock off the polymer layers efficiently can cause the profile problem. Between 1200W and standard 2500W is a trade-off zone of undercuts and overall profiles.

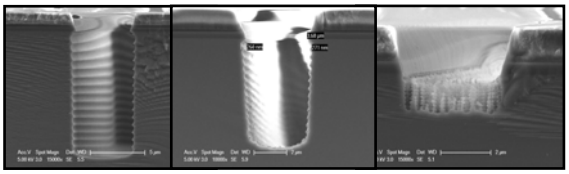


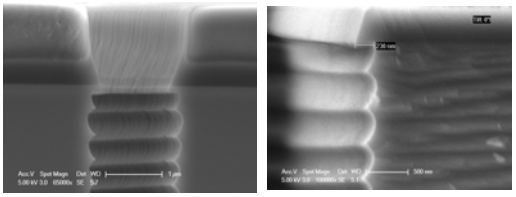
Figure 12. Profiles and undercuts for different plasma source powers (a) standard 2500W, undercut is ~500nm (b) 1200W, undercut ~200nm, profiles start to become V-shape (c) 600W, trenchs can not be etched down

Summary

Undercut dependence on various parameters such as trench width and depth, etching gas pressure, etching and passivation gas flows and source power are investigated (Table 4) Undercut can be minimized with short deposition time in each cycle, low etch gas flow or adding deposition gas during etching. However, the overall profiles can be affected if tuning these parameters to extreme. Two examples with minimal undercuts while maintaining good profiles are shown in Figure 13.

Table 4. Undercut dependence on various parameters

Parameters	Undercut trend
etch gas flow ↑	↑
etch time/cycle ↑	↑
dep time/cycle ↑	↓
trench width ↑	↑
overall trench depth ↑ (number of cyles)	--
add dep gas during etching	↓
O_2/SF_6 ↑ (5%-20%)	--



(a) **(b)**

Figure 13 Small Undercut (a) gas flow 250, undercut 243nm (b) etch time 2.5s , undercut 230nm

Acknowledgement

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Reference

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