HIGH ASPECT RATIO DEEP SILICON ETCHING

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ABSTRACT

This paper reports an improved deep reactive ion etching (DRIE) process for ultra high aspect ratio silicon trenches with reduced undercut. By ramping process pressure, etch power, and switching time, we are able to produce 5.7 µm trenches with an aspect ratio of 70 and 3 µm trenches with an aspect ratio of 97. We reduce undercut by half by adjusting the length and pressure of the passivation step.

INTRODUCTION

In recent years, deep reactive ion etching (DRIE) has become a key process in the fabrication of microelectromechanical systems (MEMS). By combining the etching power of reactive ion etching and sidewall passivation, it provides a precise anisotropic etch that can be used to create very deep etches as well as very narrow structures in silicon. The standard Bosch process for DRIE alternates between two steps: etching and passivation [1]. During the etch step, dry chemical etching is combined with ion bombardment to etch the silicon. The chemical reaction will slowly undercut the trench, so a passivation step is added which deposits a protective layer on the trench sidewalls. This combination provides the ability to etch very deep, vertical structures.

However, DRIE has several challenges when creating high aspect ratio structures [2]. Because of the alternating etch and passivation steps, the walls develop a scalloped texture. This can be reduced by adjusting the length and power of the two steps, but this typically reduces etch rate. Microtrenching occurs when the passivation layer is eroded and small trenches begin to etch off of the main trench. Aspect ratio dependent etching (ARDE), the phenomenon in which etch rate is inversely proportional to aspect ratio, causes DRIE lag and limits the maximum aspect ratio for a given opening.

Aspect Ratio Dependent Etching

ARDE limits the aspect ratio that can be achieved in both Bosch DRIE and ICP-RIE systems. At the bottom of narrow, deep features, ion bombardment and gas transport are reduced significantly [3]. This causes the features to etch slower and potentially stops etching entirely.

At the start of the etch step, the passivation layer at the bottom of the trench is physically etched by ion bombardment. These ions do not travel precisely vertically and may collide with the atmosphere, deflecting slightly. Very few of these ions reach the bottom of deep features, slowing the removal of the passivation layer. This consequently reduces the length of time that the silicon is exposed to the etch gases later in the etch step.

Additionally, gas transport is significantly reduced in narrow trenches. It becomes very difficult for the etch gases to flow to the trench bottom and react with the silicon, and it is difficult to remove the waste products from the reaction.

The reduction of ion bombardment and gas transport slows the etch as the trenches become deeper. This causes narrowing of the trench and eventually can inhibit etching altogether, setting a maximum producible aspect ratio.

Other groups have made process improvements to reduce ARDE and increase aspect ratio. Some groups have optimized etch parameters such as bias power, pressure, and gas flow rate [4,5]. In [6], oxygen is added to the etch step to assist sidewall passivation and reduce bowing. Blauw added a depassivation step before the etch step which consists of a high power, low pressure etch designed to remove the passivation layer from the trench bottom prior to etching the silicon [7]. In this paper we show significant improvement of ARDE and sidewall undercut by changing the length and pressure of the passivation step as well as optimizing the bias power, pressure and switching time of the etch step.

CONCEPT

In this paper, we introduce two methods of reducing ARDE and improving aspect ratio: ramping of the process parameters and adjustment of the passivation parameters.

Standard DRIE recipes have fixed process parameters from start to end of the etch. As the etch progresses, effects of ARDE emerge in narrow features. The parameters can be optimized to minimize these effects, but they will still occur eventually. These can be seen in Figure 1, which is a 150-min etch using our lab's standard DRIE process. The trench visibly narrows, and the etch rate slows significantly. This recipe usually provides an etch rate of around 3µm/min, but during the last half-hour of the etch, we observe etch rates of <1µm/min.

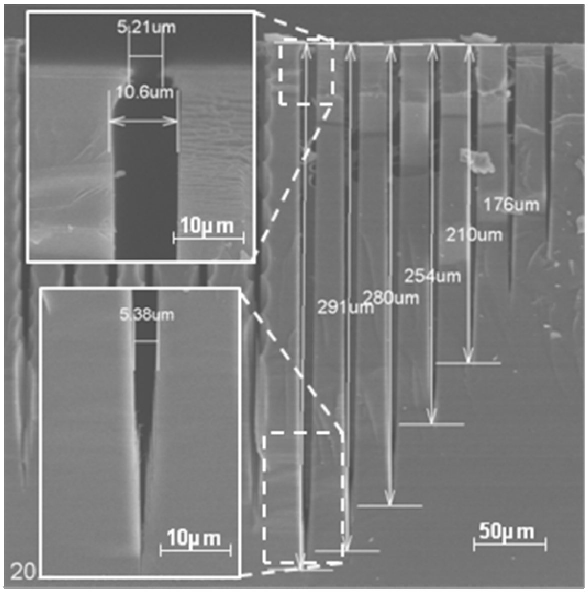

Figure 1: SEM of 1 to 5µm trenches after a 150-min etch with a standard DRIE process. The trench depth is less than 300µm and the trench narrows to a point at the bottom.

Table 1: Detailed process information for 150-min etches using the original and final DRIE recipes. The final recipe ramps the process parameter values throughout the etch.

Recipe	Etch parameters			Passivation parameters	
	Step length (sec)	Pressure (mTorr)	Bias power (W)	Step length (sec)	Pressure (mTorr)
Original	2	30	60	2.6	24
Final (start→ end)	2.6 → 5.6	30 → 15	60 → 140	2 → 3.5	24 → 34

In order to reduce the ARDE effects, we tune three parameters of the etch cycle: bias power, etch step duration, and chamber pressure. Increasing the bias power during the first second of the etch step improves ion directionality and improves passivation breakthrough. Increasing the etch step duration gives more time to flow the etch gases to the trench bottom and etch the silicon. Decreasing pressure during the etch step reduces ion collisions, increasing the number of ions that reach the trench bottom, and improves gas transport in the trenches. However, it decreases the concentration of etch gases in the chamber, slightly decreasing the etch rate.

At shallow depths, these adjustments to etch parameters are not necessary, and may in fact be detrimental to the etch characteristics. Higher power reduces mask selectivity greatly, increasing the etch time can cause undercut, and the lower power may reduce the etch rate. Instead of applying these adjustments for the entire etch, we ramp these parameters gradually and continuously over the duration of the etch. Thus the etch is better optimized at each etch depth as the etch proceeds. Some previous works have two or more sequential recipes to account for this [8], but by having the parameters vary continuously we can improve uniformity of the etch.

Our second advancement is adjustment of the passivation step parameters to reduce undercut in the etch. Making the aforementioned changes to the etch parameters not only improves the etch rate at the trench bottom, but also at the top of the trench. The increased power can eat through the passivation layer near the top of the trench and begin to etch laterally. In order to compensate for this, we increase the passivation pressure and duration. Increasing the pressure provides more reactant, reinforcing the passivation layer on the trench sidewalls. Increasing the duration of the step results in a thicker passivation layer. As with the etch parameters, the passivation parameters are ramped gradually and continuously throughout the process.

PROCESS DESCRIPTION

For our testing, we use a mask with trenches varying from 1 µm to 10 µm in width. These are patterned into a 5 µm-thick SPR220(3.0) photoresist mask using a GCA AS200 AutoStepper with 5:1 reduction.

Because of the length and power of the DRIE process, a thick oxide mask is required in addition to the photoresist. A 4 µm layer, consisting of 2 µm thermal oxide and 2 µm LPCVD oxide is used. This oxide layer is etched using an SPTS glass etcher using a recipe designed for submicron features with high sidewall verticality.

Other groups have used a hard aluminum mask [3,6]. However, metal masks can cause loading and re-sputtering issues in high power ICP systems, and are more difficult to pattern than oxide masks. In order to increase the depth of our features, a metal mask could be considered in the future.

The DRIE process, performed on an SPTS Pegasus system, starts with our standard etch designed for small features, and ramps the bias power, step durations, and process pressure throughout the etch. The final parameters, compared to the original parameters, are shown in Table 1.

RESULTS

Table 2 shows the effects of changing the various process parameters. Changing the bias power, which should improve passivation breakthrough, clearly improves the etch rate later in the process, but the trench still shows signs of narrowing. Increasing the etch duration at the end of the etch significantly reduces narrowing at the trench bottom, and also increases etch depth. Changing the etch pressure has the most dramatic effect on depth and narrowing, and when combined with the previous parameters provides very good results. However, it is clear that adjusting these parameters greatly increases the undercut at the top of the features.

Ramping etch parameters

By ramping the bias power, etch step duration, and etch pressure throughout the duration of the etch, we obtain very deep trench trenches: 335 µm for a 5.5 µm

Table 2: Etch results varying different parameters. Values are for a 5µm mask opening.

Parameter Adjusted	Etch depth	Trench bottom	Undercut
Original (150 min)	290µm	closed	2.5µm
Bias power ↑ (90 min)	230µm	1.8µm	1.2µm
Etch step duration ↑ (80 min)	230µm	2.9µm	1.5µm
Bias power ↑ Duration ↑ Pressure ↓ (120 min)	335µm	7.2µm	3.5µm
Etch parameters + Pass. Parameters (120 min)	330µm	5.2µm	2µm

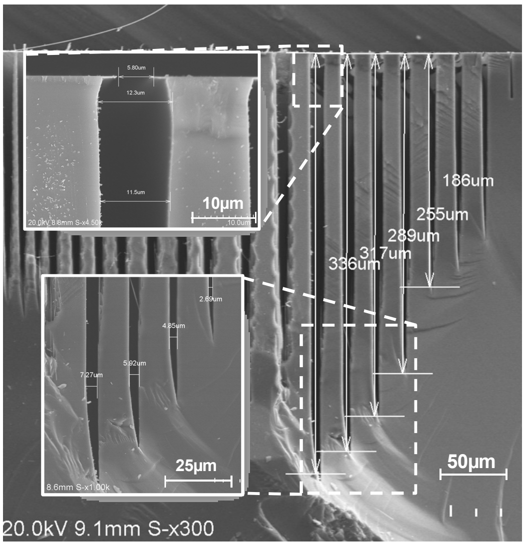

Figure 2: SEM of 1 to 5 µm trenches after a 120-min etch ramping bias power, etch time, and etch pressure. Note the large undercut at the top (3.5 µm).

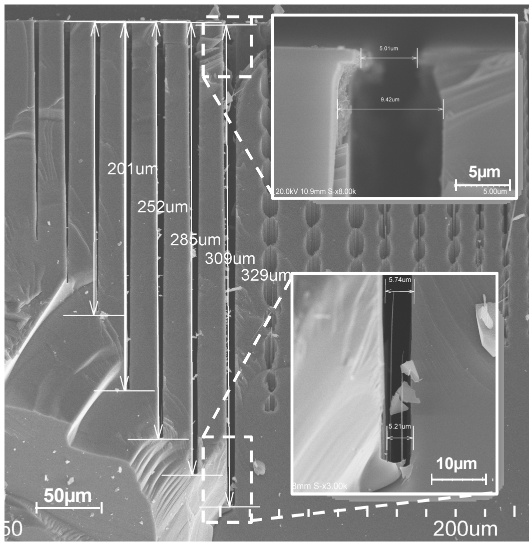

Figure 3: SEM of 1 to 5µm trenches after a 120-min etch also ramping passivation time and pressure. The undercut is reduced to less than 2µm.

trench after 120 min. However, the process results in a large undercut (greater than 3.5 µm per side) at the top of the trench. Trenches etched with this process for 120 min are shown in Figure 2.

Ramping passivation parameters

In order to significantly reduce the undercut at the top of the feature, we also ramp the duration and pressure of the passivation step. Using this technique, we fabricate the trenches shown in Figure 3 which have a similar depth but significantly reduced undercut (less than 2 µm per side). Figure 4 compares the undercut achieved with and without these passivation step adjustments.

Final process

With this revised process we have successfully etched trenches as narrow as 1 µm (190 µm deep) and as wide as 10 µm (490 µm deep). Table 3 and Figure 5 present results of these trenches, which have been etched for 150 min. We have achieved the highest aspect ratio for a given trench width ever reported in literature (Figure 6). For a 5.7 µm trench, the aspect ratio is 69.8 (compared to 58 for a 5 µm trench in [8]) and for a 3 µm trench the aspect ratio is 97.3. In [5], an aspect ratio of 107 is reported for a 375 nm trench. Because aspect ratio tends to decrease with increasing trench width (Figure 6), this is comparable to our results.

Additionally, we have shown that, while etch rate decreases over time, even for deep trenches it is still reasonably large: greater than 1.5 µm/min after 150 min for 4-5 µm trenches (Figure 7). Our aspect ratio is currently limited by the mask used to pattern the trenches. The current mask lasts for close to 180 min of etching. If we can improve our mask selectivity, we could etch longer and achieve higher aspect ratios.

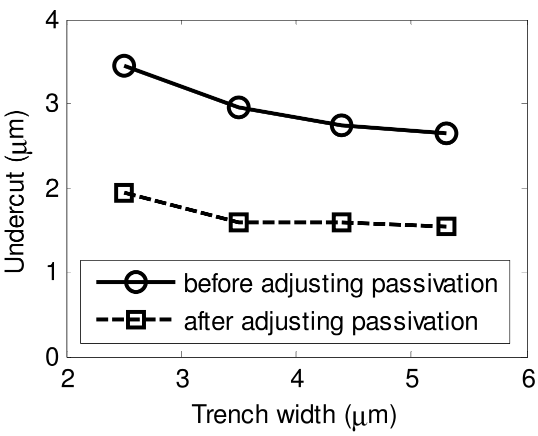

Figure 4: Undercut before and after passivation step adjustment.

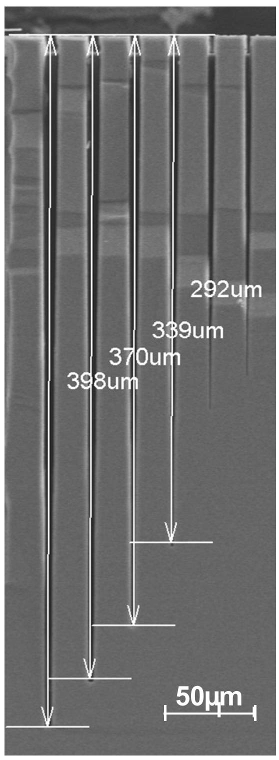

Figure 5: SEM of trenches after 150 min of etching.

Table 3: Optimized etch characteristics including depth, aspect ratio, sidewall slope, and undercut vs. trench width. The etch time is 150 min.

Mask opening	Actual trench width (μm)			Trench depth (μm)	Aspect ratio	Sidewall slope (°)	Undercut (μm)
	Top	Middle	Bottom				
2.5	6.3	3	1.7	292	97.3	89.55	1.9
3.5	7.4	3.9	2.5	339	86.9	89.59	1.95
4.4	8.8	4.7	3.4	370	78.7	89.58	2.2
5.3	10	5.7	4.2	398	69.8	89.58	2.35

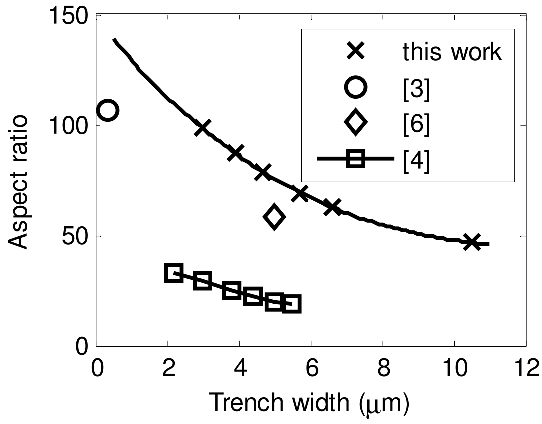

Figure 6: Aspect ratio of adjusted recipe compared to state-of-the art.

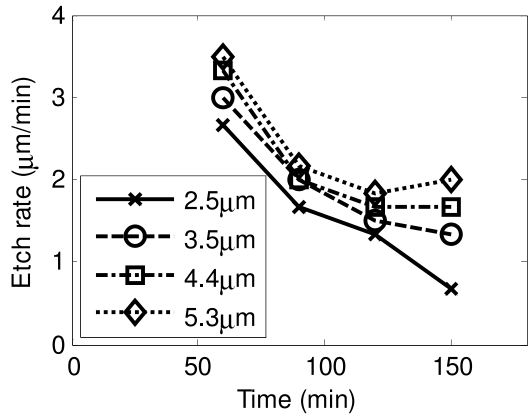

Figure 7: Etch rate over time for different trench widths.

CONCLUSION

We have developed an advanced DRIE process for etching ultra high aspect ratio features in silicon. By ramping the process parameters, including bias power, step duration, and pressure, we have significantly increased the achievable aspect ratio for trenches of 1 to 10 μm width. We have shown aspect ratios of 69.8 for a 5.7 μm trench, and up to 97.3 for a 3 μm trench. Additionally, by ramping the passivation parameters, we are able to decrease the undercut at the top of the trench to less than 2 μm for a 5 μm opening. With further optimization and an improved masking layer, we may be able to further improve the aspect ratio.

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REFERENCES

[1] F. Laermer and A. Schilp, “Method of anisotropically etching silicon,” U.S. Patent 5501893, Mar. 26, 1996.

[2] I. W. Rangelow, “Critical tasks in high aspect ratio silicon dry etching for microelectromechanical systems,” *J. Vac. Sci. Technol. A*, vol. 21, no. 4, pp. 1550-1562, 2003.

[3] J. Yeom, Y. Wu, J. C. Selby, and M. A. Shannon, “Maximum achievable aspect ratio in deep reactive ion etching of silicon due to aspect ratio dependent transport and the microloading effect,” *J. Vac. Sci. Technol. B,* vol. 23, no. 6, pp. 2319-2329, 2005.

[4] W. J. Park, *et al.*, “High aspect ratio via etching conditions for deep trench of silicon,” *Surface and Coatings Technology,* vol. 171, pp. 290-295, 2003.

[5] F. Marty, *et al.*, “Advanced etching of silicon based on deep reactive ion etching for high aspect ratio microstructures and three-dimensional micro- and nanostructures,” *Microelectronics Journal*, vol. 36, pp. 673-677, 2005.

[6] C. K. Chung, H. C. Lu and T. H. Jaw, “High aspect ratio silicon trench fabrication by inductively coupled plasma,” *Microsystem Technologies* vol. 6, pp. 106-108, 2000.

[7] M. A. Blauw, *et al.*, “Advanced time-multiplexed plasma etching of high aspect ratio silicon structures,” *J. Vac. Sci. Technol.* B, vol. 20, pp. 3106-3110, 2002.

[8] A. Kok, *et al.*, “High aspect ratio deep RIE for novel 3D radiation sensors in high energy physics applications,” *IEEE Nuclear Science Sym. Conf. Record, 2009*, pp. 1623-1627.

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