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Article

Optimization Method for the Synergistic Control of DRIE Process Parameters on Sidewall Steepness and Aspect Ratio

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Abstract

Deep Reactive Ion Etching (DRIE), as a key process in silicon micromachining, remains constrained in high-precision applications by sidewall angle deviation and aspect ratio limitations. This study systematically investigates the mapping relationship between process parameters and etching morphology, focusing on: The influence mechanism of C_4F_8 passivation time and bottom RF power on sidewall perpendicularity The effect patterns of etch cycle count, single-step time, and bottom RF power on aspect ratio and top-bottom line width (CD) difference Findings reveal: Dynamic adjustment of bottom RF power significantly influences sidewall angle. Incremental adjustment tends to cause sharp angles (decreased angular precision), while decremental adjustment tends to form obtuse angles. Simply increasing cycle count leads to a bottleneck in etch depth growth. Combining incremental bottom RF power adjustment can overcome depth limitations but induces axial variation in aperture dimensions. Optimizing the passivation-etch time ratio effectively controls etch morphology characteristics. This study achieved an etch depth of 112.2 μm for a 5 μm wide trench with an overall aperture size difference of 0.279 μm , providing a theoretical basis and practical guidance for parameter optimization in DRIE processes for high-precision silicon structure fabrication.

Keywords: sidewall; single-step time; RF power; top-bottom line width; passivation-etch time ratio

1. Introduction

As a core technology comprising etching and passivation cycles, the Bosch process holds a pivotal position in the fabrication of high aspect ratio silicon microstructures [1–3]. However, this process faces dual challenges in practice: On one hand, achieving anisotropic etching with vertical sidewall angles while maintaining consistent trench opening dimensions remains an industry-wide challenge [4,5]; On the other hand, micro-scale pattern etching is constrained by etch depth (or aspect ratio)—as the number of etch cycles increases, reactive ions and gases struggle to diffuse into confined effectively etch regions, directly limiting process performance improvements [6].

The root cause of these issues lies in the complexity of the process system: within each etching/passivation cycle, multiple parameters—including chamber pressure, etching/passivation gas flow rates, the etching-to-passivation time ratio, substrate temperature, center RF power, and bottom RF power—must be precisely controlled to establish a balanced process system [7–10]. Only through such precise control can effective regulation of etch dimensions and aspect ratio be achieved, while simultaneously ensuring consistency in silicon trench aperture size and verticality of sidewalls [11,12].

To overcome these limitations, research has focused on optimizing DRIE process parameters for micro-scale patterns, aiming to improve etch profiles and enhance etch depth [13–15]. For example, research has achieved TSV hole etching with a diameter of 50 μm and a depth of 300 μm . [16]. Exploration of Bosch processes with aspect ratios ranging from 3:1 to 7.5:1 revealed that controlling anisotropy and roughness becomes exceptionally challenging when the aspect ratio exceeds 15 [17]. In studies of 15 μm diameter hole arrays, aspect ratios as high as 26 have been achieved [18]. However, investigations into smaller dimensions reveal that the aspect ratio of the optimized 4 μm diameter holes can reach 12.5 [19,20], their cross-sectional area decreases with increasing aspect ratio, resulting in a bottom dimension less than half that of the top.

It is evident that for deep etching of microstructures related to Bosch processes, particularly in scenarios involving small apertures, a comprehensive understanding of the deep silicon etching mechanism under conditions of vertical sidewall angle and trench aperture size consistency holds critical practical significance.

Given this, this study proposes an optimized method for small-aperture etching, focusing on improving aspect ratio and uniformity of trench aperture size. Through systematic investigation of the effects of Bosch process cycles and bottom radiofrequency power on etch depth, anisotropy, sidewall angle, and aperture size uniformity, an experimental analysis-based silicon etching equilibrium model is established. This provides a universal technical solution for deep etching in the fabrication of silicon microstructures.

2. Materials and Methods

Spin-coat 4620 photoresist onto a 4-inch silicon wafer oriented along the <100> crystal direction, achieving a film thickness of 6 μm . Form the etching pattern via UV exposure, with feature dimensions of 5–25 $\times$ 5000 μm as shown in Figure 1a. Subsequently, etch the sample using a three-step Bosch process. First, the base recipe specified in Table 1 was employed, with parameters including etch cycle count, bottom RF power, C4F8 introduction time and flow rate, and SF6 introduction time. Standard process results are shown in Figure 1b. Using these parameters for etching, the etch depth-to-width ratio was enhanced by varying the etch cycle count, C4F8 introduction time, C4F8 gas flow rate, SF6 introduction time, and bottom RF power to observe the results [21].

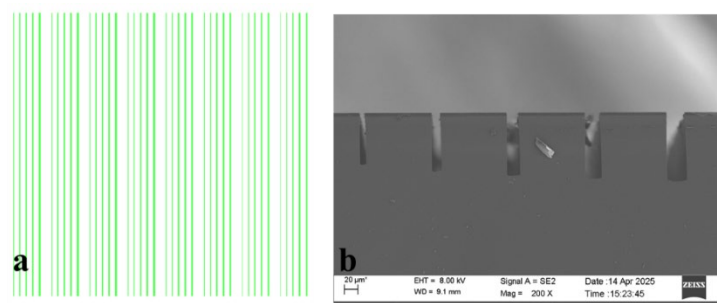


Figure 1. (a) Mask pattern: 5-25 $\times$ 5000 μm , with 100 μm spacing between patterns and 200 μm array pitch. (b) Scanning electron microscope image of the standard process.

Table 1. Basic Formulation.

Parameters	Cycles	Time/s	center C4F8/sccm	edge C4F8/sccm	center SF6/sccm	edge SF6/sccm	LFPower/W
Dep	100	1.5	180	0	0	0	10
Etch1	100	2	0	0	300	300	100
Etch2	100	3	0	0	300	300	40

3. Results

The optimized Bosch process comprises three steps: first, passivation with C_4F_8 [22–25]; second, opening the passivation layer via high-energy bombardment with SF_6 ; third, etching through chemical reaction between SF_6 and Si. During the first deposition step, fluorocarbon compounds form on the bottom and sidewalls to provide protection. In the second step, high RF power at the bottom creates strong ion traction, physically bombarding the passivation layer to open it for chemical etching in the third step. Chemical etching can be categorized into two types: spontaneous isotropic etching of F^* groups and ion-enhanced F^* group etching. The four process parameters studied in this paper are divided into two parts: the number of etching cycles, the introduction time and flow rate of C_4F_8 , and the introduction time of SF_6 , which influence the final etching morphology through chemical reactions. Meanwhile, the bottom RF power primarily affects the etching morphology through physical bombardment. The etching parameters are shown in Table 2.

Directly correlated with etch depth is the number of etch cycles. As the number of etch cycles increases, the etch depth correspondingly increases. Therefore, three sets of experiments were conducted with the number of etch cycles as the variable.

After 100 etching cycles, the etching depth of a $5\mu m$ -wide trench reached $77.49\mu m$. When the number of etching cycles was increased to 150, the etching depth reached $96.24\mu m$. Further increasing the cycles to 180 yielded an etching depth of $95.57\mu m$, which was close to the depth achieved at 150 cycles. This demonstrates that simply increasing the number of etching cycles does not lead to further increases in etching depth. This is because the small aperture area gas replacement becomes insufficiently rapid. Once etching reaches a certain depth, gas cannot continue to propagate downward, causing the etch depth to plateau at a threshold when cycles are increased further.

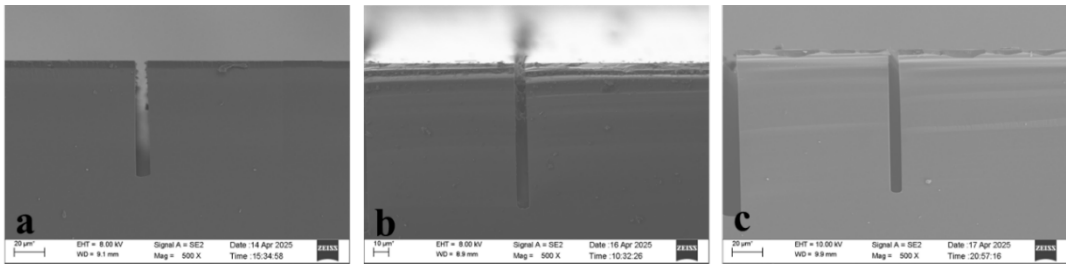


Figure 2. (a, b, c) show SEM images after 100, 150, and 180 etching cycles, respectively.

Table 2. Etching Parameter Experiments.

Parameters		Cycles	Time(sec)	center C_4F_8/scc m	edge C_4F_8/scc m	LFPower
A	Dep	100→150→180	1.5	180	0	10
	Etch1		2	0	0	100
	Etch2		3	0	0	40
B	Dep	180	1.5/1.5→1.7	180	0	10
	Etch1		2	0	0	100-120/100-110
	Etch2		3-3.5/3-3.2	0	0	40
C	Dep	180	1.7/1.7-1.9	180	50	10
	Etch1		2	0	0	100-110→100-120
	Etch2		2.9→3	0	0	40
D	Dep	200	1.8	180	50	10
	Etch1		1.8	0	0	100-100→120

Etch2	2.5	0	0	40
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To enable gas penetration to deeper etching regions, we devised two approaches: one involves increasing the bottom RF power to enhance the bottom's attraction to ions, allowing them to reach the etching bottom and continue downward etching; the other extends the etching gas introduction time to increase ion concentration, thereby promoting downward etching. Consequently, the following experiments were conducted.

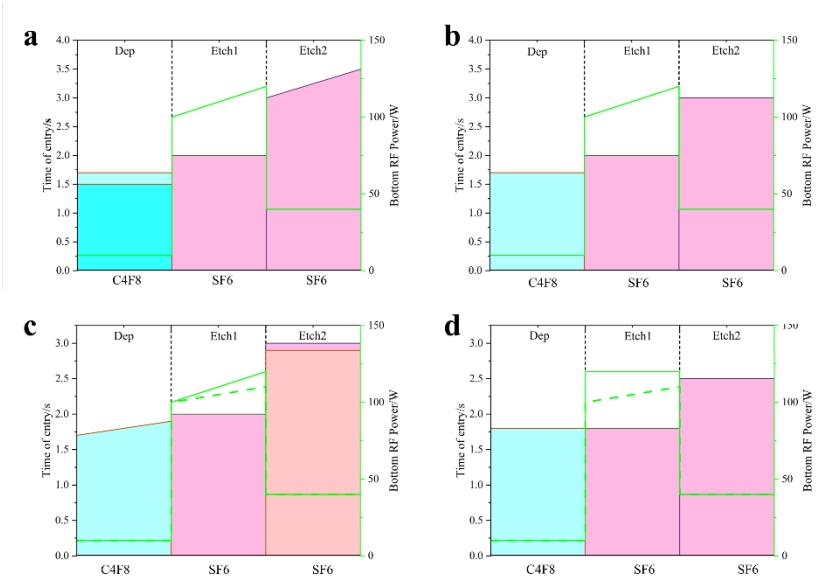


Figure 3. Etching parameter diagram. (a) Blue bars represent C₄F₈ introduction time (lighter blue indicates the second experimental group, identical to the first group except for this variable); pink bars denote SF₆ introduction time for two and three; green dashed line shows bottom RF power level. (b) Blue bars represent C₄F₈ introduction time; pink bars represent SF₆ introduction time in the second and third steps; green dashed line indicates bottom RF power level; (c) Blue bars represent C₄F₈ introduction time; pink bars represent SF₆ introduction time in the second and third steps (orange indicates variables for the second experimental group); green dashed line indicates bottom RF power level (dashed line indicates variables for the second experimental group); (d) Blue bars represent C₄F₈ introduction time, pink bars indicate SF₆ introduction time for the second and third steps, and the green dashed line shows bottom RF power level (dashed line denotes the second set of experimental variables);.

As etch depth increased, both etch gas flow time and bottom RF power were ramped up. When the chemical etch time was adjusted from a constant 3 seconds to 3.5 seconds as the number of etch cycles increased, and the bottom RF power was increased from 100W to 120W over the same number of cycles, the etch depth reached 114.3 μm .

The bottom RF power increases with etch depth, meaning that as etching progresses downward, the bottom exhibits greater ion attraction. When ions reach the bottom, sputtering occurs, compromising sidewall protection. During the third etching step, lateral etching occurs, leading to increased lateral etching as etching progresses—that is, the opening size increases with depth. Specifically, the opening dimensions at the top, middle, and bottom of the pattern exhibit variations, with a maximum difference of 1.005 μm (between top and bottom). To mitigate this dimensional variation, analysis indicated insufficient sidewall passivation as a potential cause. Consequently, the passivation gas exposure time was appropriately extended from 1.5 seconds to 1.7 seconds, reducing the maximum opening size difference to 0.894 μm .

Increasing the passivation gas exposure time yields a slight improvement in the opening size variation. To enhance sidewall passivation, one can either extend the passivation gas exposure time or increase the passivation gas flow rate. Both approaches enhance sidewall passivation to reduce

opening size variation. Alternatively, decreasing etch time lowers etch ion concentration, thereby reducing consumption of sidewall passivation and improving opening size variation. To further minimize opening size variation, the edge passivation gas flow rate was increased from 0 sccm to 50 sccm. The etch time was reduced back to the original 3 seconds, resulting in a reduced opening size difference of 0.781 μm .

The improvements to the above formulation had little effect on dimensional variation. Further analysis revealed that since bottom RF power increases with etch depth, extending passivation time also increases with etch depth. An alternative approach involved further reducing etch gas time while diminishing the increase in bottom RF power with etch depth. This reduced ion traction, decreased sputtering energy upon bottom impact, and consequently minimized consumption of sidewall passivation. Based on this, two sets of experiments were conducted. One set extended the passivation gas introduction time from 1.7s to 1.9s as the number of etching cycles increased, reducing the aperture size difference to 0.838 μm . The other group further reduced the etching gas time to 2.9 seconds and decreased the bottom RF power from 100-120 to 100-110, narrowing the aperture size difference to 0.67 μm .

Following the aforementioned formulation adjustments, the variation in aperture size difference remained insignificant. Therefore, the formulation underwent comprehensive modification: the passivation time was uniformly set to 1.8 seconds regardless of etch depth. Similarly, the second-step passivation time was fixed at 1.8 seconds irrespective of etch depth. This reduction in duration decreased ion concentration, lowered bombardment intensity, and minimized consumption of sidewall passivation. The third step's chemical etching time was adjusted to 2.5 seconds, lowering the ion concentration and reducing chemical etching. The bottom RF power was set to 100-110, with edge passivation gas flow at 50 sccm. The etching results showed an aperture size difference of 0.67 μm , exhibiting faster etching in the middle with smaller apertures at the top and bottom (bowing effect).

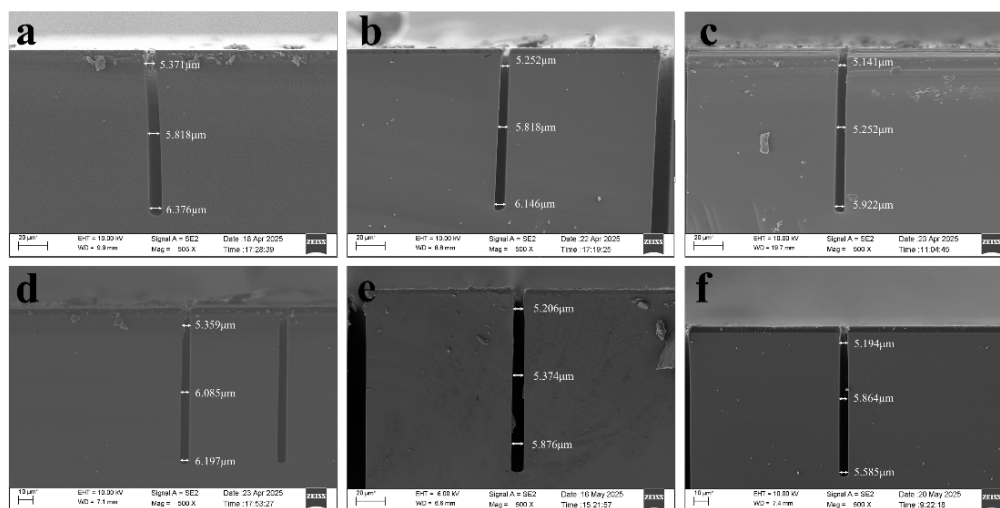


Figure 4. SEM images of etching results. (a) and (b) show SEM results from the first experimental group; (c) shows SEM results from the second experimental group; (d) and (e) show SEM results from the third experimental group; (f) shows SEM results from the fourth experimental group.

Sputtering on the sidewalls. This facilitates simple and convenient operation across various etch depths by eliminating variables that change with etch cycle count. Therefore, based on the aforementioned recipe, the bottom RF power was adjusted to 120W. The resulting etch aperture size variation was 0.279 μm . The overall recipe contains no variables that change with each cycle count, and the aperture size variation also reached 0.279 μm .

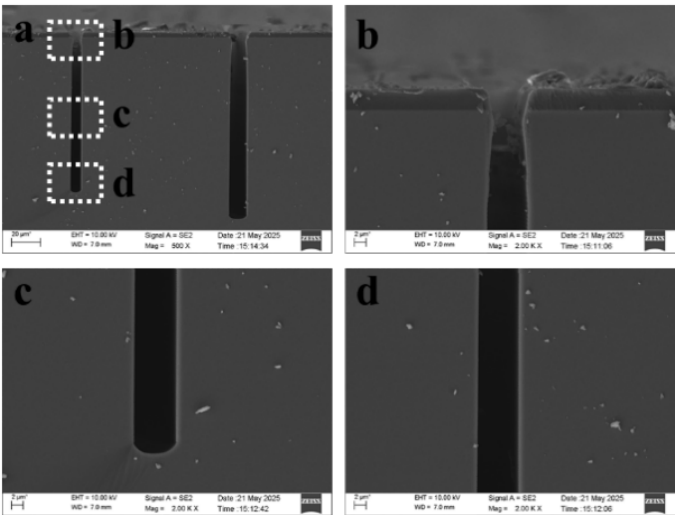


Figure 5. SEM images of etching results. (a) Overall etching morphology; (b) Top enlarged morphology; (c) Middle enlarged morphology; (d) Bottom enlarged morphology.

Finally, a three-step Bosch process was employed to etch 4-inch silicon wafers using optimized parameters. The uniformity of bottom corner height differences and etch depth uniformity were measured at five points: top, center, bottom, left, and right. The measurement locations are shown in Figure 6. The measured etch depth and aperture size difference data for the five points are presented in Table 3. The etch depth uniformity was 3.09%. The uniformity formula is as follows:

$$Uniformity=\frac{D_{max}-D_{min}}{2\times D_{average}}$$

(1)

Table 3. Etching Results Data.

Position	Etch Depth/µm	Opening Size Difference/µm
center	106.662	0.279
up	106.1	0.279
bottom	108.3	0.335
left	109.427	0.340
right	108.3	0.340

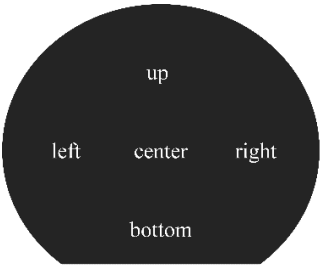


Figure 6. 4-inch wafer test position.

4. Discussion

This study investigates the plasma etching process for 5µm-wide trench structures, with the core objective of enhancing the etch depth-to-width ratio while reducing the overall opening size variation (i.e., dimensional deviation between the top, middle, and bottom openings of the trench). It

systematically summarizes the process optimization strategies to achieve this goal. The results demonstrate that precise control of key Bosch process parameters—including single-step deposition time, single-step etching time, and bottom RF power—significantly improves trench D/A ratio and effectively reduces overall opening size variation, successfully achieving the predetermined research objectives. The core mechanism of this process control strategy is as follows: Optimizing bottom RF power enhances the ion capture capability at the trench bottom. This alleviates the shortage of etchant supply at the bottom caused by gas replacement lag, addressing the critical bottleneck of “insufficient bottom etching drive” during DBR enhancement. Simultaneously, it reduces directional deviation during ion sputtering, minimizing non-uniform etching caused by ion reflection. Simultaneously, rational matching of single-step deposition time enables stable protective layer formation on trench sidewalls, preventing excessive sidewall etching. The synergistic effect of bottom RF power and single-step deposition time further suppresses expansion of aperture size deviation, ultimately achieving precise control over trench morphology.

The optimization scheme proposed in this study provides a critical theoretical foundation and directly implementable technical solution for developing plasma etching processes for “high-precision trench structures” in microelectromechanical system (MEMS) device manufacturing. It holds clear practical value and promising application prospects for advancing the manufacturing precision of core MEMS device structures, such as microfluidic channels and sensor electrode trenches.

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