Novel Dry Etch Process Technology Enabling Precision at the Nanoscale: Pushing the Limits of Advanced EUV Patterning

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As extreme ultraviolet (EUV) lithography continues to advance the definition of increasingly complex and densely packed patterns, it becomes imperative to evaluate the capability of dry etch processes to accurately and reliably transfer these features into underlying film stacks. This study investigates the critical challenges associated with etching EUV-defined structures, with a particular focus on mitigating ion reflection—one of the primary contributors to critical dimension (CD) bias, profile distortion, and localized CD uniformity (LCDU) variation in high-aspect-ratio geometries. By integrating advanced dry etch techniques such as plasma chemistry optimization, ion energy control, and sidewall passivation, we demonstrate improved anisotropy and pattern fidelity. These findings underscore the essential role of etch process innovation in enabling precise pattern transfer for next-generation logic and memory devices.

Index Terms: **Dry etch, ion-reflection, Complex, Passivation, EUV Lithography**

I. INTRODUCTION

Ion reflection, as illustrated in Fig. 1(a), occurs when incident ions are deflected off feature sidewalls or topographical variations during the dry etch process. This phenomenon can lead to CD bias, LCDU variations, profile distortion, etch non-uniformity—effects that are particularly detrimental in high-aspect-ratio and three-dimensional (3D) structures. These challenges are further amplified in EUV lithography, where intricate geometries and reduced resist robustness demand precise control over etch dynamics. To mitigate these effects, we employed advanced dry etch techniques, including plasma chemistry optimization, ion energy modulation, and sidewall passivation, as shown in Fig. 1(b) and Fig. 1(c). These strategies effectively suppress ion reflection and enhance anisotropy, enabling more accurate pattern transfer. Our results demonstrate that CD loss between the EUV photoresist and post-etch layers can be constrained to less than 10Å, while defectivity continues to decline—meeting the stringent requirements of advanced EUV patterning for logic and memory nodes. This work underscores the critical role of dry etch process innovation in enabling precise pattern transfer for complex EUV lithography. The integration of conformal passivation and process tuning not only improves CD control and LCDU but also supports continued device scaling in the semiconductor industry.

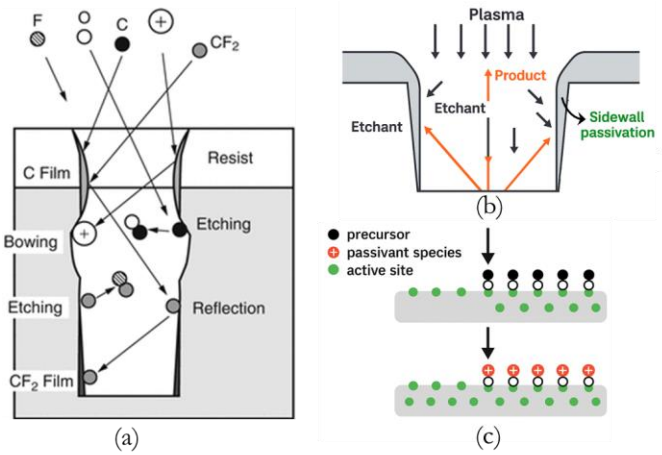

Fig. 1 Schematic diagram of Dry etching mechanisms. (a) ion reflection [1] (b) formation of sidewall passivation through plasma chemistry [2] (c) atomic layer deposition for conformal thin film coating [3].

II. METHODOLOGY AND RESULTS

A. Dry Etching Challenges in Overcoming Ion Reflection

Sustaining surface area is essential for effective chip scaling, particularly in the memory industry where preserving surface integrity is critical for continued device miniaturization. As feature pitch shrinks to sub-10 nm dimensions, it becomes imperative to develop innovative dry etch strategies that maintain surface area without compromising pattern fidelity. Due to the irregular and highly complex nature of EUV pattern etching, multiple surface regions are etched simultaneously, as illustrated in Fig. 2. Feature width plays a significant role in influencing ion behavior and etching outcomes. In wide spaces, ions can access the trench bottom more directly, resulting in minimal ion reflection and a more uniform etch profile. In contrast, narrow spaces tend to reflect more ions off the sidewalls, dispersing ion trajectories and increasing reflection events.

This elevated ion reflection in dense regions can lead to undesirable effects such as micro-trenching, etch lag, distortion of the large-to-small surface area ratio, and profile asymmetry. These challenges complicate precise control of the etching process and underscore the need for advanced etching process tuning to ensure consistent CD control and defect suppression across varying pattern densities.

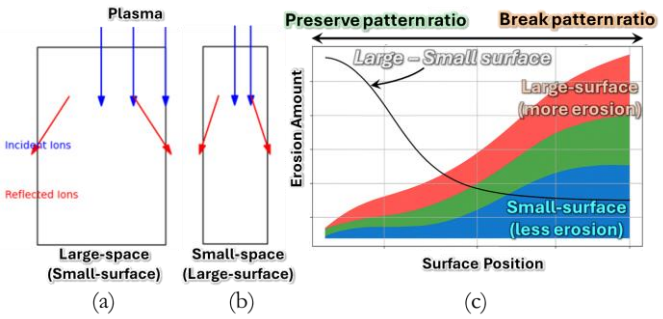

Fig. 2 Comparison of ion reflection behavior in different pattern geometries. (a) large-space and (b) small-space pattern (c) comparison of erosion amounts in different areas. (blue arrows: represent incident ions directed toward the substrate; red arrows: indicate reflected ions bouncing off the sidewalls)

B. Analysis of Dry Etching for Sustaining Complex and Irregular Patterns

In DRAM fabrication utilizing EUV lithography, the dry etching process presents increased complexity due to the intrinsic limitations of EUV resists and the prevalence of irregular pattern geometries. These resists typically exhibit lower etch selectivity and diminished mechanical robustness, making them particularly susceptible to plasma-induced damage and line-edge roughness (LER) during etching. These vulnerabilities are further exacerbated in irregular patterns—such as those illustrated in Fig. 3—where non-uniform feature shapes and densities cause localized variations in ion flux and surface charging. These conditions can lead to CD distortion, profile asymmetry, and even pattern collapse. As shown in Fig. 3(a), a complex pattern is precisely defined using EUV exposure, while Fig. 3(b) demonstrates the successful transfer of this pattern into the underlying film through dry etching.

Let us denote the large-area pattern as **L** and the small-area pattern as **S**, as illustrated in Fig. 3(a). In the context of EUV-based DRAM fabrication, dry etching presents significant challenges in accurately transferring the L pattern while maintaining low defectivity. As shown in Table I(a)(b) and visualized in Fig. 4(a)(b), successful pattern transfer can be achieved, preserving the original L:S ratio defined during EUV exposure. However, deviations from this ideal outcome are frequently observed. A prominent issue is the substantial CD loss of the L pattern post-etching, primarily attributed to ion reflection effects. When features of varying dimensions are etched concurrently, ions reflected from the sidewalls of smaller features can enhance the etch rate of adjacent larger features. Consequently, the CD of L erodes more rapidly than that of S, disrupting the intended pattern fidelity.

This phenomenon is exemplified in Table I(c) and Fig. 4(c), where the disparity in etch rates between L and S leads to a distortion of the original pattern proportions. Although less common, Table I(d) and Fig. 4(d) illustrate a scenario where dry etching fails to preserve the EUV-defined L:S ratio altogether. These cases underscore the critical need for optimizing plasma conditions and etch chemistries to mitigate CD bias, enhance LCDU, and ensure consistent defectivity performance across varying pattern densities.

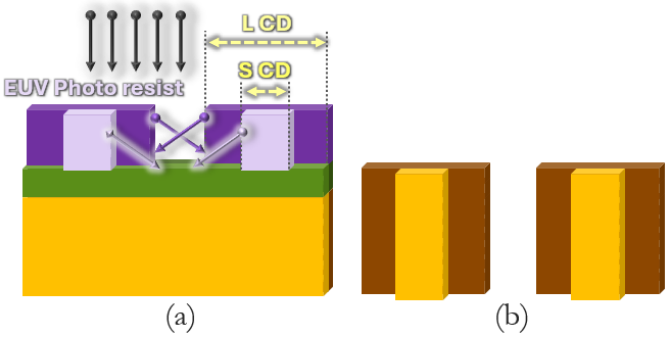

Fig. 3 EUV pattern complexity and pattern transfer through Dry etching. (a) EUV pattern, L and S CD definitions, schematic diagram illustrating ion reflection between L S features. (b) transferred pattern into underlying film via Dry etching.

$$Photo\ Pattern\ Ratio = L\ CD\ post\ photo - S\ CD\ post\ photo \quad (1)$$

$$Etch\ Pattern\ Ratio = L\ CD\ post\ etch - S\ CD\ post\ etch \quad (2)$$

$$Pattern\ Loss = Photo\ Pattern\ Ratio - Etch\ Pattern\ Ratio \quad (3)$$

The feature size ratios for photolithography and dry etching are independently monitored, as defined by Equation (1) and Equation (2), respectively. The deviation in pattern fidelity introduced during the etching process is quantified by Equation (3), which captures the extent of pattern ratio loss. Our objective is to achieve the outcome illustrated in Table I(a), where the CD ratio between large-area (L) and small-area (S) features is preserved post-etching. Specifically, the dry etch process should maintain the original L:S CD ratio defined during EUV exposure while simultaneously increasing the surface area of both feature types. This dual goal enhances overall pattern fidelity and supports robust device performance across varying pattern densities.

Table I. The individual variation in L CD and S CD caused by Dry etching, it determines the ability on preserving the original EUV pattern ratio.

Case	L CD after Dry etch	S CD after Dry etch	L-S CD	Sustain EUV shape
(a)	↑	↑	Keep	Yes
(b)	↓	↓	Keep	Yes
(c)	↓	↑	Decreases	No
(d)	↑	↓	Increases	No

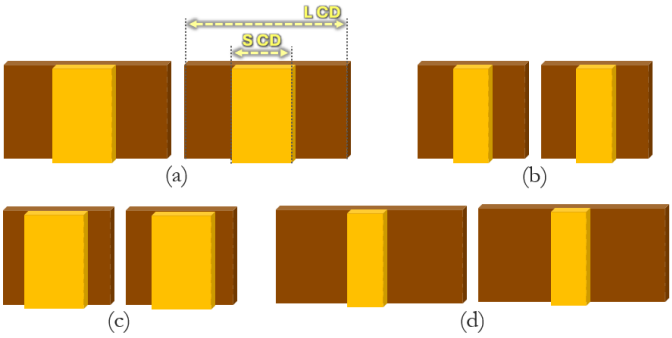

Fig. 4 Pattern transfer from EUV resist to the underlying film through Dry etching. (a) simultaneous increase in L CD and S CD (b) simultaneous decrease in L CD and S CD (c) decrease in L CD while S CD increases (d) increase in L CD while S CD decreases.

In complex pattern etching, in addition to previously discussed metrics such as CD, pattern ratio, and LCDU, another essential index to consider is **defectivity**. This parameter is particularly critical due to its frequent trade-offs with inline metrics, making it one of the central challenges in process optimization. For larger features, the predominant defect risk is **bridging**, as illustrated in Fig. 5(a), whereas smaller features are more susceptible to **breaking**, as shown in Fig. 5(b). The simultaneous occurrence of both defect types within the same die significantly complicates the etching process, demanding precise control over plasma conditions and etch chemistry to ensure pattern fidelity and minimize yield loss.

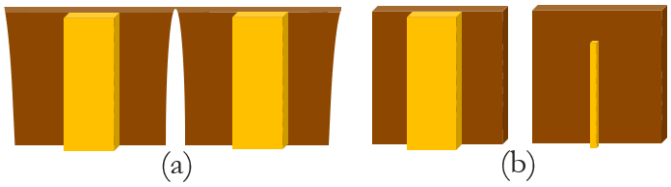

Fig. 5 Schematic diagram of defectivity. (a) bridging defects observed in large features (b) broken patterns occurring in small features.

C. Dry Etching Approach to Achieving Target Dimensions for the Intricate and Complex EUV pattern

The primary objective of this study is to minimize CD loss in large-area features (L) during the dry etching process to enhance overall pattern integrity. In addition to preserving the L–S CD ratio, other key factors such as LCDU and defectivity must be considered to ensure robust pattern fidelity. This discussion begins with an evaluation of photolithography strategies, followed by an analysis of dry etching approaches.

The stochastic nature of EUV exposure introduces variability in resist thickness and edge placement error (EPE), which complicates the etch process window. Irregular features—particularly those with high aspect ratios or non-linear contours—are prone to aspect ratio-dependent etching (ARDE), resulting in incomplete etching or tapered profiles. Fig. 6(a) illustrates a high aspect ratio structure where limited transport of etching species and ion flux attenuation at the feature bottom lead to reduced etch rates. In contrast, Fig. 6(b) depicts a low aspect ratio structure with more uniform access to etching species, enabling consistent etch depth.

ARDE significantly impacts CD control and sidewall angle, especially in deep reactive ion etching (DRIE) processes. These challenges necessitate precise control of plasma chemistry and ion energy to mitigate resist erosion and maintain pattern fidelity. Our investigation focuses on two critical parameters: EUV resist thickness, as shown in Fig. 7(a) and Fig. 7(b), and dose utilization, both of which play a pivotal role in optimizing etch performance across varying feature geometries. The primary objective is to minimize L CD loss during the etching process to achieve a higher level of pattern integrity. In addition to maintaining the feature shape (L-S CD), factors such as LCDU and defectivity must also be considered.

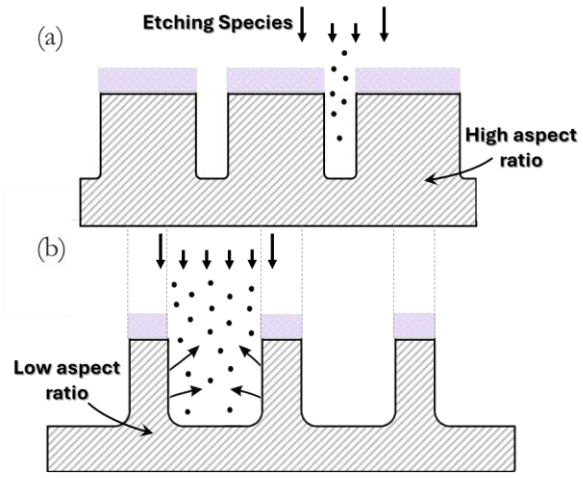

Fig. 6 Aspect ratio-dependent etching behavior. (a) high aspect ratio structure and (b) low aspect ratio structure.

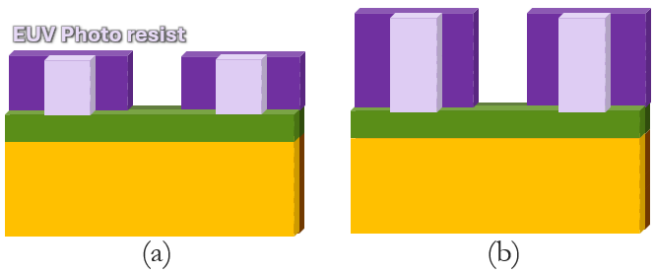

Fig. 7 Schematic diagram of EUV photoresist thickness. (a) thin EUV photoresist and (b) thick EUV photoresist.

Resist thickness plays a pivotal role in determining pattern fidelity, particularly in complex layouts with varying feature densities. A thicker resist, as illustrated in Fig. 8(b), generally offers superior etch resistance and mechanical stability,

which aids in preserving pattern integrity during subsequent dry etching steps. However, increased thickness can compromise resolution due to enhanced light scattering and reduced image contrast, especially in dense or irregular pattern regions.

Conversely, a thinner resist, shown in Fig. 8(a), improves resolution and CD control for fine features, making it advantageous for intricate patterns with small critical dimensions. While an increase in L CD can enhance the L–S CD ratio, it also introduces risks such as pattern collapse, LER, and etch-through defects—particularly in high aspect ratio structures. Therefore, optimizing resist thickness requires a careful balance between resolution, etch durability, and defectivity to ensure reliable pattern transfer and robust device performance.

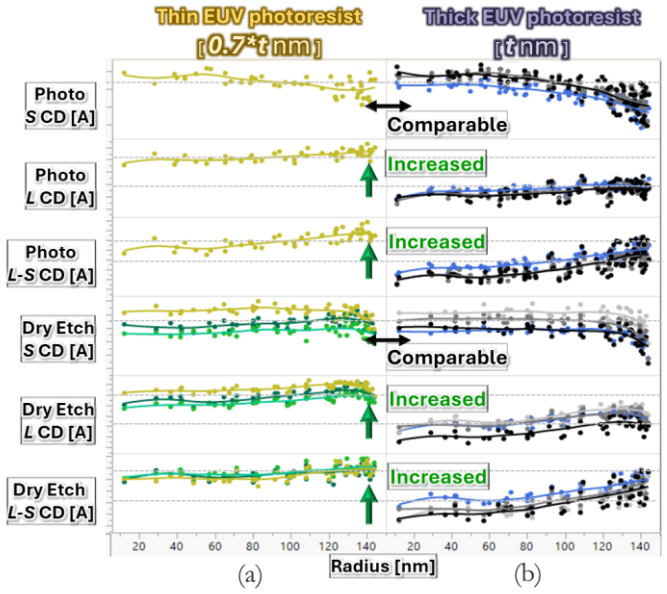

Fig. 8 Comparison of photo and Dry etch CD performance under different EUV photoresist thicknesses. (a) thin photoresist and (b) thick photoresist. (t: thickness)

Exposure dose plays a critical role in determining photoresist performance, directly influencing CD accuracy and LCDU. In complex patterning, a higher dose improves feature separation and reduces the risk of bridging in large-area features (L). However, it can lead to underexposure in small-area features (S), resulting in broken lines or incomplete pattern transfer. This trade-off is particularly pronounced in layouts with mixed feature sizes, where dose optimization must be carefully tuned to avoid CD bias and pattern ratio distortion.

Conversely, a lower dose enhances pattern contrast and reduces stochastic variation, contributing to improved CD uniformity and reduced LER. Nonetheless, it also increases the likelihood of resist sensitivity loss, line bridging, and potential overexposure in large features. As illustrated in Fig. 9, applying a lower dose results in an increase in the photo-defined L–S CD, indicating improved resolution and pattern fidelity at the lithography stage. However, this improvement does not translate into a corresponding increase in the final L–S CD after dry etching.

This discrepancy suggests that the final etch profile is not solely governed by the photoresist pattern. Instead, etch ion reflection—affected by trench geometry, ion energy, and angular distribution—continues to play a dominant role in defining the final CD. Therefore, to fully leverage the benefits of improved photo CD, it is essential to optimize etch process parameters, including plasma chemistry and ion dynamics, to ensure consistent pattern fidelity across varying feature geometries.

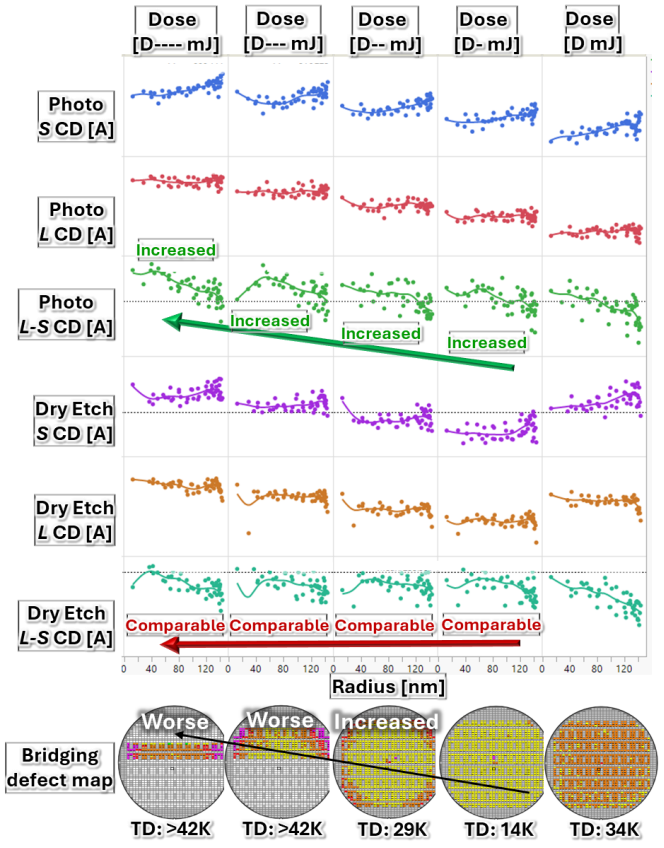

Fig. 9 Comparison of photo, dry etch CD and defectivity performance under dose skew conditions. (D: EUV exposure dose; TD: total defect count)

D. Dry Etch Approaches for Maintaining EUV Pattern Integrity

Prior to developing the dry etch recipe, the overall strategy can be segmented into three critical stages. The first stage focuses on protecting the EUV resist divots, as illustrated in Fig. 10(a) and Fig. 10(b). This involves reinforcing the top resist layer to shield divot structures while ensuring that the trench bottom remains sufficiently open to facilitate effective scum removal. Overprotection at this stage may result in residual scum, which adversely affects CD control and compromises pattern transfer fidelity. The second stage

emphasizes thorough descum at the resist bottom, as shown in Fig. 10(c). This step is essential for eliminating residual scum and minimizing footing effects—issues that are particularly pronounced in EUV lithography due to the thinner resist layers and lower etch resistance compared to conventional 193i resists [4]. Once the resist profile is stabilized and scum is adequately cleared, the third stage involves the actual pattern transfer. At this point, the EUV-defined pattern is etched into the underlying film stack, as depicted in Fig. 10(d). Given the susceptibility of EUV patterns to collapse and CD degradation during etching, precise tuning of ion energy, angular distribution, and etch selectivity is imperative to preserve the original pattern fidelity [5][6].

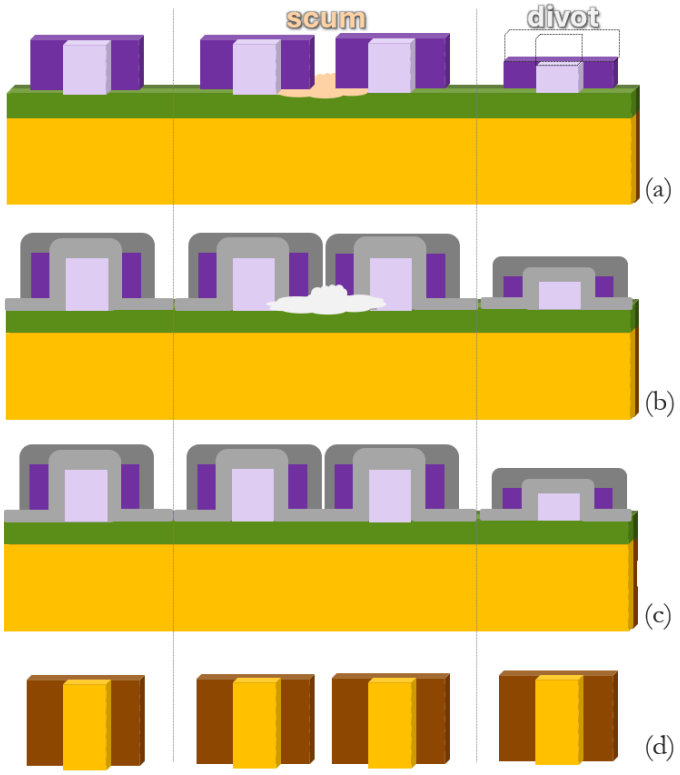

Fig. 10 Strategic framework for designing EUV-compatible Dry etch recipes. (a) resist scumming and divot (b) top-heavy deposition and sidewall passivation during Dry etch (c) descum process (d) pattern transfer into the underlying film.

To enhance EUV resist protection during the dry etch process, two key approaches can be employed. The first involves **Atomic Layer Passivation Control**, a cycle-based technique that enables precise surface modification at the atomic scale. This method reinforces the resist top surface and mitigates divot erosion by depositing ultra-thin, conformal layers through alternating plasma reactions. It offers fine control over film thickness and uniformity, making it particularly effective for preserving pattern integrity in complex 3D structures and minimizing surface erosion and LER. However, excessive cycle counts may result in over-deposition, especially in smaller patterns, leading to L–S CD shrinkage due to polymer accumulation in wider-space regions, as illustrated in Fig. 11(a). This technique is also applicable to protecting other films beyond the resist layer.

The second approach utilizes **fluorocarbon-based chemistries**, such as CF_4 and CH_2F_2. These gases decompose in plasma to form polymer layers that deposit on the resist surface, serving as a protective barrier against ion bombardment and enhancing etch selectivity [7][8][9]. Unlike Atomic Layer Passivation Control, this method is more sensitive to pattern density. Open areas between small features tend to accumulate more polymer, which can lead to non-uniform CD shrinkage, as shown in Fig. 11(b). While effective for descum and etch selectivity enhancement, excessive polymer deposition may hinder scum removal and compromise CD fidelity. Therefore, optimizing gas ratios and flow rates is critical to achieving balanced deposition across diverse pattern geometries.

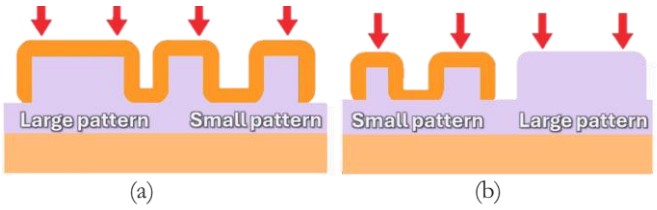

Fig. 11 Schematic diagram of Dry etching mechanisms. (a) concept of atomic layer passivation (b) deposition characteristics of fluorocarbon-based compounds on large and small features.

As illustrated in Fig. 12, adjusting the number of atomic layer passivation cycles enables fine-tuned control over film thickness and uniformity, particularly across large-area features. This method ensures excellent conformality on complex 3D structures, which is especially beneficial for minimizing surface loss and preserving pattern integrity in irregular EUV patterns characterized by non-uniform feature densities and geometries. However, increasing the number of passivation cycles introduces a notable reduction in the L–S CD ratio. This trend suggests that deposition occurs more readily in smaller patterns than in larger ones. The relatively wider spacing between small features provides more open area for fluorocarbon-based deposition, resulting in more pronounced CD shrinkage in dense regions. This non-uniform accumulation highlights the importance of optimizing cycle count and deposition dynamics to balance resist protection with dimensional fidelity across varying pattern scales.

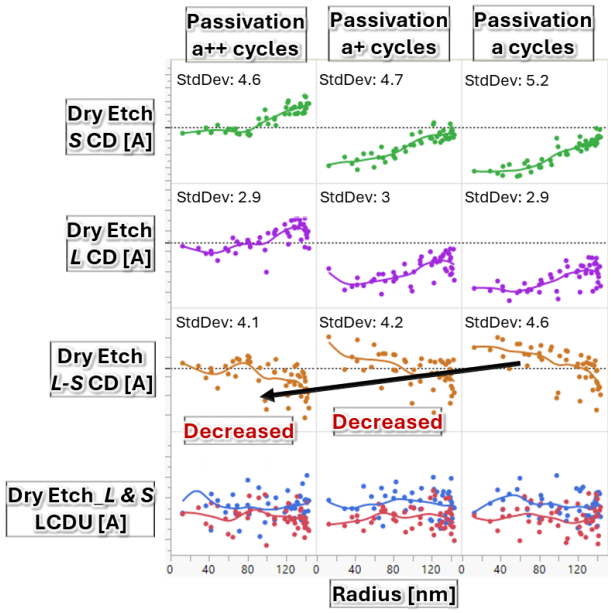

Fig. 12 Dry etch CD performance under atomic layer passivation cycle skew. (a: atomic layer passivation cycles)

E. Mitigating Trade-offs in Minimizing Surface Area Loss During Dry Etching

To achieve optimal L–S CD control, atomic layer passivation alone is insufficient; it must be complemented by precise tuning of etch chemistry—particularly the ratio and flow of gases such as CF_4 and CH_2F_2—to balance deposition and etching across varying pattern densities. This combined approach mitigates pattern loading effects and promotes uniform CD control across both large and small features. Advanced etch strategies, including multi-step etch sequences, hardmask integration, and real-time endpoint detection, are increasingly critical for robust pattern transfer and defect suppression in EUV-enabled DRAM nodes.

Following these enhancements, the dry etch process successfully transfers the amplified pattern features onto the underlying layers with high fidelity. This is achieved by increasing the descum (DS) duty cycle (DC), which has been identified as a key factor influencing L CD preservation. Additionally, fine-tuning the DS time is essential for protecting L CD features, which are particularly vulnerable to plasma-induced erosion.

In advanced DRAM patterning, especially under irregular EUV exposure conditions, maintaining CD fidelity across varying feature sizes remains a significant challenge. The descum step, utilizing N_2/CH_2F_2 plasma chemistry, plays a pivotal role in this context. Beyond its primary function of removing residual resist and scum, the descum step directly influences the local deposition-to-etch (dep/etch) dynamics, which are critical for preserving both L and S CD features. The N_2/CH_2F_2 mixture provides a tunable plasma environment: CH_2F_2 contributes to fluorocarbon polymer deposition, offering sidewall passivation as shown in Fig. 13(a)(b), while N_2 stabilizes the plasma and suppresses excessive polymer buildup.

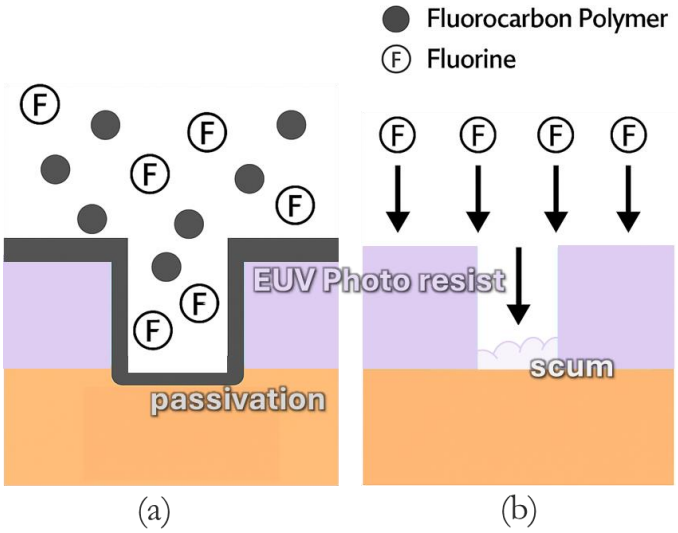

Fig. 13 Schematic diagram of (a) top-heavy deposition with sidewall passivation and (b) descum using fluorocarbon-based chemistries.

By adjusting the descum time, the dry etch process can be selectively biased toward either deposition or etching, depending on the CD size and pattern density. In small CD (S) regions, extended descum time may result in excessive etching, leading to CD shrinkage or profile distortion due to insufficient polymer protection. Conversely, in large CD (L) regions, shorter descum time may cause incomplete scum removal, resulting in micro-loading effects or bridging between features. Therefore, a time-optimized descum step is essential to locally balance the deposition-to-etch (dep/etch) ratio, ensuring adequate polymer protection in L regions while enabling effective cleaning in S regions.

While this strategy successfully achieves the target L CD, a concurrent increase in pattern bridging has been observed. This phenomenon is attributed to the use of deposition-prone gases in the dry etch process, combined with atomic layer passivation. Although these measures effectively protect L CD from plasma-induced erosion and help meet the photo-defined L–S CD ratio, they inadvertently elevate the risk of bridging, as illustrated in Fig. 14.

Striking a balance between CD preservation and bridging defect mitigation is therefore essential. Through a design of experiments (DOE) approach, adjusting the gas flow rates of N_2 and CH_2F_2 has proven effective in reducing bridging while maintaining the benefits in L CD [10]. As a result, the dry etch process achieves an optimized balance among CD control, LCDU, and defectivity.

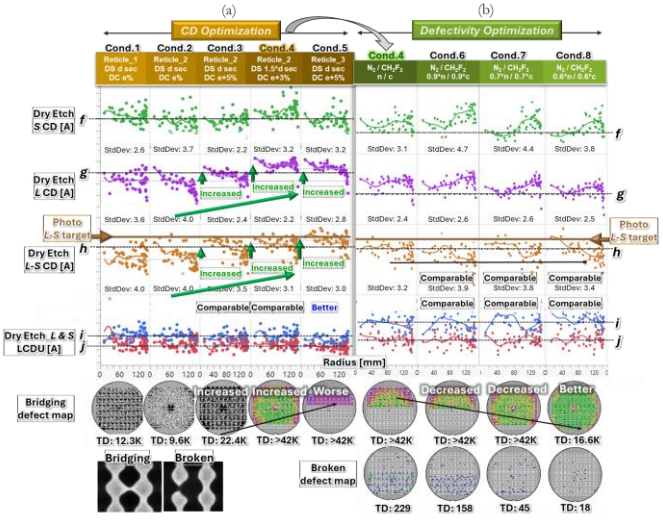

Fig. 14 CD and defectivity performance as a function of (a) descum time and duty cycle and (b) N_2/CH_2F_2 gas flow rate skew. (d: descum time; e: descum duty cycle; n: N_2 flow rate; c: CH_2F_2 flow rate).

III. Conclusion

Advanced dry etch techniques are essential for mitigating ion reflection effects that contribute to CD bias, profile distortion, and etch variability in high-aspect-ratio EUV structures. By optimizing plasma chemistry and ion energy, and integrating atomic layer passivation, we achieved enhanced anisotropy and minimized CD loss—particularly preserving the surface area of complex and irregular EUV features. Our approach-maintained CD loss within 10Å between the EUV photoresist and dry etch steps, while simultaneously reducing defectivity and preserving pattern fidelity, which is critical for continued device scaling.

These results underscore the importance of this novel dry etch methodology—combining conformal passivation and process tuning—in enabling precise pattern transfer for advanced EUV lithography. The improvements demonstrated in CD control, LCDU, and defectivity support the reliable scaling of both logic and memory technologies, reinforcing the role of etch process innovation in next-generation semiconductor manufacturing.

Acknowledgment

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