

Mechanism-Driven Etch-Passivation Balance Engineering for LCDU Convergence Across Hybrid EUV Geometries

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Hybrid Extreme Ultraviolet (EUV) patterns containing both wide and narrow features introduce additional complexity in pattern transfer due to feature-dependent plasma etch responses, creating simultaneous challenges in localized critical dimension uniformity (LCDU, 3σ) and pattern fidelity. In particular, narrow features inherently exhibit poorer LCDU due to their heightened sensitivity to plasma-induced critical dimension (CD) variation. In this work, the etch-passivation interactions governing differential CD evolution across feature types are investigated. These differences originate from geometry-dependent variations in ion and radical transport between wide and narrow features, leading to imbalanced pattern transfer and amplified variability at narrow dimensions. A mechanism-driven etch-passivation balance engineering strategy is developed to overcome the conventional fidelity trade-off and enable LCDU convergence across hybrid EUV geometries. The rebalanced etch-passivation improves 13% narrow-feature local uniformity and defectivity while preserving wide-feature and pattern fidelity.

Index Terms: Dry etch, Hybrid, EUV Lithography

I. INTRODUCTION

EUV lithography enables continued device scaling through increasingly complex layouts with higher pattern density and reduced CD, as illustrated in Fig. 1. As hybrid EUV architecture becomes more prevalent, simultaneous control of LCDU and pattern fidelity becomes more challenging. Unlike single-feature patterns, hybrid layouts contain coexisting feature dimensions that respond differently during plasma processing. These differences originate from plasma-surface interactions, where variations in ion transport, radical accessibility, and polymer deposition alter local etching and passivation kinetics. Consequently, ion reflection, micro loading, and aspect-ratio-dependent etching (ARDE) drive divergent profile evolution and dimensional variability across pattern types.

The impact becomes more pronounced in narrow features, where reduced dimensions and tighter pitch increase sensitivity to transport imbalance and surface-reaction fluctuations. As a result, local variations are amplified, leading to greater LCDU degradation and increasing difficulty in achieving dimensional convergence across hybrid layouts. Therefore, robust pattern transfer requires engineering of the etch-passivation balance to reduce geometry-driven variability and enable concurrent improvement of LCDU and pattern fidelity.

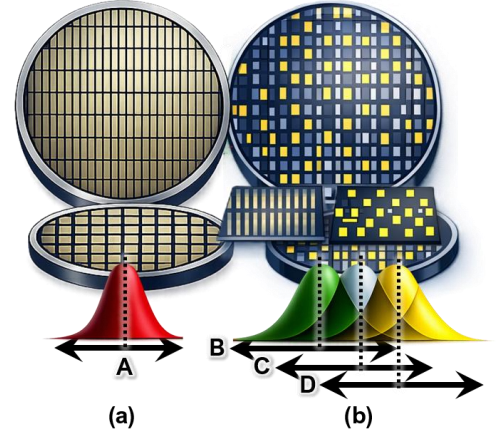


Fig. 1 Comparison of EUV patterning architectures. (a) Single-feature layout containing a uniform geometry with consistent dimensional behavior. (b) Hybrid layout comprising multiple coexisting feature dimensions that exhibit different pattern-transfer sensitivities, creating additional challenges for achieving LCDU convergence and pattern fidelity.

II. METHODOLOGY AND RESULTS

A. Feature-Size Dependence of LCDU in Hybrid Geometries

Under nominal plasma conditions, pattern evolution is governed by the local balance between material removal and passivation retention. While sufficient ion and radical fluxes support stable processing, transport effects cause this balance to deviate among different feature dimensions, as illustrated in Fig. 2 and Fig. 3.

For narrow features, restricted transport pathways increase susceptibility to variations in species delivery and by-product removal. Consequently, fluctuations in the etch-passivation balance become more pronounced, amplifying dimensional variability. In contrast, wider features

experience less transport constraint and exhibit comparatively stable evolution.

This increased sensitivity in narrow features results in higher LCDU and reinforces the inverse relationship between CD and LCDU. As hybrid layouts incorporate increasingly diverse dimensions, achieving LCDU convergence becomes progressively more difficult. Therefore, mitigating transport-induced imbalance is essential for reducing dimensional variability across mixed-feature geometries.

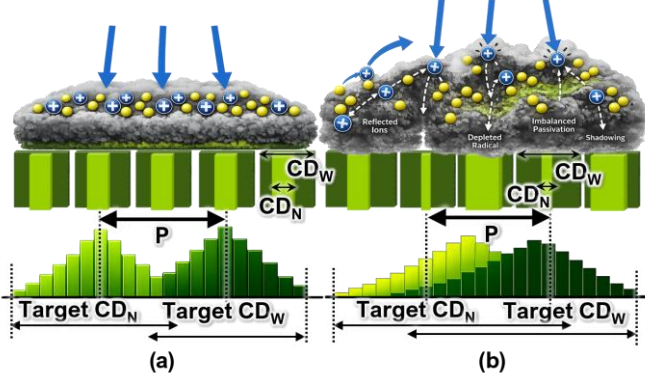


Fig. 2. Conceptual illustration of feature-size-dependent etch-passivation behavior. (a) Balanced ion-radical interactions provide uniform passivation and consistent dimensional control across features. (b) Geometry-induced transport imbalance, including ion reflection, radical depletion, and passivation non-uniformity, disrupts local etch-passivation balance, leading to broadened CD distribution and increased LCDU.

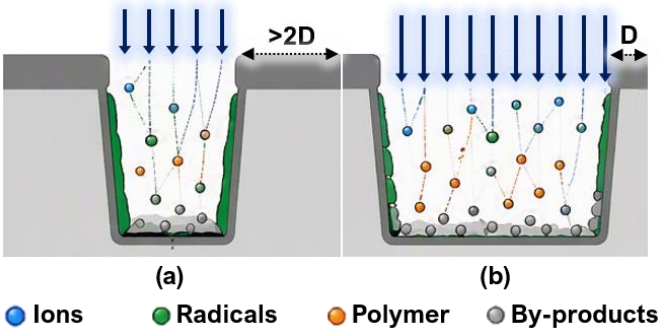


Fig. 3 Comparison of plasma transport and passivation behavior in wide and narrow features. (a) Wide features exhibit relatively unrestricted species access and stable passivation conditions. (b) Narrow features experience transport constraints that increase sensitivity to local plasma variations, resulting in greater susceptibility to dimensional variability.

B. Mixed-Dimension Pattern Fidelity Constraint

In hybrid geometries, pattern fidelity is strongly influenced by dimension-dependent plasma behavior. Different feature dimensions exhibit distinct dimensional responses to the same process condition, producing asymmetric CD shifts and profile variations across coexisting features, as illustrated in Fig. 4.

While reducing dimensional variability is essential for LCDU improvement, process changes that benefit one feature type may induce undesired dimensional responses in another. Consequently, LCDU improvement is often accompanied by pattern-fidelity constraints, particularly in layouts containing both narrow and wide features. This creates a coupled relationship that requires simultaneous control of dimensional uniformity and profile integrity.

Such behavior indicates that successful LCDU optimization cannot rely solely on dimensional correction, but instead requires management of the underlying etch-passivation balance that governs pattern evolution across mixed-feature geometries.

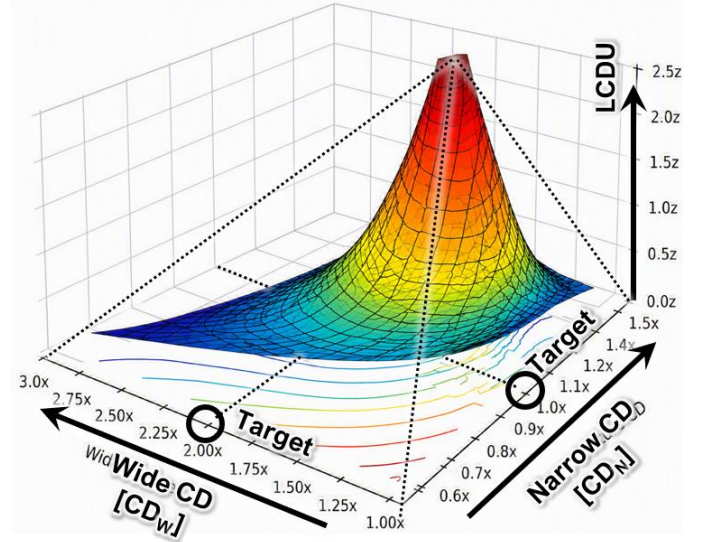


Fig. 4 Schematic LCDU landscape across narrow- and wide-feature dimensions. Independent target dimensions for both feature types constrain the available process window, highlighting the challenge of achieving simultaneous LCDU convergence and pattern-fidelity preservation.

C. Duty-Cycle Engineering for LCDU Stabilization

In EUV patterning, descum functions as a pattern-conditioning step that removes residual material while preserving photoresist integrity. As illustrated in Fig. 5, reducing pulse duty cycle enhances sidewall passivation by increasing the relative contribution of passivation-forming reactions.

Because narrow features experience stronger transport constraints, enhanced passivation provides greater stabilization against local plasma fluctuations. Consequently, variations in the etch-passivation balance are moderated, reducing sensitivity to local plasma fluctuations. As shown in Fig. 6, LCDU is improved with minimal impact on mean CD, partially relaxing the conventional inverse relationship between CD and LCDU.

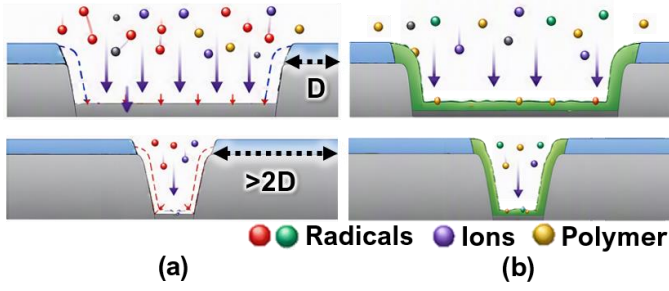


Fig. 5 Mechanism of duty-cycle engineering in pulsed descum. (a) High duty cycle favors ion-assisted material removal through increased plasma exposure. (b) Low duty cycle promotes passivation retention and sidewall protection, rebalancing etching and passivation reactions to improve pattern-transfer stability.

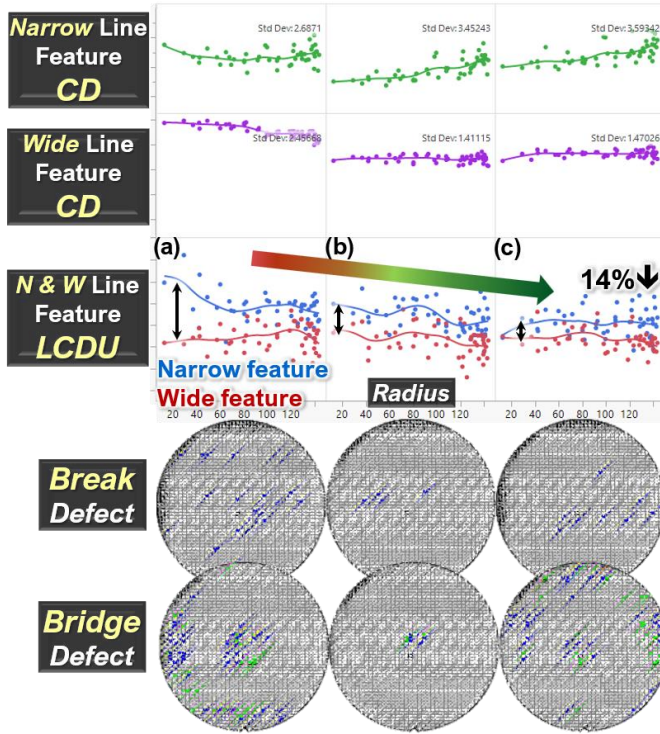


Fig. 6. Effect of duty-cycle engineering on feature CD and LCDU. Duty-cycle optimization, combined with Atomic Layer Deposition (ALD) passivation, progressively improves LCDU from the baseline condition (a) through the LCDU-driven condition (b) to the converged condition (c), while maintaining both narrow- and wide-feature CD near their target dimensions.

D. Descum-Trim Balance for Pattern-Fidelity Preservations

Building upon the descum-enabled pattern-conditioning strategy, trim processing is introduced to achieve the target CD through controlled lateral material removal. However, excessive trimming can disrupt sidewall protection, increase profile perturbation, and amplify dimensional variability, as illustrated in Fig. 7.

As dimensional reduction progresses, narrow and wide features respond differently to material removal, resulting in increasing profile divergence. Without sufficient sidewall

protection, these differences can lead to asymmetric CD shifts and degraded pattern fidelity.

Therefore, maintaining an appropriate balance between passivation preservation and dimensional correction is critical. By sustaining adequate sidewall protection while limiting excessive profile disturbance, the process promotes more uniform evolution across mixed-feature geometries while preserves target dimensions.

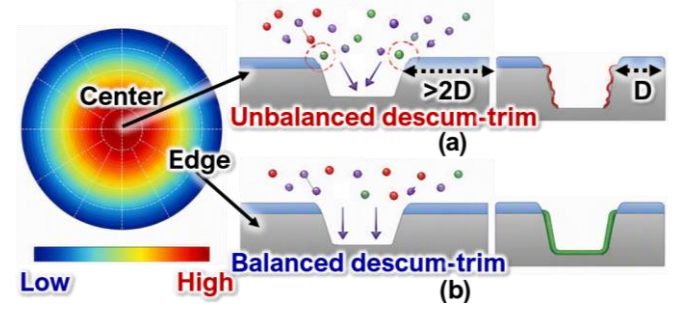


Fig. 7 Comparison of descum-trim balance conditions. (a) Excessive descum-trim imbalance amplifies sidewall perturbation and dimensional variability. (b) Balanced descum-trim operation maintains adequate sidewall protection while preserving dimensional control, promoting more uniform pattern evolution.

The results suggest that maintaining an appropriate balance between pattern conditioning and dimensional trimming is essential for stabilizing pattern evolution. Within this process window, sidewall development becomes more uniform across narrow features, resulting in reduced wafer-center LCDU with minimal impact on mean CD.

The defect behavior shown in Fig. 8 further supports the existence of a balanced etch-passivation regime, where wafer-center LCDU is reduced by 13% and key defectivity by 30% without compromising target CD. Collectively, these results demonstrate that coordinated descum-trim control can suppress feature-dependent transfer asymmetry and promote more consistent pattern evolution across hybrid geometries.

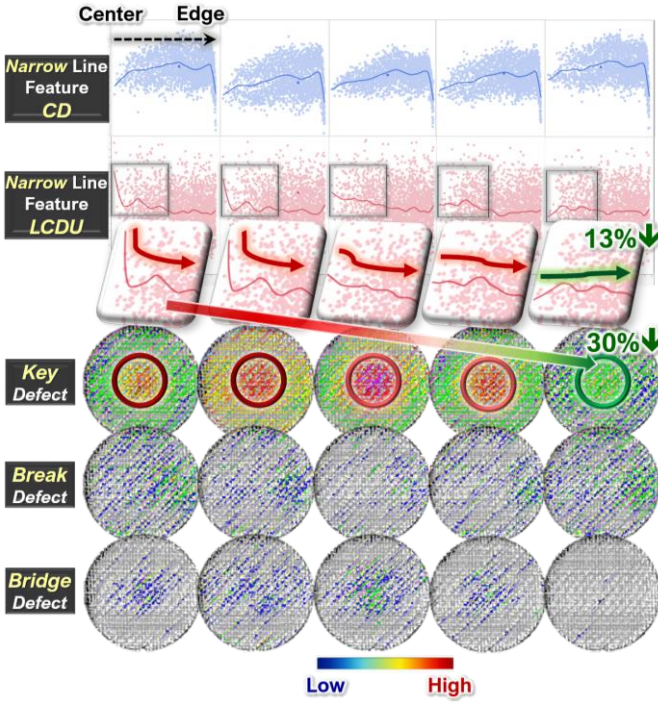


Fig. 8 Evolution of narrow-feature CD, LCDU, and defectivity under different descum-trim conditions. (a) Baseline. (b) Passivation-enhanced. (c) Intermediate balanced. (d) Balanced etch-passivation. (e) Stabilized pattern-transfer condition. Progressive balancing of passivation preservation and dimensional correction reduces wafer-center LCDU by 13% and key defectivity by 30% while maintaining target CD, demonstrating improved pattern-transfer stability.

E. Integrated Etch-Passivation Balance Engineering

The combined implementation of duty-cycle engineering and descum-trim balance establishes a unified etch-passivation framework. Together, these approaches provide a mechanism-based strategy for simultaneously improving LCDU and preserving pattern fidelity across hybrid EUV geometries.

III. CONCLUSION

The results demonstrate that LCDU degradation in hybrid EUV geometries is governed not solely by mean CD, but by the stability of feature-size-dependent pattern evolution. Variability arising from mixed-dimension interactions amplifies dimensional non-uniformity and profile divergence, creating significant challenges for pattern transfer.

Through integrated etch-passivation balance engineering, incorporating both duty-cycle engineering and descum-trim balance control, dimensional variations are suppressed while target dimensions are maintained. The balanced process stabilizes sidewall evolution, reduces LCDU amplification, and enables concurrent improvement of LCDU and pattern fidelity. These findings establish a mechanism-driven framework for overcoming the

conventional trade-off between LCDU and pattern fidelity, providing a scalable strategy for robust pattern transfer in increasingly complex EUV architectures.

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