Formulated surface conditioners in 50 nm immersion lithography: simultaneously reducing pattern collapse and line-width roughness

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ABSTRACT

With the introduction of immersion lithography into IC manufacturing for the 45nm node, pattern collapse and line width roughness (LWR) remain critical challenges that can be addressed by implementing formulated surface conditioners. Surface conditioners are capable of solving multiple issues simultaneously and are easily integrated into the post-develop photolithography process.

In this paper, we assessed the impact and reported our findings using a formulated surface conditioning solution in an immersion lithography process to improve the non-pattern collapse and LWR process windows on 300mm Si wafers having 50 nm L/S features. The non-pattern collapse and LWR process window results were then compared to wafers processed using traditional developer processing methods, a DI Water (DIW) rinse.

We report our findings using Focus Exposure Matrix (FEM) wafers having 50nm dense lines/spaces (L/S) and a 2.4:1 aspect ratio to determine the non-collapse and LWR process windows. An ASML TWINSCAN XT:1700i™ Scanner and a 6%attPSM mask were used to pattern the FEM and LWR wafers. The wafers were then developed using an optimized developer recipe on an RF3™ coater-developer track. Each wafer was analyzed and evaluated to determine the impact to CD and LWR with respect to the .non-pattern collapse process window.

Formulated surface conditioners having dual capabilities, reduced pattern collapse and LWR, have demonstrated that multiple ITRS Roadmap goals can be achieved and easily implemented into standard IC processing in order to meet these challenges.

Keywords: surface conditioner, LWR, process optimization, process window, lithographic DOF, lithographic EL, useable DOF, useable EL, 50 nm dense lines, pattern collapse
1. INTRODUCTION

The introduction of immersion lithography has enabled the extension of optical lithography to the 45 nm node. With this integration, line width roughness (LWR) and pattern collapse are exacerbated and remain major lithography concerns in meeting the industry roadmap\(^1\). One consequence of minimizing film thickness to eliminate pattern collapse is the reduction in the acceptable resist-etch budget. Even if resist-etch budget is addressed, LWR issues remain and cannot be resolved by only improving the aerial image contrast\(^2,3\) via optical settings (e.g. NA, partial coherence).

Improvements may be made via the resist/BARC combination but there are severe implications to the resist/BARC integration which negatively impact device performance. With the use of \textsuperscript{R}OptiPattern\textsuperscript{\textregistered}, significant benefits including LWR and pattern collapse reduction can be achieved without risks to device performance.

In previous work\(^4\), we have demonstrated that LWR and pattern collapse can be reduced simultaneously by integrating surface conditioners into the in-situ post-develop process. Traditionally, lithographers evaluate outputs such as depth-of-focus (DOF) and exposure latitude (EL) independently of one another without considering pattern collapse or LWR. When evaluating LWR, lithographers tend to use the nominal optical exposure conditions (e.g. NA, partial coherence, etc.) across a wafer to determine a resist’s performance. Even when DOF and EL are considered simultaneously, pattern collapse and LWR are typically not factored into the analysis. In reality, comprehensive resist performance can be accurately determined only when DOF, EL, pattern collapse, and LWR are evaluated simultaneously and with consideration to the respective process windows.

In this paper, we discuss 50 nm immersion lithography and the significance of evaluating LWR in the context of the “useable” process window. We illustrate how using the simplistic view of LWR, DOF, or EL independently of one another can result in erroneous conclusions. We further demonstrate how surface conditioners, compared to DI water, provide the benefit of reducing LWR and eliminating pattern collapse while providing improved DOF, EL, and useable process window.

2. EXPERIMENTAL

2.1 Wafer processing

Immersion lithography experiments were conducted using a litho-cell consisting of a Sokudo RF\(^{3,1}\textsuperscript{TM} coater-developer track interfaced to an ASML TWINSCAN XT:1700i ArF scanner to process 300 mm Si wafers. The scanner used annular illumination conditions to image 50 nm and 65 nm dense, 1:1 L/S features into Resist 1 (TOK TArF P6239) and 65 nm dense, 1:1 L/S features into Resist 2 (TOK TArFP6111). After patterning the wafers with 50 nm and 65 nm L/S, the wafers were evaluated using the Hitachi S-9380 II CD-SEM.

Wafers were coated with 120 nm of Resist 1, 42 nm of 1C5D AZ-Clariant Bottom Anti-Reflective Coating (BARC), and 90 nm of TCX-041 JSR Top Coat to process 50 nm dense, 1:1 L/S. All wafers were developed using 0.26N of \textsuperscript{R}OptiYield\textsuperscript{\textregistered} CD developer from Air Products. \textsuperscript{R}OptiPattern\textsuperscript{\textregistered} Smooth surface conditioner was used for the in-situ, post-develop surface treatment to simultaneously eliminate pattern collapse and reduce LWR. The surface conditioner was applied onto the wafer after development and post-develop-DI Water rinse while the wafer was still wet with DI Water. The surface conditioner was allowed to puddle for 15 seconds followed by a spin dry.

Wafers were also coated with 150 nm of Resist 2, 38 nm of 1C5D, and 90 nm of TCX-041 to process 65 nm dense, 1:1 L/S. Resist 2 is not suited for 50 nm 1:1 L/S lithography.

The non-collapse LWR process window is defined as the process window of resist L/S features not having no pattern collapse while meeting the CD (i.e. CD $\pm$ 10%) requirement and reducing LWR (e.g. $\leq$ 8 nm, 3$\sigma$). Each SEM micrograph image was reviewed to determine the non-collapse CD and LWR process windows. Process outputs (i.e. DOF, EL, LWR, and process window) not considering pattern collapse, are referred to as the “lithographic” output (e.g. Lithographic DOF). Outputs considering pattern collapse are referred to as the “actual” or “useable” process output.
All wafers were developed using OptiYield® CD developer to generate 50 nm L/S FEM’s and cross-section data to
determine Lithographic DOF, non-collapse DOF, Lithographic EL, non-collapse EL, Lithographic LWR, and non-
collapse LWR process windows. The results are compared to the standard litho cell process which uses DI Water.

2.2 Exposures

For each process setting, two wafers were exposed with a Focus Exposure Matrix (FEM) having 21 energy columns and
21 focus rows to determine the process windows.

Wafers were exposed on an ASML TWINSCAN XT:1700i ArF scanner using a 6% AttPSM mask for both 65 nm and
50 nm features with the following illumination conditions. The 50 nm L/S were processed using x-y polarization while
the 65 nm L/S were not.

50 nm 1:1 L/S

- Resist(s):
  - TArF P6239 using 120 nm and 105 nm film thickness
- NA = 1.2
- $\sigma_o/\sigma_i = 0.94/0.74$ annular illumination and x-y polarization
- TArF P6239: Best Energy (BE) = 38.0 mJ/cm², Best Focus (BF) = 0.0 µm
- TArF P6239 FEM’s:
  - Dose: 38 mJ/cm² in 1.0 mJ increments
  - Focus: 0 µm in 0.03 µm increments

65 nm 1:1 L/S

- Resist(s):
  - TArF P6239 using 120 nm film thickness
  - TArF P6111 using 150 nm film thickness
- $\sigma_o/\sigma_i = 0.93/0.69$ annular illumination and no polarization
- TArF P6239: Best Energy (BE) = 47.5 mJ/cm², Best Focus (BF) = 0.0
- TArF P6111: Best Energy (BE) = 32.0 mJ/cm², Best Focus (BF) = 0.0
- TArF P6239 FEM’s:
  - Dose: 36 mJ/cm² in 1.0 mJ increments
  - Focus: 0 µm in 0.03 µm increments
- TArF P6111 FEM’s:
  - Dose: 31 mJ/cm² in 1.0 mJ increments
  - Focus: 0 µm in 0.04 µm increments

2.3 Metrology and figures of merit investigated

2.3.1 Measurements and analysis

CD and LWR measurements and SEM micrographs were generated using a Hitachi S-9380 II CD-SEM. To reduce the
influence of spurious measurements to LWR, multiple points within the field-of-view (FOV) were measured and
averaged within each die having a unique FEM setting. CD measurements, using a linear fit in Excel, helped determine
DOF at best energy and EL at best focus. Process windows were analyzed using KLA-Tencor’s Prodata® software and
Excel to generate the process window illustrations.

A quadratic polynomial fit through focus for the LWR measurements and the minimum value of the fit were compared
for the various process conditions.
3. RESULTS AND DISCUSSION

To effectively determine resist performance requires that DOF, EL, pattern collapse, and LWR be evaluated simultaneously and with consideration to the respective process windows. Section 3.1 will establish that if analyzed independently of one another (Figures 1-3), one can mistakenly conclude that DI Water and surface conditioner behave similarly.

3.1 65 nm 1:1 L/S

The Lithographic DOF (Figure 1) of DI Water and OptiPattern® Smooth are compared for 120 nm of TArF P6239 and 150 nm of TArF P6111 resists patterned with 65 nm L/S. The Lithographic DOF performance of DI Water and OptiPattern® Smooth are similar when processing TArF P6111 and TArF P6239 resist systems.

Based on Figure 1, similar Lithographic DOF performance is realized for DI Water and OptiPattern® Smooth surface conditioner.

![Figure 1: Lithographic DOF, 120 nm of TArF P6239 and 150 nm of TArF P6111 Resist](image)

The Lithographic EL performance of DI Water is compared to OptiPattern® Smooth (Figure 2) for TArF P6239 and TArF P6111 resist processes. DI Water and OptiPattern® Smooth surface conditioner have similar Lithographic EL performance at this point.
The LWR performance data (Figure 3) illustrates a significant reduction in LWR, approximately 20%, for both TArF P6111 and TArF P2369 resist systems when using OptiPattern® Smooth surface conditioner compared to DI Water. However, the actual analysis is incomplete and performance is not fully understood when using LWR as the only measure of success to compare OptiPattern® Smooth to DI Water.

Reviewing each SEM micrograph and plotting the measured data (Figures 4A, 4B) illustrates surface conditioner’s ability to improve the useable process window as compared to DI Water. The useable process window is defined as, the area within the bounds of the CD and LWR curves that does not exhibit pattern collapse and meets the target CD (CD ± 10%) requirement while reducing LWR (≤ 10.0 nm, 3σ). When considering CD and pattern collapse, OptiPattern® Smooth (Figure 4B) increased useable DOF approximately 150% versus DI Water (Figure 4A). For LWR (≤ 10.0 nm, 3σ), OptiPattern® Smooth increased DOF to 0.56 µm from approximately 0.22 µm for DI Water.

When simultaneously considering CD, LWR, and pattern collapse, OptiPattern® Smooth provides a more robust and functional process window with which to operate versus DI Water.
By not considering pattern collapse, the traditional manner of comparing DOF, EL, and LWR does not permit for proper analysis of the process window. As a consequence, the actual process window may not be properly quantified and determined when evaluating OptiPattern® Smooth and comparing it to a DI Water-only process. The “useable” process window (Figures 4A, 4B) can only be determined when CD, EL, DOF, LWR, and pattern collapse are considered simultaneously. When analyzing all figures of merit simultaneously, it is evident that DI Water has a significantly smaller process window compared to OptiPattern® Smooth. When evaluating DOF and EL alone, one erroneously concludes that DI Water has a viable process window.

![Graphs showing LWR Window and CD Non-Collapse Window](image1)

**Figure 4A:** (DI Water)  
**Figure 4B:** (OptiPattern® Smooth)  
**Figure 5A:** DI Water  
**Figure 5B:** OptiPattern® Smooth

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<th>Output</th>
<th>DI Water</th>
<th>OptiPattern® Smooth</th>
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<tr>
<td>LWR (nm, 3σ)</td>
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<td>DOF NOT considering CD + LWR &lt; 10.0 nm, 3σ</td>
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<td>DOF WHILE considering CD + LWR &lt; 10.0 nm, 3σ</td>
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<td>0.56</td>
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Table A: Benefits Summary in 150 nm of TArF 6111 Resist, OptiPattern® Smooth versus DI Water
3.2 50 nm 1:1 L/S

The 65 nm L/S data validates that the traditional methodology of comparing DOF, EL, and LWR independently of one another, while excluding pattern collapse, does not allow for proper analysis of the useable process window. By analyzing 50 nm L/S features, we will prove the same conclusions can be made concerning LWR, pattern collapse, and the useable process window.

50 nm L/S were processed into 120 nm and 105 nm of TArF P6239 resist. CD and LWR were measured within each die across the wafer. SEM micrograph images of the 50 nm L/S were generated and reviewed to determine if pattern collapse was prevalent at each measurement site. The CD, LWR, and SEM image data of sites identified as not having collapse were used to plot the useable DOF, EL, and process window graphs (Figures 6, 7, and 8).

Lithographic DOF (Figure 6) performance data of DI Water was compared to that of OptiPattern® Smooth. The data illustrates wafers treated with OptiPattern® Smooth surface conditioner eliminated the DOF difference, 270 nm, between “BE” and “-10% CD” versus wafers treated with DI Water. Based on Lithographic DOF at BE, no additional process improvements are evident.

DI Water Lithographic EL performance data is compared to that of OptiPattern® Smooth (Figure 7) using 50 nm L/S patterned into 120 nm and 105 nm of TArF P6239 resist. DI Water and OptiPattern® Smooth surface conditioner have similar Lithographic EL performance at this point.
The 50 nm L/S Lithographic LWR (Figure 8) data illustrates LWR is reduced approximately 20% for the 120 nm film thickness and approximately 14% for the 105 nm film thicknesses when treated with OptiPattern® Smooth surface conditioner. As stated previously, the data is incomplete and performance not fully understood when using LWR as the only measure of success when comparing surface conditioners such as OptiPattern® Smooth to DI Water.

The process area is defined as the area within the curve meeting the CD (50 nm ± 10%) criteria and simultaneously reducing LWR (≤ 8.0 nm, 3σ) and eliminating pattern collapse (Figure 9). When comparing wafers coated with TArF 6239 resist, the wafers treated with OptiPattern® Smooth have a 100% larger EL and 50% larger DOF, when considering the useable CD process window compared to DI Water. When factoring LWR (≤ 8.0 nm, 3σ) and CD, OptiPattern® Smooth improves EL 100% and DOF 50% versus DI Water.

Compared to DI Water, one ascertains wafers processed with OptiPattern® Smooth have a larger useable process window with which to operate in while simultaneously considering CD, LWR, and pattern collapse.

The data reemphasizes the importance of considering LWR and CD process overlap and pattern collapse (Figures 9, 10A, 10B) to properly determine the actual process window.
<table>
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<tr>
<th>Output</th>
<th>DI Water</th>
<th>OptiPattern® Smooth</th>
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</thead>
<tbody>
<tr>
<td>LWR (nm, 3σ)</td>
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<td>LWR Reduction (%)</td>
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<td>DOF Improvement (%)</td>
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<td>EL (%) WHILE considering LWR &lt; 8.0 nm, 3σ</td>
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Table B: Benefits Summary in 120 nm of TArF 6239 Resist, OptiPattern® Smooth versus DI Water
4. CONCLUSIONS

In this paper, the importance of considering all aspects of the useable process window (i.e. DOF, EL, CD, and pattern collapse) to properly quantify and determine the capabilities of processing with a surface conditioner versus DI Water was established. As LWR requirements become more aggressive, resist systems were shown to be the gating factor that negatively impacts LWR, pattern collapse performance and were resolved by employing materials such as surface conditioners.

Comprehensive analysis of the data determined the useable process window exhibited significant LWR and pattern collapse reduction simultaneously when using surface conditioners versus DI Water in an in-situ, post-develop process for a 50 nm immersion lithography process.

When comparing wafers treated with surface conditioner versus DI Water (Figures 6, 7) in the initial analysis, both Resist 1 and Resist 2’s EL and DOF displayed no apparent improvement for the 50 nm features. Upon considering LWR < 8.0 mm, it is immediately evident that surface conditioners reduced LWR approximately 20% versus DI water. When considering the non-collapse process window and LWR, the improvement to the useable process window (Figure 9) is evident. Without considering pattern collapse and traditional lithography parameters simultaneously, the surface conditioner’s benefits would have been inconclusive. By using a comprehensive method to analyze the process window, a more accurate assessment of the process was determined.

Surface conditioners such as OptiPattern® Smooth demonstrate the ability to improve the useable DOF up to 320%, useable EL up to 100%, and useable LWR up to 23% while reducing pattern collapse 100%.
REFERENCES


