2D and 3D photoresist line roughness characterization

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ABSTRACT

Lithographic scaling is approaching 16 nm feature dimensions. Besides the manufacturing challenges, metrology is also suffering with feature scaling: Scanning microscopy is struggling to capture the roughness of the new photoresist platforms for ArF and extreme-UV lithography, thinner and more sensitive to electron bombardment. Moreover, standard figure of merit such as feature dimensions and line roughness should be integrated with fractal analysis and frequency evaluation, both needed to understand the root-causes of resist roughness. For this purpose, 3D sidewall information are likely to be required in order to choose the best process settings to reduce the roughness after exposure and during pattern transfer.

In this paper, line width/edge roughness characterization is reported by means of power spectral density and fractal analysis. These results are compared with 3D atomic force microscopy and thickness measurements. A synthetic 3D surface reconstruction model is then extrapolated from the power spectral densities.

The full method is tested on a plasma-based smoothing technique, where the patterned resist is exposed to plasma-UV light in order to reduce the roughness before the etch steps. Between 15% and 50% edge roughness reduction is obtained, at the cost of resist thickness loss and line shape deterioration.

1. Introduction

Many doubts have been raised on the maturity of the advanced lithographic techniques (multiple patterning with ArF immersion, Extreme-UV Lithography – EUVL, direct writing techniques) to reach the roughness specification required for the future technological nodes [1]. All the elements composing the optical lithographic process contribute to the final resist roughness [2]; however, with feature scaling, metrology starts playing a fundamental role in roughness detection and evaluation.

The most common tool used to characterize the lithographic processes after exposure is the Critical Dimension Scanning Electron Microscope (CD-SEM). Top-down SEM images are characterized by means of secondary electron signal line profile analysis to obtain 2D information of the defined pattern: CD, CD uniformity, Line Edge and Width Roughness (LER, LWR), are widely used figure of merit to evaluate the performance of lithographic processes [3]. Moreover, Ohtuji, Naulleau, and Constantoudis [4–6] have introduced and developed software to obtain Power Spectral Density (PSD) analysis to assess roughness contributions in the frequency domain.

Secondary electron signal line profile analysis is the easiest but very thorny technique to detect edge variations along 2D top-down SEM images. With the feature scaling, resist thickness reduction and soften material to electron bombardment are often implemented, with a consequent Signal-to-Noise (S/N) contrast ratio drop. Moreover, 3D information about the pattern profile (i.e. surface edge roughness) is inevitably lost. 3D techniques, such as CD Atomic Force Microscopy (CD-AFM), cross-section Field Emission SEM (FE-SEM), optical spectroscopy, or SEM images modeled with physical electron scattering are being developed in order to support 2D analysis, but they are still in experimental phases, or not suitable for mass production measurements [7,8].

In this paper, both 2D and 3D analyses are performed to characterize the roughness evolution of ArF-immersion resist patterns under plasma-vacuum UV (VUV) light smoothing technique [9–11]. Top-down CD-SEM was compared with CD-AFM analysis: respectively 3σLWR reduction up to 15% and 50% was found for the same samples. A qualitative comparison with cross-section Field Emission SEM (FE-SEM) images was then performed in order to explain this discrepancy. Resist thickness reduction and line profile modification...
is suspected to be the root-cause for the 3σLWR difference between the considered techniques [12,13].

From this work, it appears clear that the integration of 2D and 3D analysis is likely to be required for post-litho process characterization, in order to obtain the full picture of the resist roughness evolution before pattern transfer.

This paper is divided into two main sections: in the first part, the experimental setups of lithographic process and metrology are reported; the second section is dedicated to the roughness modeling by means of PSD analysis, while in the third section 2D and 3D analysis are reported for both 100 nm isolated lines and 45 nm half pitch lines/spaces pattern.

2. Materials and methods

2.1. ArF immersion lithographic exposure

ArF exposures were performed with an ASML XT:1900Gi scanner, interfaced with a SOKUDO RF3i coat and development system for resist coating, soft bake, post-exposure bake, and development. The mask selected was 6% Attenuated Phase Shift for 45 nm technological node. 105 nm of chemically amplified organic resist on 95 nm of bottom anti-refractive coating were spin on 300 mm bare Silicon wafers. Two different mask patterns were analyzed in order to compare the different behavior of the VUV-smoothing technique:

- 100 nm isolated line (Fig. 1a–d).
- 45 nm lines and spaces – 90 nm pitch (dense pattern, Fig. 1b–e).

To print such features, 20° quadruple illumination, with Numerical Aperture = 1.2, NAin/out = 0.78/0.96 and XY polarized light was used (Fig. 1c).

2.2. VUV exposure and blanket wafer measurement

Plasma VUV exposures were performed in an EAGLE 12-UV cure chamber from ASM using 172 nm excimer lamp at an intensity of 30 mW/cm². At 100 °C, nitrogen flow was 4slpm resulting in a pressure of 6.6 kPa. The wafer temperature was monitored in a separated experiment using a Plasma Temp C4 wafer from KLA-Tencor and shown to be constant at 105 °C, with a uniformity of ±2 °C.

Mass measurements were performed before coating, after coating and after exposure on a SF3 and OC23 tools from Metryx. Thickness and density were measured on an Aleris spectroscopic ellipsometry from KLA-Tencor.

2.3. Metrology setting

2.3.1. Top-down CD-SEM for 2D roughness analysis

Hitachi CG4000 CD-SEM was used on both isolated and dense pattern to collect 2D information about CD, 3σLWR and 3σLER after exposure and after VUV-smoothing treatment. Image capturing parameters were chosen to minimize resist damaging and preserve the S/N contrast ratio [14]. The setting used was:

- e-Beam current: 8 pA.
- Accelerating voltage: 500 V.
- Depth of focus beam mode.
- Pixel number: 512 × 512.
- Magnification: Asymmetric Field of View (FoV) with 300KX in x direction (perpendicular to the lines) and 49kX in y direction, for a total size of 0.450 × 2.755 μm².
- Frame number: 16.

Asymmetric FoV was selected to collect Low Frequency (LF) roughness, in accordance with ITRS specifications (Fig. 1d and e). ITRS requests 2 μm line length in order to collect at least 90% of the roughness spectrum, and reduce the uncertainty in CD measurements [1,15].

Frequency analysis was performed on CD-SEM top-down images with LERDEMO software, developed by Demokritos National Center for Scientific Research [6]. By means of the Height–Height Correlation Function (HHCF), correlation length (\( \xi \)), correlation factor (c-factor) and PSD were calculated. The HHCF quantifies the correlations among edges points, and therefore gives information about the spatial aspects of LER; \( \xi \) is the distance up to which the edge points are correlated, or ‘know about’ each other, while the c-factor quantify how much the edges of a single line are correlated one to each other [16]. The c-factor is defined as [3]:

\[
c = \frac{\sigma_{\text{LWR}}^2 - (\sigma_{\text{LER}}^2 + \sigma_{\text{LER},1}^2)}{2 \times \sigma_{\text{LER}}^2 \sigma_{\text{LER},1}^2}
\]

where \( \sigma_{\text{LWR}} \), \( \sigma_{\text{LER}} \), and \( \sigma_{\text{LER},1} \), are the standard deviation of the line-width, right and left line edge respectively.

PSD analysis gives the roughness distribution in the frequency domain. By using the Parseval theorem, it is possible to demonstrate that the area subtended by the PSD is proportional to \( \sigma_{\text{LER}}^2 \). PSD can be calculated with the Wiener–Khinchin theorem, Fourier anti-transforming the autocorrelation function, related to the HHCF by:

\[
\text{HHCF}^2 = 2 \times \left( R^2 - \text{Autocorrelation} \right)
\]

where \( R \) is the standard r.m.s. value of the points along the measured line edge. In Fig. 2a, PSD of an isolated resist line is reported (black dotted line): it is calculated from the CD-SEM image shown in Fig. 1d. Considering only few edges, the PSD results quite noisy, especially in the LF region, where only few sampling points are taken. PSD analyses of 125 averaged isolated lines on different wafers processed in the same way are reported in the same graph (grey lines): these curves result perfectly superimposed, proving the beneficial effect of averaging multiple images to minimize the sampling noise. Such metrology was found beneficial for other figures of merit: Fig. 2b and c reports respectively CD and 3σLWR trends (black

![Fig. 1](https://example.com/fig1.png)

Fig. 1. (a and b) Top-down CD-SEM image for isolated and dense lines after lithographic exposure (symmetric FoV: 300KXx300KX equivalent to 0.450 × 0.450μm²). (c) Sketch of the off-axis illumination used for printing isolated and dense structures. The full circle represents the NA of the optical system, the black poles represent the 0th diffraction orders, while the grey poles represent the 1st diffraction orders. (d and e) Top-down CD-SEM image for isolated and dense lines after lithographic exposure (asymmetric FoV: 300KXx49KX equivalent to 0.450 × 2.755 μm²).

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curves), and their 3σ distribution (grey curves) upon number of averaged images. Stable values are reached only after 50 images (100 edges). The black dots represent each single image measurement.

2.3.2. CD-AFM for 3D roughness analysis

CD-AFM (Insight 3D AFM from Veeco Instrument) was also used to measure the 3σLWR of isolated line before and after VUV smoothing treatment. This technique has been described in more details elsewhere [17,18]. The particularities of this AFM are the flared tip and the ability to scan in the Z direction enabling the measurement of the pattern sidewalls. Thus, this technique allows a 3D pattern reconstruction giving access to information such as pattern profile and 3σLWR along the sidewalls.

The resolution of the CD-AFM is not the same in the three directions. The lateral resolution on a planar surface (along the x and y directions) is in the order of 1 nm. The lateral resolution on the sidewall depends on the tip diameter along y and on the tip edge radius along z. The AFM tips (CDR50S from Veeco instrument) used in this study have a diameter of about 50 nm, edge radius values typically between 10 and 15 nm and a lateral stiffness of 1.6 N/m. Because of the tip shape and of its oscillation, no information can be obtained on the last 15 nm at the bottom of the pattern. Accordingly, for 3σLWR measurement, only the line widths 20 nm above the bottom were taken into account.

The experimental protocol was the following: 150 scan-lines were taken over 3 μm length (with a step-size of 20 nm), five times on the same resist line. The 3σLWR values given in this study are the average of these five measurements.

2.3.3. Cross-section FE-SEM for 3D roughness evaluation

Qualitative 3D roughness evaluations were performed using Hitachi SU8000 Ultra High Resolution FE-SEM (UHR FE-SEM) with a working voltage of 3 kV, and current of 10.5 μA. To prevent possible resist damage, the samples were coated with platinum (2–3 atomic layers). Isolated lines and large pad areas were captured and used for resist profile check.

3. Roughness modeling

Line edge surface was calculated by reverting the PSD obtained with the LERDEMO software (Fig. 3). Because the PSD removes the phase component from the spectra, a randomly distributed phase in the $[-\pi; \pi]$ range was injected. The calculated surface size along the line (y-direction in Fig. 3) is given by the FoV used during the image capturing:

$$\text{FOV} = \text{line-length}_{y}\frac{1}{f_{\text{min}}} = 2.755 \text{ μm}$$  (3)

with a pixel size given by the distance in between two harmonics in the PSD spectrum (i.e. the pixel size of the SEM image along the lines) [19]:

$$\text{pixel-size}_{y} = \frac{1}{\Delta f} = 5.39 \text{ nm}$$  (4)

Rectangular FoV is generally used to measure longer lines, without losing resolution along the direction of the protrusions, where the pixel size is 0.88 nm. For the line edge surface reconstruction,
30 pixels (equivalent to ~26 nm) were used (z direction in the figure), to have enough statistics for the phase injections.

The described line edge modeling method allowed comparing the impact of different VUV doses on the pattern edges.

Before proceeding with the experimental results, an important consideration must be made. PSD analyses are performed on 2D CD-SEM images, which represent the 3D resist features through a 2D top-down reconstructions. Hence, these spectra do not contain any real information of the sidewall or the profile, rather a 2D integration of the roughness. Therefore, the above mentioned surface reconstruction represents only qualitatively the 3D sidewall roughness. To quantitatively evaluate it, CD-AFM measurement must be used.

### 4. Results

#### 4.1. 2D analysis: Top-down CD-SEM

#### 4.1.1. Isolated lines

Seven 300 nm wafers were exposed as described in Section 2. On each wafer, different VUV post-lithography treatments were applied in order to analyze how 3σLER and 3σLWR evolve upon VUV dose (in mJ/cm²). LERDEMO analysis on CD-SEM top-down images is reported in Table 1; all the results are an average of 125 images/wafer. Top-down CD-SEM images are reported in Fig. 4.
The VUV dose applied was controlled upon time in the plasma chamber: 0 mJ/cm² exposure process was also analyzed (Table 1, second row) to evaluate any possible resist modification due thermal effects given by the heated chuck during the process. No difference was found compared to the reference wafer.

From the data it is noticed an initial CD shrink and 3σLWR/LER reduction upon VUV dose, followed by CD and roughness increment. As will be shown in the next section, this behavior is mainly due to resist reflow. 3σ increases as expected, but also the c-factor slightly decreases upon VUV dose: this means that the correlation between edges increases, minimizing the LWR respect to the LER Eq. (1).

Table 2
LERDEMO results of 45 nm half-pitch dense lines upon VUV-smoothing process dose. In the last column, the ratio of the analyzed line edge surface divided by a perfectly flat surface is reported.

<table>
<thead>
<tr>
<th>CD (nm)</th>
<th>3σCD (nm)</th>
<th>3σLWR (nm)</th>
<th>3σLER (nm)</th>
<th>3σ (nm)</th>
<th>c-Factor</th>
<th>Area edge ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference average</td>
<td>39.2</td>
<td>1.7</td>
<td>6.9</td>
<td>4.8</td>
<td>26.7</td>
<td>0.002</td>
</tr>
<tr>
<td>VUV_60 mJ/cm²</td>
<td>37.2</td>
<td>1.6</td>
<td>6.5</td>
<td>4.6</td>
<td>27.0</td>
<td>0.004</td>
</tr>
<tr>
<td>VUV_120 mJ/cm²</td>
<td>36.7</td>
<td>1.7</td>
<td>6.4</td>
<td>4.4</td>
<td>29.3</td>
<td>0.006</td>
</tr>
<tr>
<td>VUV_240 mJ/cm²</td>
<td>38.8</td>
<td>1.8</td>
<td>6.3</td>
<td>4.3</td>
<td>36.3</td>
<td>0.008</td>
</tr>
<tr>
<td>VUV_360 mJ/cm²</td>
<td>43.3</td>
<td>2.6</td>
<td>6.4</td>
<td>4.5</td>
<td>41.4</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Fig. 6. Resist thickness (black curve), mass (dark-grey curve) and density (light-grey curve) measurement upon VUV dose, reported in relative units.

The VUV dose applied was controlled upon time in the plasma chamber: 0 mJ/cm² exposure process was also analyzed (Table 1, second row) to evaluate any possible resist modification due thermal effects given by the heated chuck during the process (∼100 °C). No difference was found compared to the reference wafer.
It was also possible to estimate the sidewall surface from the PSD analysis: the resist edge surface resulted 6 times more extended compared to a perfectly flat edge (Table 1, last column), and the surface reduction due to VUV light is only on the order of 5–15%. PSD trends for different VUV doses are reported in Fig. 5: a full description of the roughness frequencies contained along the line edges is so obtained. All the PSD resemble the general behavior reported in previous works [20]: a plateau in the LF region (confirming that the detection of lines longer than 2 μm is not needed), followed by an amplitude drop due to the optical system cut-off (≈12 μm⁻¹ for the illumination system used [14]). By PSD comparison, three main differences can be noticed upon VUV dose: LF roughness increase with the VUV dose. This effect is common for thermal processes, where resist reflow is expected [21]. LF roughness deterioration is often combined with more negative c-factor (more correlated edges). A second effect is noticed in the mid-frequency (MF) range from 4 to 30 μm⁻¹ (30–250 nm periodicity), where roughness decreases increasing the VUV dose. The third effect, in the very High Frequency (HF) roughness, is related to the S/N contrast ratio of the top-down CD-SEM on different wafers: for high VUV dose, frequencies higher than 40 μm⁻¹ are highly affected by aliasing noise due to the Nyquist frequency cut-off.

Fig. 7. FE-SEM cross-section images of 100 nm isolated lines and 1 μm pads for (a) reference wafer, (b) 120 mJ/cm² VUV dose, (c) 360 mJ/cm² VUV dose and (d) 1980 mJ/cm² VUV dose applied.
Typically, when resist thickness decreases, the S/N contrast ratio worsens, and the CD-SEM noise contribution grows, detected as HF roughness (Fig. 5) for 480 mJ/cm² PSD. For 480 mJ/cm², the S/N contrast ratio estimated by PSD comparison is less than half of the reference spectrum. The deterioration of the S/N ratio corresponds to roughly 0.5 nm 3σLWR overestimation just due to the measurement noise. As a consequence, wafers exposed with VUV doses higher than 480 mJ/cm² were not considered in our analysis.

4.1.2. Dense lines

The same evaluation was performed on 45 nm half-pitch lines (Table 2) CD and roughness trends follow the behavior showed for the isolated lines, with few exceptions: the c-factor becomes more positive upon VUV dose, showing that the degree of correlation between nested lines (45 nm space) is more important than in the isolated case.

PSD analysis showed a substantial agreement with the trends found for the isolated lines: roughness mitigation for frequencies between 4 and 30 μm⁻¹ and S/N contrast ratio deterioration for high VUV doses. Due to thinner lines, 360 mJ/cm² of VUV dose was considered the limit before a more severe image contrast drop.

4.2. 3D analysis of isolated lines: cross-sections and CD-AFM

A more complete 3D characterization of the resist response to VUV exposure was performed with several techniques: the graph reported in Fig. 6 shows the trends of the resist thickness, wafer mass, and resist density of blanket wafers (no lithographic pattern defined) upon VUV plasma exposure. Most of resist thickness, mass and density drop occur for doses below 1 J/cm². Further dose increment does not change the resist properties. These trends suggest that the VUV light starts affecting the resist composition from low doses, causing lactone and oxygen evaporation due to polymers scission [22]. Roughness mitigation and thickness reduction may be caused by scission mechanism occurring in the resist and evaporation of volatile polymer fragment due to the photo-etching [23]. These effects explain the initial CD shrink, followed by reflow at higher VUV doses, characterized by a CD growth, and S/N contrast ratio deterioration.

Cross-sections images for isolated lines and large structures (pads with CD > 1 μm) were taken for four different wafers (Fig. 8). Left: profile of an isolated line captured with CD-AFM measurement. Each profile represents a resist line exposed with different VUV dose. Right: sidewall 3σLWR as a function of line height. Data points taken too close to the top (above 80 nm) and the bottom (below 15 nm) of the line are excluded due to measurement artifacts which lead to roughness overestimation.

**Fig. 8.** Left: profile of an isolated line captured with CD-AFM measurement. Each profile represents a resist line exposed with different VUV dose. Right: sidewall 3σLWR as a function of line height. Data points taken too close to the top (above 80 nm) and the bottom (below 15 nm) of the line are excluded due to measurement artifacts which lead to roughness overestimation.

**Fig. 9.** CD and 3σLWR trends upon VUV dose for LERDEMO (black curve), Hitachi (light-grey curve) and CD-AFM (dark-grey curve). Both LERDEMO and Hitachi were run on the same top-down CD-SEM images.

\[ f_{Nyquist} = \frac{A}{2} = 92.92 \text{ μm}^{-1} \]
(Fig. 7): resist reflow and thickness loss are clearly visible already at 120 mJ/cm². From these images it is possible to notice how the smoothing effect concerns in particular the mid-top part of the structures, leaving almost unchanged the footing present at the bottom of the edges. The remaining 3rlwr/er after pattern transfer will be mostly originated by this last roughness [22–24]. In Fig. 7d, resist pattern after a 1920 mJ/cm² VUV exposure is reported, where the edges of the structures are barely visible.

CD-AFM measurements were performed on isolated photoresist lines before and after VUV exposure using the experimental protocol described in Section 2. Fig. 8 shows the average resist profiles reconstructed by CD-AFM upon VUV dose. Significant resist top loss is observed, in agreement with ellipsometry thickness measurement performed on blanket wafers. Moreover, CD reflow is also visible at the bottom of the lines. For very high VUV doses (1920 mJ/cm²) resist top loss and CD reflow stop, and no other change is noticed.

3rlwr of the reference wafer was measured along the resist height, as shown in the right graph of Fig. 8. Roughness values in the middle are quite constant, however, data points taken too close to the top and the bottom of the lines were excluded from the averaging, due to measurement artifacts caused by the tip shape, which led to roughness overestimation.

3rlwr comparison between top-down CD-SEM and CD-AFM is then reported in Fig. 9: 3rlwr trends overlap only for Hitachi and LERDEMO, both based on the same top-down CD-SEM images. CD-AFM reported a more abrupt change as function of the VUV dose, showing much higher roughness for the reference case, followed by almost 50% 3rlwr mitigation at 360 mJ/cm². Top-down CD-SEM analyses reported only 15%. The CD-SEM 3rlwr value obtained for the reference wafer is 3 nm lower than the CD-AFM value. This discrepancy can be explained by the impact of the e-beam on photoresist that tends to shrink and smooth the resist, similar to the VUV light effect presented in this work. Moreover, the top-down image capturing performed by the CD-SEM integrates the secondary electrons that hit the 3D resist edges in a 2D image, averaging the roughness along the resist height. Both metrology tools show however the same 3rlwr trend upon VUV exposure dose, namely a decrease of the 3rlwr up to 360 mJ/cm².

Despite this difference, the minimum roughness value is in good agreement for all the analysis, and all of them recorded 3rlwr deterioration at higher VUV doses.

CD behavior upon VUV dose is similar for all the methodologies, except a fixed difference due to the different thresholds used [14]. Also for CD-AFM, roughness and CD evaluations for high VUV doses are not reported due to measurement reliability issues related to resist thickness reduction.

5. Discussion and conclusions

In this work, line width/edge roughness analysis for ArF immersion photoresist on isolated and dense structures is reported. Patterned wafers were exposed to plasma-VUV light at different doses in order to smooth the lines. Roughness characterization was performed by means of power spectral density and fractal analysis on top-down SEM images. These results were consequently compared with 3D AFM measurements, and Field Emission SEM cross sections. Thickness, density and mass measurements were performed on blanket wafers. A synthetic 3D surface reconstruction model was then extrapolated from the spectra.

It was found that the smoothing power of the plasma VUV-light upon applied dose differs between the considered metrologies: up to 50% roughness reduction was obtained from CD-AFM, meanwhile only 15% was captured by top-down SEM analysis. Cross sections, thickness and mass measurements confirmed the severe thickness loss and CD shrink measured by AFM. Density measurement suggests also that the VUV light affects the resist composition, causing lactone and oxygen evaporation due to polymers scission. This effect allow a partial surface reconstruction of the edges with a consequent roughness and surface energy reduction, as implied in the edge roughness modeling. However, cross sections show that the roughness at the bottom of the lines (footing) is not mitigated by the plasma VUV light.

From this work, it appears evident that roughness evaluations are strongly metrology-dependent. Figures of merit as CD, 3rler, 3rlwr should be considered as relative rather than absolute numbers which reflect the reality. Comparison of different techniques for roughness analysis, in particular for organic materials, seems to be necessary to well characterize the lithographic process, and the patter transfer steps.

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