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# 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 3$\sigma$LWR 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

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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 in three 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° quadrupole illumination, with Numerical Aperture = 1.2, $\sigma_{\text{in/out}}$ = 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/cm$^2$. 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 μm$^2$.
- 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]:

$$c - \text{factor} = \frac{\sigma^2_{\text{LWR}} - (\sigma^2_{\text{LER},r} + \sigma^2_{\text{LER},1})}{2 * \sigma^2_{\text{LER},r}\sigma^2_{\text{LER},1}} \quad (1)$$

where $\sigma_{\text{LWR}}$, $\sigma_{\text{LER,r}}$ and $\sigma_{\text{LER,l}}$, are the standard deviation of the linewidth, 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 $\sigma^2_{\text{LER}}$. PSD can be calculated with the Wiener–Khinchin theorem, Fourier anti-transforming the autocorrelation function, related to the HHCF by:

$$\text{HHCF}^2 = 2 * (R^2 - \text{Autocorrelation}) \quad (2)$$

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

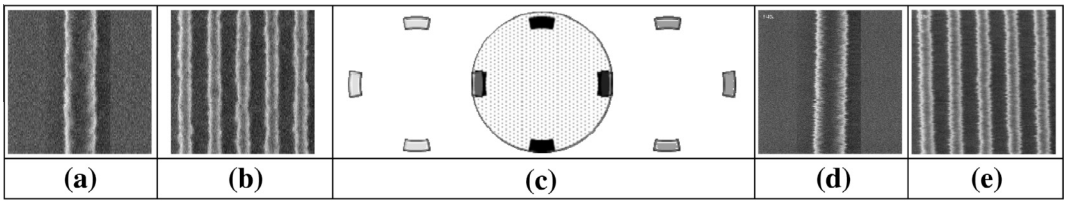

**Fig. 1.** (a and b) Top-down CD-SEM image for isolated and dense lines after lithographic exposure (symmetric FoV: 300KXx300KX equivalent to 0.450 × 0.450μm$^2$). (c) Sketch of the off-axis illumination used for printing isolated and dense structures. The full circle represents the $NA$ of the optical 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 μm$^2$).