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Impact of line edge roughness patterns on the reconstructed critical dimensions in scatterometry

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Summary

In angular resolved scatterometry, the measured diffraction intensities are effected by structure roughness. We investigate this impact by rigorous finite element method (FEM) calculations for an EUV photomask with periodic line-space structures. Repeated calculations for large FEM domains with stochastically chosen line and space widths are applied. Complementary simulations based on a 2D-Fourier transform method for samples of binary 2D gratings confirm the FEM results. The edge roughness of the binary 2D gratings are modelled by a power spectrum density (PSD) function providing a more realistic approach for line roughness.

Scatterometry

Scatterometry as a non-imaging optical method in wafer metrology is also relevant to masks designed for Extreme Ultraviolet Lithography ($\lambda \sim 13.5$ nm). The goal is to determine the critical dimensions (CD), i.e., the geometric profile parameters of the mask from measured diffracted light pattern and to estimate their uncertainties.

The numerical simulation of the diffraction process for 2D periodic structures is done by FEM solution of the two-dimensional Helmholtz equation. If the light diffraction patterns are given by the measured diffraction intensities $\mathbf{y}^{meas} = (y_1, \ldots, y_m)$, the geometry by the parameter vector $\mathbf{p} = (p_1, \ldots, p_n)$, and the FEM solution by the nonlinear operator mapping $\mathbf{f}(\mathbf{p}) = (f_1(\mathbf{p}), \ldots, f_m(\mathbf{p}))$, then the inverse problem of scatterometry is solved minimizing the norm $\|\mathbf{y}^{meas} - \mathbf{f}(\mathbf{p})\|$.

We consider the jth measured value as the sum of the model function and a noise contribution $y_j = f_j(\mathbf{p}) + \epsilon_j$. This means that the measurements are noisy realizations of the model. Supposing independent measurements and no systematic errors, the variances of the noise contributions can be modelled as being normally distributed with zero mean, i.e., $\epsilon_j \sim \mathcal{N}\left(0, \sigma_j^2\right)$ and composed of two independent random variables:

$$\sigma_j^2 = (a \cdot f_j(\mathbf{p}))^2 + b^2.$$

The first term $(a \cdot f_j(\mathbf{p}))^2$ indicates a linearly dependent noise, the second term b^2 an independent background noise.

We apply a maximum likelihood estimation to solve the inverse problem. Along with the CD values, further relevant quantities like the noise parameters of the measured diffraction intensities are reconstructed from the measured scattering efficiencies, i.e., the following likelihood function has to be maximized:

$$\mathcal{L}(a, b, \mathbf{p}) = \prod_{j=1}^{m} \left(2\pi \left((a \cdot f_j(\mathbf{p}))^2 + b^2\right)\right)^{-1/2} \times \exp\left[-\frac{(f_j(\mathbf{p}) - y_j)^2}{2\left((a \cdot f_j(\mathbf{p}))^2 + b^2\right)}\right]$$

Modeling line roughness

The uncertainties of the reconstructed geometric parameters depend on the uncertainties of the input data and can be estimated by various methods like Monte Carlo or approximative covariance methods. Unfortunately, aperiodic perturbations in the examined line structures affect the uncertainties too. In order to examine the impact of line roughness, first we perform a large number of simulations for FEM domains with large periods, each containing many pairs of line and space with stochastically chosen widths (cf. Fig. 1).

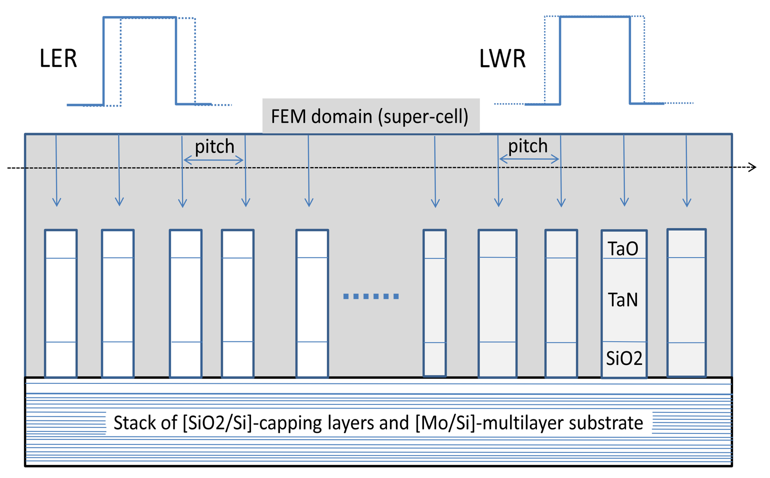

FIGURE 1: Profile model used for line edge (LER) and line width (LWR) roughness in a large FEM computation domain: randomly changed center positions for LER (left) and randomly changed line widths for LWR (right) are superimposed independently to create LEWR perturbations.

Secondly, we apply a 2D Fourier transform (FTM) method to calculate the diffraction pattern for samples of rough apertures composed of several slits. The rough apertures are representing binary 2D gratings (cf. Fig. 2).

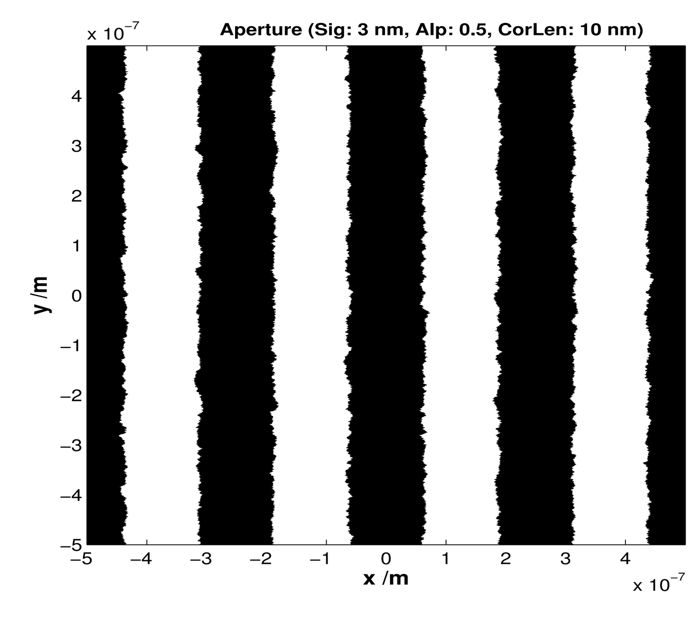

FIGURE 2: Aperture model used for 2D Fourier transform approach: Roughness of the edges of the aperture slits is provided by a power spectrum density function, which depends on a standard deviation, a correlation length and a roughness exponent.

Impact on Efficiencies

For both methods we compare the calculated light efficiencies of the rough samples with those of the unperturbed line-space structures, i.e., the relative deviations from the 'non-rough' reference structures are investigated. Fig. 3 (a) reveals the details of an FEM example. A systematic decrease of the mean efficiencies for higher diffraction orders along with increasing variances is observed and established for different degrees of roughness.

For the 2D FTM approach, very similar results are obtained confirming the FEM results (cf. Fig. 3 (b)). Note, that the line edge roughness of the 2D binary gratings is already fairly realistic.

Assuming that σ_r describes an aperiodic perturbation of the line edges and that the diffraction order n_j is given by the parameter $k_j = 2\pi n_j/pitch$, the mean normalized deviations can be approximated by

$$\frac{f_{j,ref}(\mathbf{p}) - \overline{f_{j,pert}}}{f_{j,ref}(\mathbf{p})} \approx 1 - \exp(-\sigma_r^2 k_j^2).$$

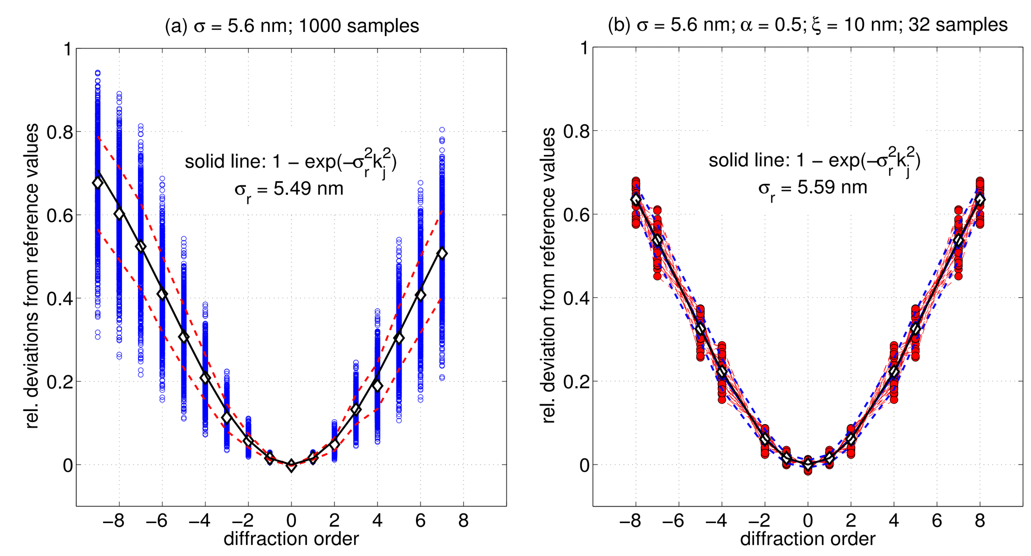

FIGURE 3: Normalized deviations from the efficiencies of the unperturbed reference line structure (for two examples), depicted as circles; diamond symbols represent the mean deviations of all samples; dashed lines indicate the mean efficiency ± standard deviation; solid lines depict the exponential approximation; (a) for FEM simulations and (b) for 2D-Fourier simulations of a binary grating.

As a consequence the revealed LEWR-bias has to be included in the model by an order dependent damping factor (comparable to the Debye-Waller factor for the damping of scattering X-rays in crystals):

$$y_j = \exp\left(-\sigma_r^2 k_j^2\right) \cdot f_j(\mathbf{p}) + \epsilon_j,$$

with $\sigma_j^2 = \left(a \cdot \exp\left(-\sigma_r^2 k_j^2\right) \cdot f_j(\mathbf{p})\right)^2 + b^2$.

Doing so, the reconstructed CDs (at the middle height of the absorber lines) of experimental data are in excellent agreement with measurements from 3D atomic force microscopy (cf. Fig. 4).

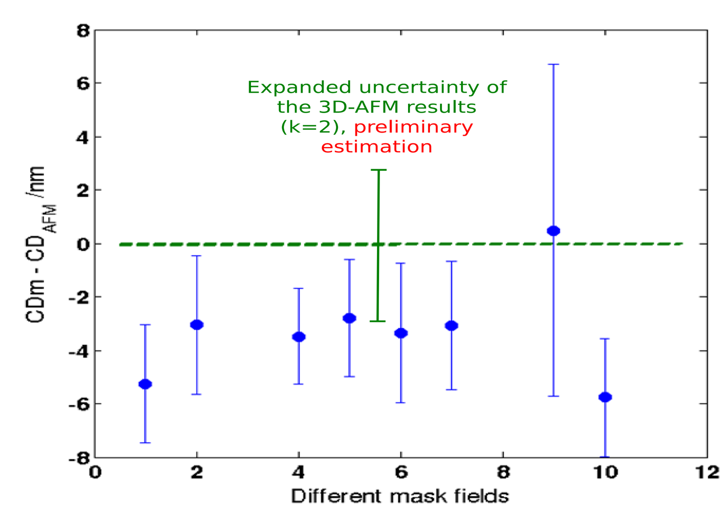

FIGURE 4: Comparison of the evaluations of the middle CD of eight different mask fields of an EUV photo mask between scatterometric evaluations (considering the bias due to LEWR) and scanning 3D atomic force micrsocopy (3D-AFM).

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