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# Impact of different stochastic line edge roughness patterns on measurements in scatterometry - A simulation study

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ABSTRACT

The impact of line edge roughness (LER) on measured light diffraction pattern of photo masks is investigated. This is relevant for scatterometry as an accurate, indirect method in wafer metrology to determine geometry parameters of periodic surface structures from scattered light intensities. The sensitivity to roughness increases the smaller the wavelength of the incident light is. For EUV scatterometry at 13.5 nm, the efficiencies of many higher diffraction orders can be measured. In the nanometer range they are sensitive to deviations from the ideal periodic straight line structure such as LER. Applying the Fraunhofer approximation, we calculate the far field diffraction pattern of an illuminated 2D aperture plane composed of many rough slits by its 2D-Fourier transform. The rough edges of the aperture gaps are created by means of power spectrum density (PSD) functions used with a random complex exponential phase term. A simple theory neglecting correlation in the roughness profile predicts for the intensities an exponential decrease with the diffraction order and the standard deviation of the roughness amplitude which can be tested by our numerical solutions. The calculated light intensities for a rough aperture are compared with the ones found for an ideal periodic aperture whose edges are straight lines. Ensembles of rough apertures with different values for the imposed standard deviation of the roughness amplitude $\sigma$, the linear correlation length $\xi$, and the roughness exponent $\alpha$ were examined. The validity of the exponential decrease was investigated for correlation lengths $\xi$ from 5 nm up to 1000 nm and roughness exponents $\alpha$ from 0.3 to 1.0. It was found that the results for the exponential correction factor deviate substantially from the mentioned theoretical value for large correlation lengths and small roughness exponents.



## 1. Introduction

Non-imaging metrology methods like scatterometry (cf. Fig. 1) are in contrast to optical microscopy non diffraction limited and grant access to the geometrical parameters of periodic structures like structure width (critical dimension CD), period (pitch), sidewall angle or height of trapezoidal bridges (lines) [1,2]. Scatterometry is an indirect optical method. From scattered relative light intensities, i.e. the measured efficiencies, the geometrical parameters of irradiated surface profiles and their uncertainties are reconstructed. The evaluation of structure dimensions on photo masks and wafers in lithography [3,4] is an important application. In the semiconductor industry both the feature sizes and the required limit of measurement uncertainty decrease continuously and shorter wavelengths like extreme ultraviolet (EUV) at 13.5 nm will be applied. Besides conventional metrology techniques like atomic force, electron and optical microscopy, scatterometry is an established tool for the characterization of such structures (cf. e.g. [5,6]). However, scatterometry requires a-priori knowledge for an appropriate modeling of the light diffraction pattern and reconstruction of geometrical profiles. Typically, the surface structure is sought in a certain class of gratings described by a finite number of parameters, and these parameters are confined to certain range.

The conversion of measurement data into desired geometrical parameters depends crucially on a high precision rigorous modeling by Maxwell's equations [7–9] which reduce to the two-dimensional Helmholtz equation if geometry and material properties are invariant in one direction. For the numerical solution, a lot of methods have been developed (cf. e.g. [10–16]). Among them also finite element methods (FEM) are used where the infinite domain of computation is truncated to a finite one by coupling with boundary elements (cf. e.g. [17–19] and compare the alternative approach in e.g. [20]). To compute highly oscillatory fields, generalized finite element methods are available (cf. e.g. [21–24])

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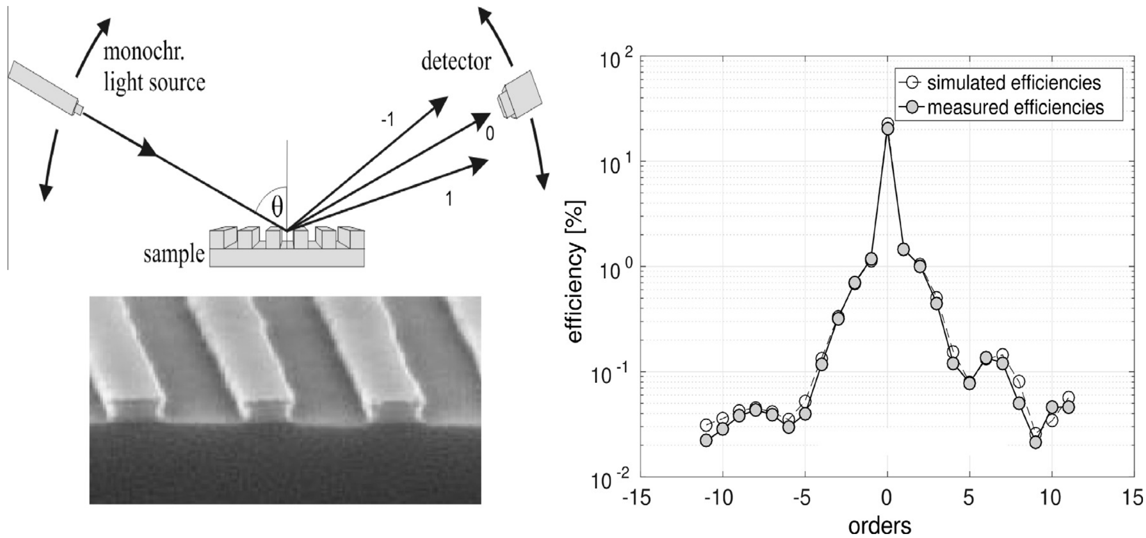


**Fig. 1.** Measurement principle of scatterometry, scatterogram with measured or simulated efficiencies and SEM picture of a periodic line-space structure.

and accurate numerical solutions for wavelengths $\lambda$ in the EUV range are possible.

Apart from the forward computations by solving the Helmholtz equation, the solution of the inverse problem, i.e., the reconstruction of the grating profiles and interfaces from measured diffraction data, is the true task in scatterometry. Like many inverse problems, the inverse problem of scatterometry is ill-posed [25] and prior knowledge is required. A common approach for its regularization is to set up an equivalent low dimensional optimization problem with a weighted least squares function of the residuals [26,27]. The prior knowledge in this case includes information not only about the geometrical profile of the investigated probe, but also knowledge of the variances of the measured data, i.e., the statistical error model of the measurements has to be known [28].

A comparison of the reconstructed profiles using EUV-scatterometry and the results obtained using atomic force and electron microscopy [29] has revealed that scatterometry can underestimate the sidewall angle, an important feature of the EUV-mask, by several degrees. Imperfect modeling is supposed to be one of the main reasons for this result [26,30,31]. In particular, to get more reliable simulations and reconstructions, effects like line edge roughness (LER) and further model based impacts have to be taken into account (cf. [32,28,33,34] for the details).

Torcal-Milla et al. [35], and also Kato and Scholze [31] have suggested approximative analytical expressions for the impact of line edge roughness on the scattered efficiencies. They have applied Fraunhofer's diffraction method on gratings with randomly disturbed periodicity, i.e., the Fourier transform of the reflectivity function of perturbed binary gratings were investigated. They found damping of the mean efficiencies with increasing diffraction orders, which was confirmed by rigorous FEM simulations for a real EUV mask [32]. In these FEM investigations, large computational domains containing many line-space structures with stochastically chosen widths were used. Hence, these results were still obtained for a simplified model of rough line edges, i.e., without modeling the line edges as a stochastic process with a prescribed autocorrelation function analogously to what is often done in the metrology of rough geometries. There are several publications [36–38], where the modeling of line edge roughness as a stochastic process starts with an exponentially decaying autocorrelation function for the position $p(r)$ of an edge point at distance $r : p(r) = \sigma^2 e^{-(r/\xi)^{2\alpha}}$ where $\sigma$ is the standard deviation of the roughness amplitude, $\xi$ is the linear correlation length, and $\alpha$ is a roughness exponent. Randomized line edge profiles can be generated by calculating or approximating the associated power spectrum density function $\mathrm{PSD}(r^{-1})$ belonging to the autocorrelation function $p(r)$ and subsequently applying an inverse Fourier transform with a random phase uniformly distributed in the range of $[0, 2\pi]$. For instance, Bergner et al. [36] use a similar approach to generate rough line edge profiles of 2D-binary gratings to calculate its impact on the angular dependence of the specular, 0th order reflectance at wavelengths around 633 nm. Torcal-Milla et al. [35] have investigated gratings with rough edges in the visible optical range by applying the Rayleigh-Sommerfeld approach for near field simulations and the Fraunhofer approximation for the far field pattern. They found light intensities with exponential attenuation factors depending on $\sigma$ and the diffraction order. Schuster et al. [39] have studied the impact of LER for silicon gratings on the basis of sinusoidal perturbations for the line positions with amplitudes in the range of 2–8 nm and for wave-lengths of 400 and 250 nm, respectively.

The objective of the present paper is to demonstrate that the LER-induced attenuation of the mean efficiencies for higher diffraction orders is supported by a stochastic model of line edge roughness combined with a fast approximative calculation of the relative light intensities in the far field. The LER simulation uses a 2D binary aperture plane with many slits whose boundary lines are rough. The roughness is controlled by an autocorrelation function depending on a standard deviation $\sigma$, a correlation length $\xi$ and a roughness exponent $\alpha$. To consider the impact of correlations lengths pending 1 μm, we apply also larger aperture planes up to several microns in each direction. Avoiding time consuming rigorous numerical calculations, the light intensities are approximately computed by a fast 2D-Fourier transform of the light distribution of the binary aperture plane applying the Fraunhofer approximation.

## 2. Modelling the impact of LER

The mathematical models for the scatterometric measurement process consist of a nonlinear operator that maps the geometry parameters onto the aforementioned efficiencies. The unknown parameters are mapped into the measured efficiencies. The vector of parameters $\mathbf{p} := (p_j)_{j=1}^{N}$ fixes the grating geometry and the solution of the boundary value problem for every set of parameter

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