Influence of line edge roughness in optical critical dimension metrology

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Abstract. We present the impact of line edge roughness (LER) on the optical critical dimension (OCD) metrology of nanostructures. The consideration of LER in OCD requires numerically expensive forward models and is therefore usually neglected. We present an analytical approach that allows estimation of the impact on the uncertainty. Systematic differences between CD measured by SEM and OCD were observed in different experiments. While SEM is basically sensitive to the local volume density, optical methods are sensitive to the permittivity of the material. We discuss an analytical upper bound on the contribution of the LER. For high index gratings, the contribution is as high as 3.7 nm for TM-polarized light and 1.2 nm for TE-polarized light, making this crucial for sub-nanometer metrology.

INTRODUCTION

Line edge roughness (LER) refers to the statistical fluctuation of point positions along an edge, relative to a best-fit line determined from all examined points on the edge. In Figure 1 a typical SEM image of a of a resist mask is shown. The causes of LER are rooted in the stochastic nature of the individual processes involved in edge definition. These processes include electron shot noise in electron beam lithography, photon shot noise in optical lithography, the random distribution of molecules involved in solubility changes, and the length of polymer chains[1,2].

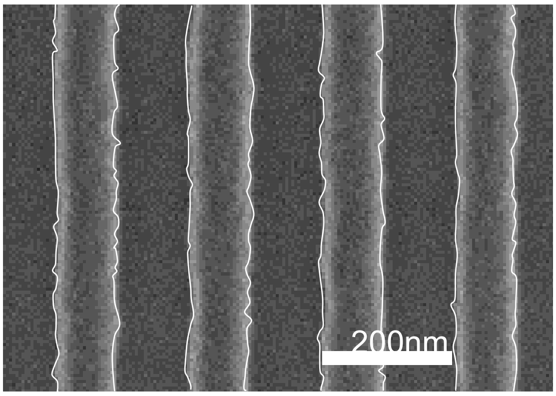

Figure 1: SEM image of a resist mask with 200nm period. The edges are highlighted.

LER is inherent in any manufacturing process and cannot be completely avoided. It must therefore be considered both in understanding the functionality of devices and in the metrology that accompanies their manufacture.

Optical critical dimension metrology (OCD) is based on the measurement of light scattered from the nanostructure under very well controlled conditions. The geometry and material data are usually obtained by setting up a forward model followed by numerical inversion. Unfortunately, forward models including LER are extremely numerically costly. Hence, LER is typically neglected for OCD metrology. Nevertheless, a systematic deviation between CD measured with SEM and OCD were experimental observed[3].

Line edge roughness

LER can be modeled as a superposition of multiple harmonic oscillations with different spatial frequencies and amplitudes. This description is often achieved using power spectral density (PSD), derived from the Fourier transformation of the edge position y(x) along a length L. The LER is typically measured from SEM images. The here used method is described in more details elsewere[3]. In short: several tens of SEM images are recorded with great care to not distort the resist. Then the edge positions are deduced from these images by an edge detection algorithm without prior image filtering. Afterwards, the data is fitted to a representation of the PSD:

$$PSD(f) = 2\sigma^2\xi\left(\frac{\sqrt{\pi}\Gamma\left(H+\frac{1}{2}\right)}{\Gamma(H)}\right)\Big/\left[1+(2\pi f\xi)^2\right]^{H+1/2}. \qquad (1)$$

With the parameters: standard deviation σ, correlation length ξ, Hurst Exponent H and Γ representing the Gamma function. In Figure 2 a typical PSD of an electron beam resist is shown[4].

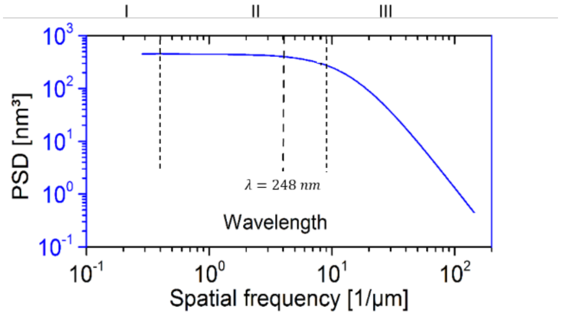

Figure 2 : Power spectral density in dependency of the spatial frequency plotted for a typical electron beam resist. The three lines are showing (I) the long, (II) intermediate and (III) short range interaction with light [4].

Modelling

Classically the CD is determined using scanning electron beam microscopy. Here, the signal depends in a complex manor on the interaction with electrons, the topography and materials. Due to different averaging processes along the edge (e.g. due to limited beam size, averaging along the edge, edge detection algorithm etc.) the signal used follows a sigmoid behavior.

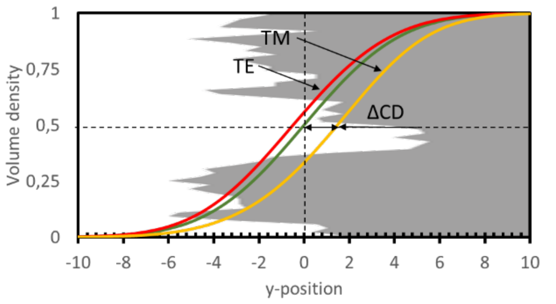

Figure 3: The grey area shows an enlarged view of an edge with LER. Green line: Volume density as a function of y-position (orthogonal to the edge). Red and yellow lines: refractive index dependence for TE and TM polarised light, respectively.

This sigmoid behavior of the volume density can be described as follows:

$$\rho_\mathrm{m}(y) = \frac{1}{2}\left(1 + \mathrm{erf}\left(\frac{y}{\sqrt{2}\sigma}\right)\right), \tag{2}$$

assuming that the Hurst exponent can be neglected. To understand the impact of the LER to the OCD metrology the relation between wavelength and inverse spatial frequency must be considered, see [4] for more details. Here, only the high spatial frequencies range is of importance. The geometry is much smaller than the wavelength of incident light. Therefore, we can describe the interaction using an effective medium approach assuming dielectric material. With the the effective refractive index n_{eff} is calculated for TM:

$$n_\mathrm{eff} = 1/\sqrt{\frac{\rho_\mathrm{m}}{{n_m}^2} + \frac{(1-\rho_\mathrm{m})}{{n_{sur}}^2}} \tag{3}$$

and TE :

$$n_\mathrm{eff} = \sqrt{\rho_\mathrm{m}{n_m}^2 + (1-\rho_\mathrm{m}){n_{sur}}^2}, \tag{4}$$

polarized light. From Eq. 3 and Eq 4 the difference to the volume density Eq. 2 can be calculated for TM:

$$\Delta CD_{TM} = \sqrt{2}\sigma\,\mathrm{erf}^{-1}\left(\frac{2}{\frac{1}{{n_m}^2}-1}\left[\frac{4}{(n_m+1)^2} - 1\right] - 1\right) \tag{5}$$

and TE:

$$\Delta CD_{TE} = \sqrt{2}\sigma\,\mathrm{erf}^{-1}\left(\frac{n_m+3}{2(n_m+1)} - 1\right) \tag{6}$$

polarized light. In Figure 4 the dependency of the deviation measured by OCD to that measured with SEM from the refractive index is shown. Especially for high index materials such as silicon with n=3.5 large deviation $\Delta\mathrm{CD}_{TM} = 3.7$ nm and $\Delta\mathrm{CD}_{TE} = 1.2$ nm arise.

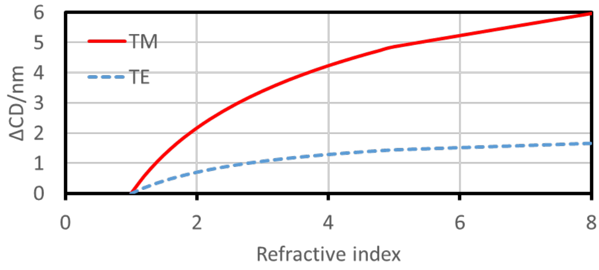

Figure 4 Deviation of the measured CD in dependence of the real refractive index.

Conclusion

We presents a method that uses simple analytical estimations to determine the maximum uncertainty attributed solely to the line edge roughness in optical critical dimension measurements. The effect tends to be overestimated since standard deviation from the entire power spectral density is used instead of only the relevant portion (Figure 2 Section III). However, the results give an very simple approach and underline that more research required in this direction.

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