Substrate Roughness and LER investigated by EUV Scatterometry

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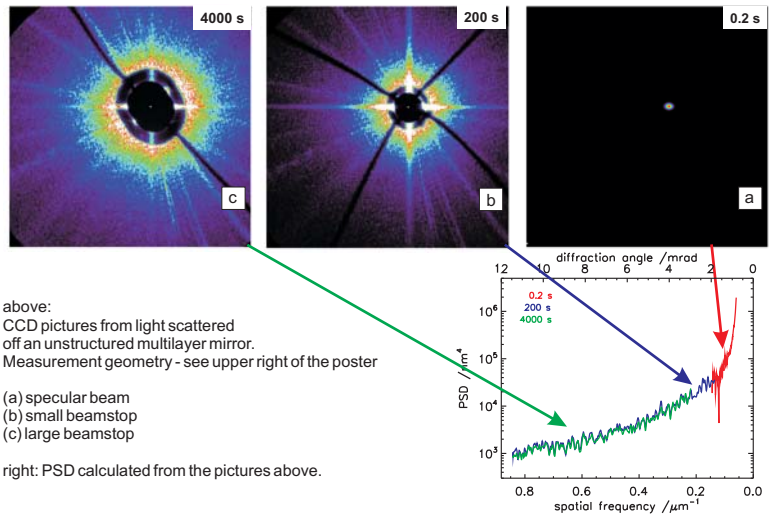
Introduction

With ever shrinking feature sizes, roughness of surfaces and features on lithography masks reaches the dimension of the features themselves. Therefore, roughness becomes a crucial parameter for the performance of photomasks. It must be characterized properly and its effects included into simulations. With the planned increase of NA from 0.25 to 0.7 the acceptance angle at the mask side increases from ±3.6° to ±10°. The mask performance must be characterized over this full angular range. For off-axis illumination at NA 0.7, the maximum diffraction angle accepted by the optical system is 20°, corresponding to a spatial wavelength of 40 nm. This spatial range is not accessible with DUV radiation. Hence, at-wavelength measurements are required. Using EUV scatterometry, PTB is able to investigate periodically structured samples as well as surface roughness in the 40 nm to 10 µm spatial wavelength range. Exemplary results of multilayer roughness measurements are shown. For lines and spaces on masks we were able to show that disregarding line roughness in evaluating scatterometry data leads to an underestimation of side wall angles. We also present a profile reconstruction including a roughness estimate derived from scatterometry data.

Surface roughness

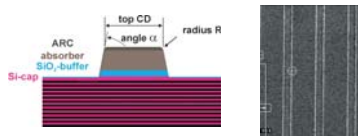


above:
CCD pictures from light scattered off an unstructured multilayer mirror.
Measurement geometry - see upper right of the poster

(a) specular beam
(b) small beamstop
(c) large beamstop

right: PSD calculated from the pictures above.

Periodically structured samples

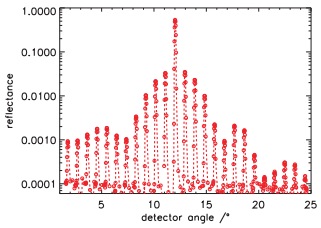


above: Sample as sketch and SEM micrograph

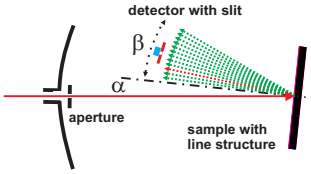
Measurands:
regular, periodic structures (1D-, 2D-gratings)
Geometrical properties
ensemble:
- pitch

individual:
- structure width
- structure height
- edge angles
- edge profiles

Measurements

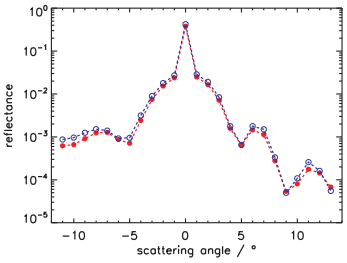


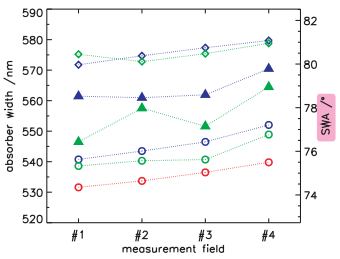
diffracted intensity as function of detector angle, λ=13.65 nm
140 nm absorber lines, 840 nm pitch



goniometric measurement:
scanning detector angle
at fixed incidence angle

Numerical fit and profile reconstruction





EUV scattering at fixed angle of incidence, 6°
- measured
- best fit

- top CD: SEM DUV and EUV scatterometry
- bottom CD: DUV and EUV
- SWA: DUV and EUV

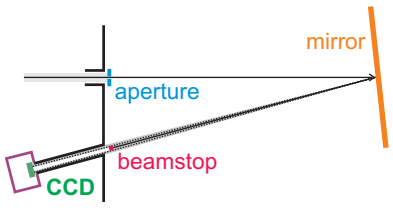
SWA by AFM > 85° !

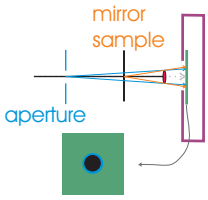
References

- A. Kato, F. Scholze, 'Effect of line roughness on the diffraction intensities in angular resolved scatterometry', *Appl. Opt.* **49** (2010) 6102-10
- F. Scholze, B. Bodermann, H. Groß, A. Kato, M. Wurm, 'First steps towards traceability in scatterometry', *Proc. SPIE* **7985** (2011) 79850G-1
- A. Kato et. al., 'The effect of line roughness on the diffraction intensities in angular resolved scatterometry', *Proc. SPIE* **8083** (2011) 80830K-1
- F. Scholze, A. Kato, C. Laubis, 'Characterization of nano-structured surfaces by EUV scatterometry', *JPCS* **311** (2011) 012006

CCD measurement scheme

The beam enters the experiment and is formed through the aperture.The mirror sample under test sits on a goniometer for alignment. By changing the angle of the mirror, the specular and the scattered light is directed onto a CCD. If necessary, a beam stop can be employed to cut out the specular beam for increased sensitivity for the scattered light.

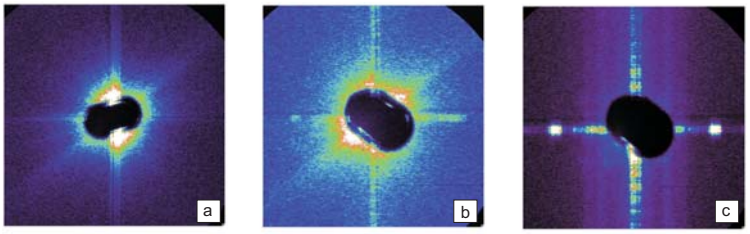


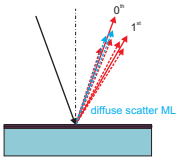


Shadows as seen on CCD

The beamstop on the CCD pictures shown exhibits a central completely black shadow and a partial shadow around the central shadow. These are different shadows due to different distances from scattersource to beamstop, the partial shadow beeing due to scatter from the aperture whereas scatter from the sample has a closer sourcepoint and therefore is visible outside the partial shadow.

Multilayer roughness and absorber line roughness

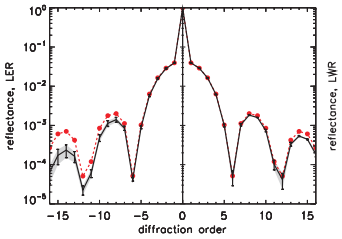




above: Near normal incidence scatter distributions measured with EUV. Shown are the scatter from the open ML without any absorber lines (a), with beamstop for the specular beam. (b) shows the diffraction around the 0th order for a field of 160 nm wide absorber lines at 1:2 duty cycle and (c) the same structure around the 1st order.
left: Visualization of the geometry employed.

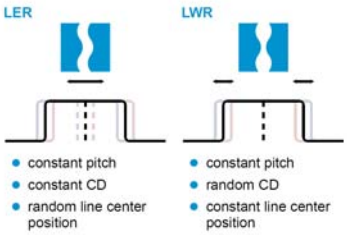
Analytical approach

Model: Fraunhofer diffraction of a binary grating → $I(k) = I_0(k)e^{-k^2\sigma^2}$ for LER and $I(k) = I_0(k)e^{-2k^2\sigma^2}$ for LWR



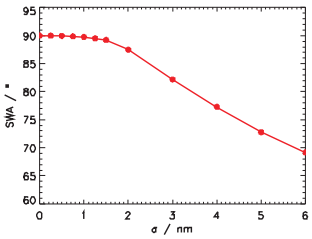
Simulation values
- undamped Fraunhofer approximation
- damped diffraction intensity: σ = 10 nm
LER left - LWR right

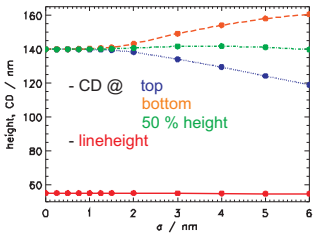
Roughness model



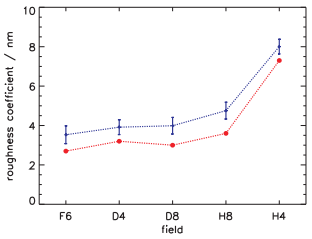
Numerical experiment

The effect visible in this numerical experiment shows characteristics comparable to measurements. Therefore it is reasonable to assume roughness of the kind our model describes causes the deviations of the reconstructed SWA and experimental data by AFM.





Roughness reconstruction



$$F(\vec{p}) = \sum_i w_i \left(I_i^{sim}(\vec{p}) - I_i^{meas}\right)^2$$

$$F(\vec{p},\sigma) = \sum_i w_i \left(I_i^{sim}(\vec{p})e^{-k_i^2\sigma^2} - I_i^{meas}\right)^2$$

Including roughness as paramter into the profile reconstruction yields a roughness coefficient from the measured data.
left: CDU 3σ by CD-SEM
roughness σ by EUV scatterometry

Good correlation between disparate methods!

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