Evaluation EUV scatterometry for CD characterization of EUV masks using rigorous FEM-simulation

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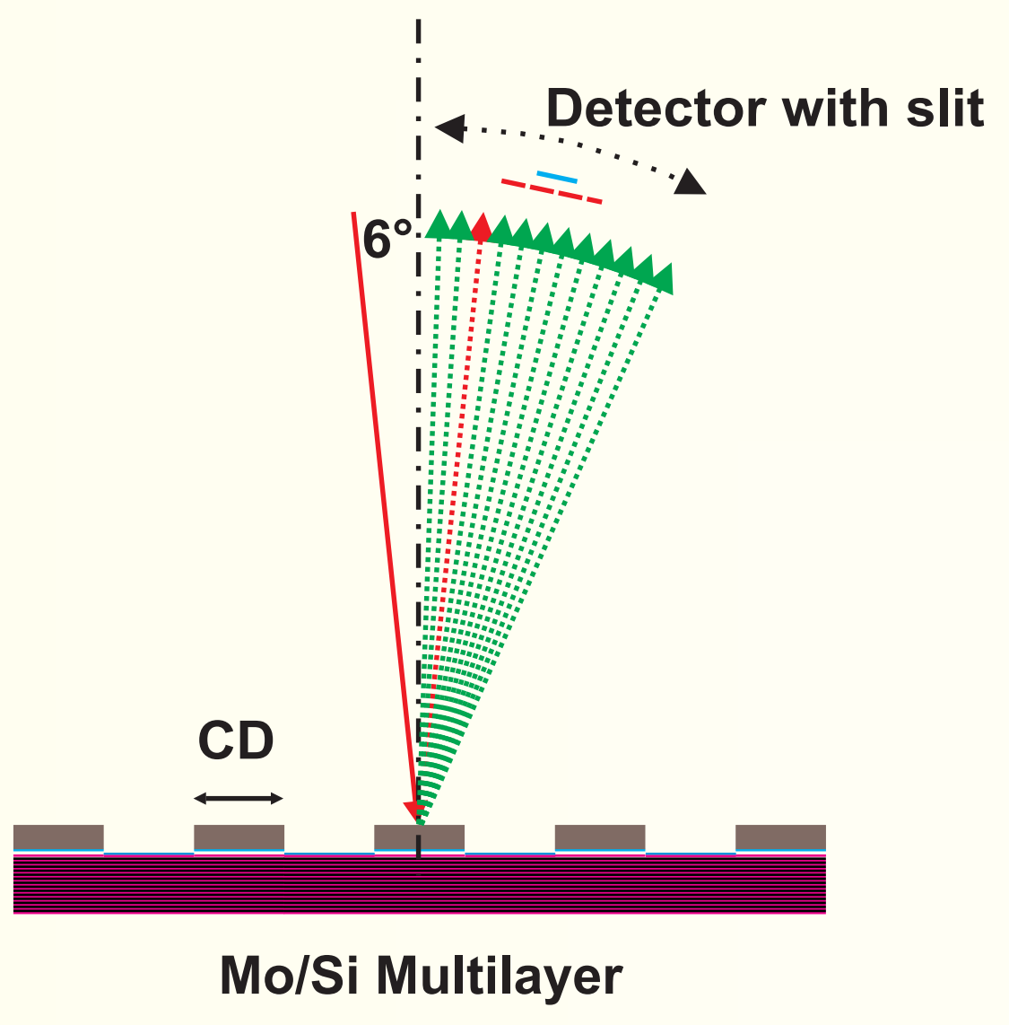
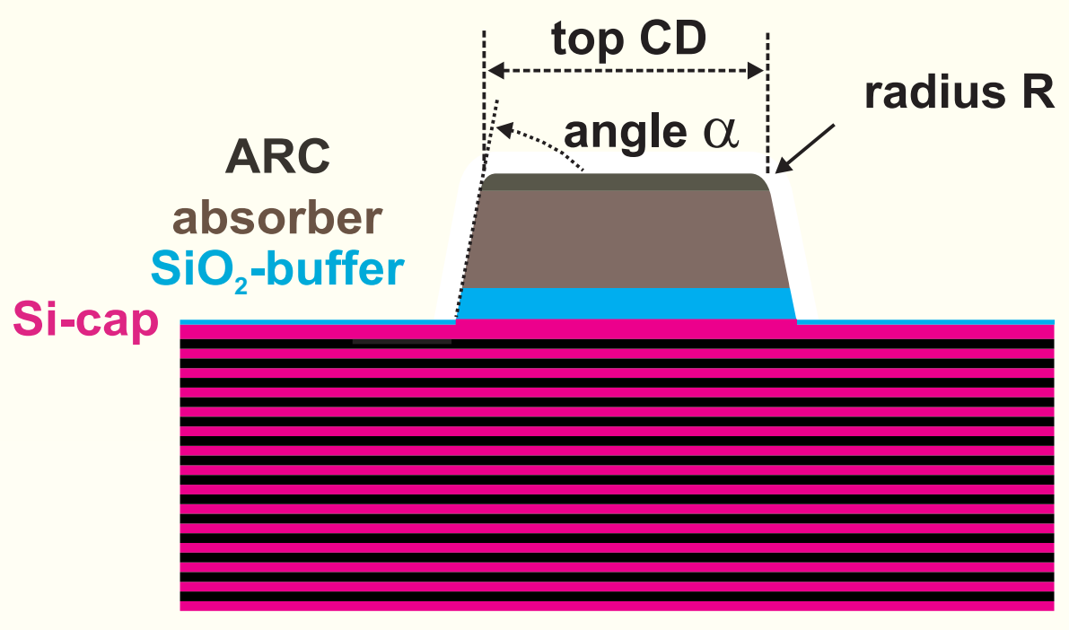
Scatterometry, the analysis of light diffracted from a periodic structure, is a versatile metrology for characterizing periodic structures, regarding critical dimension (CD) and other profile properties. When exposing an EUV mask with EUV radiation of 13.5 nm, the radiation is reflected by the multilayer stack which is about 300 nm thick. For EUV radiation, all layers in the stack contribute to the reflection. Therefore, only EUV scatterometry[1] provides direct information on the mask performance comparable to an EUV lithography tool. With respect to the small feature dimensions on EUV masks, the short wavelength of EUV is also advantageous since it provides more diffraction orders as compared to UV. PTB's EUV reflectometer[2,3] at the storage ring BESSY II[4] allows mask surface scanning in Cartesian coordinates at 10 µm positioning reproducibility. The probed area (photon beam size) is about 1 mm square. We present measurements on prototype EUV masks and we demonstrate the use of EUV scatterometry to determine the CD and side-wall geometry of lines using rigorous calculations of EUV diffraction.

scheme of scatterometry for line profile determination

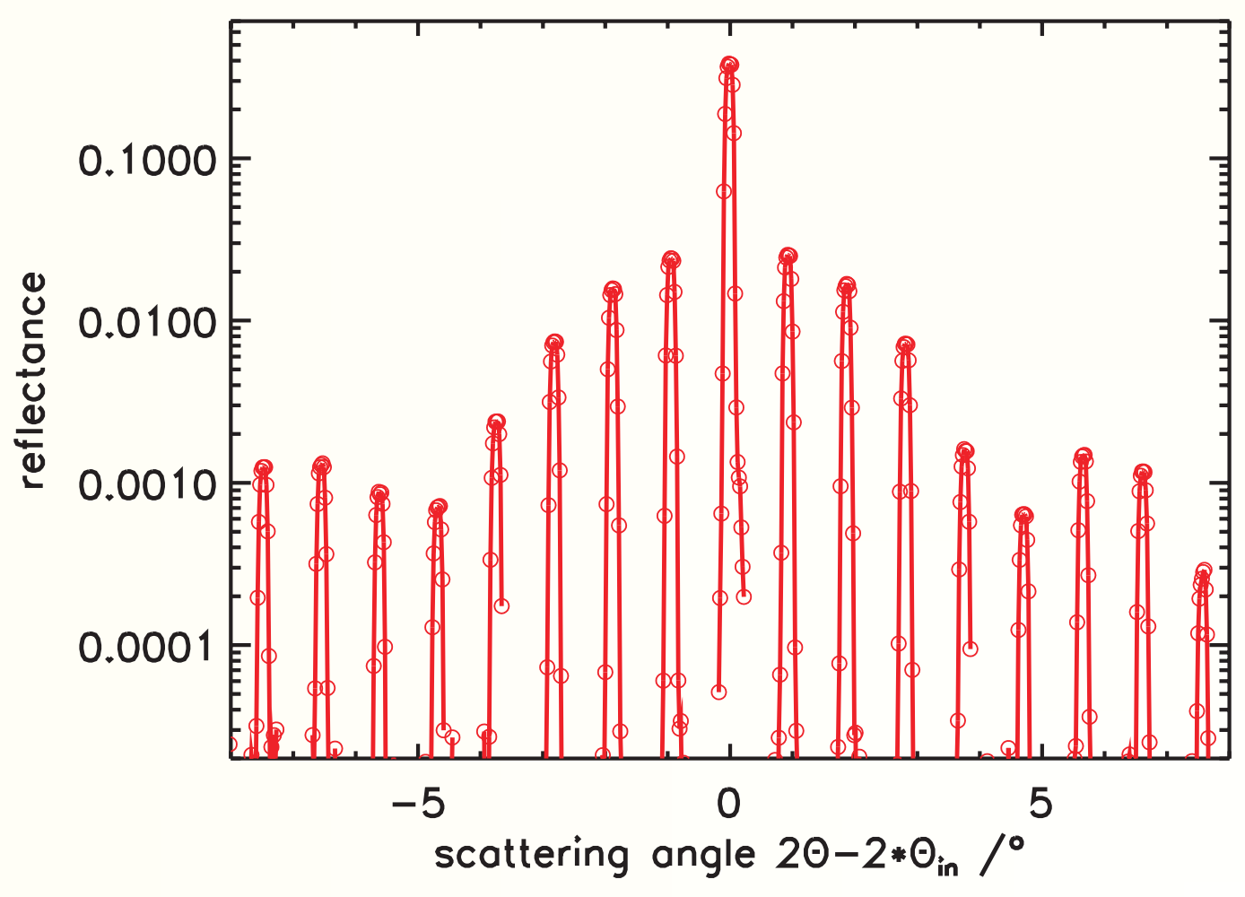




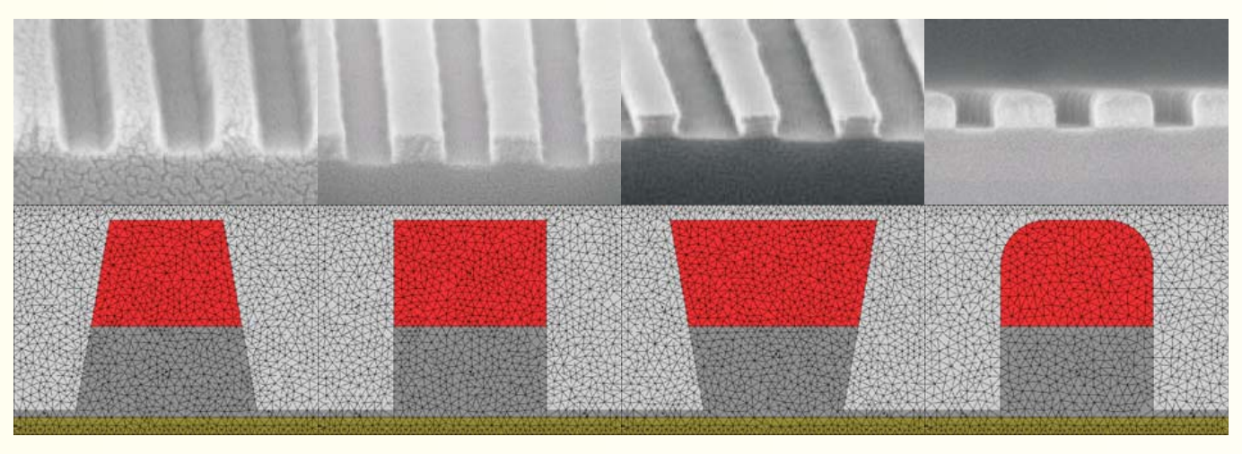
design:

line width	140 nm
pitch	840 nm (1:5 duty cycle)
sidewall angle	90°
line height	74 nm

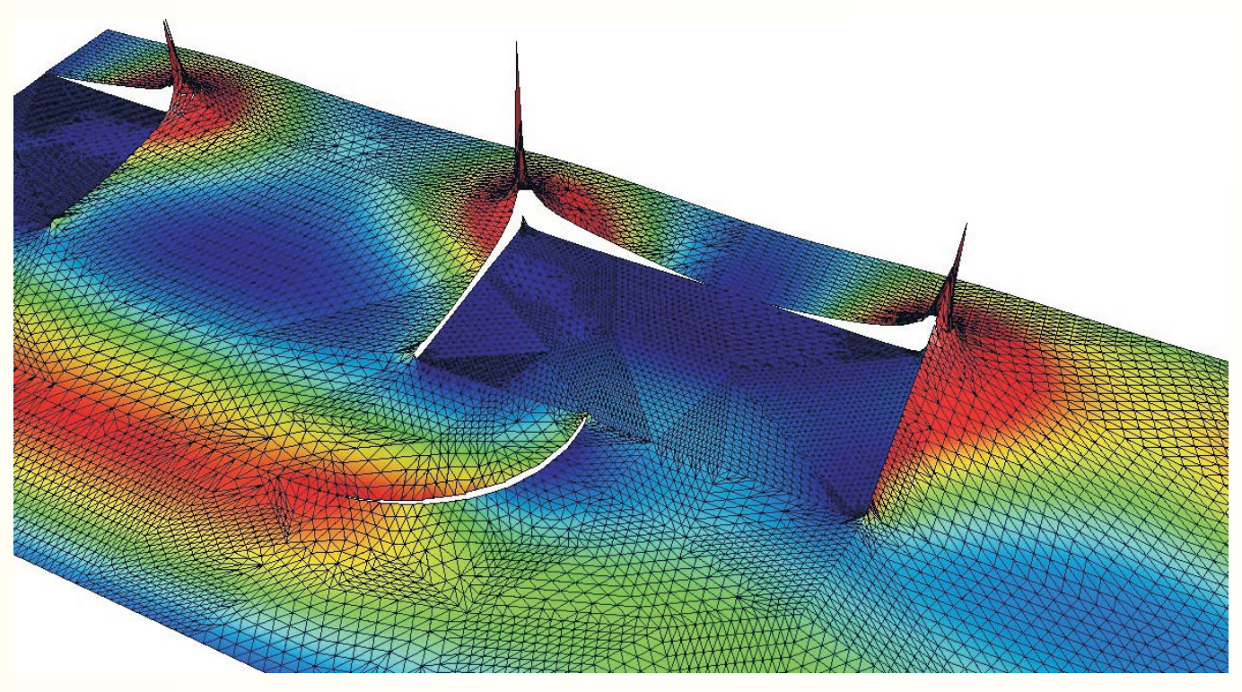
Scheme of scatterometry measurements (above): The detector angle is scanned at fixed entrance angle of 6°.
The geometrical parameters, top CD, sidewall angle, height, and top corner radius, indicated right above, are varied for simulation.
At right, a typical measurement of diffracted intensity as function of detector angle is shown, λ=13.65 nm.



FEM simulation of EUV scatterometry



SEM pictures of EUV mask patterns and corresponding triangulated geometries for FEM computation.



FEM solution for the electric field propagating through a phase mask. The electric field has singular behavior at corners of the absorber and discontinuities at material interfaces.

The measured diffraction orders of EUV masks do not carry direct information about the absorber line profile. In order to deduce the geometrical parameters we perform finite element (FEM) simulations of EUV scatterometry.

The FEM method is especially suited for this application:

- Maxwell's equations are solved rigorously without approximations
- The flexibility of triangulations allows modelling of almost arbitrary structures (see above)
- With appropriate localized ansatz functions physical properties of the electric field like discontinuities and singular behaviour can be modelled very accurately (see above)
- The convergence of the FEM method to the exact solution is proven mathematically

In our work we used the FEM solver JCMharmony which has been successfully applied to various electromagnetic field computations like waveguide structures[5], DUV phase masks[6], and other nano-structured materials[7].

references

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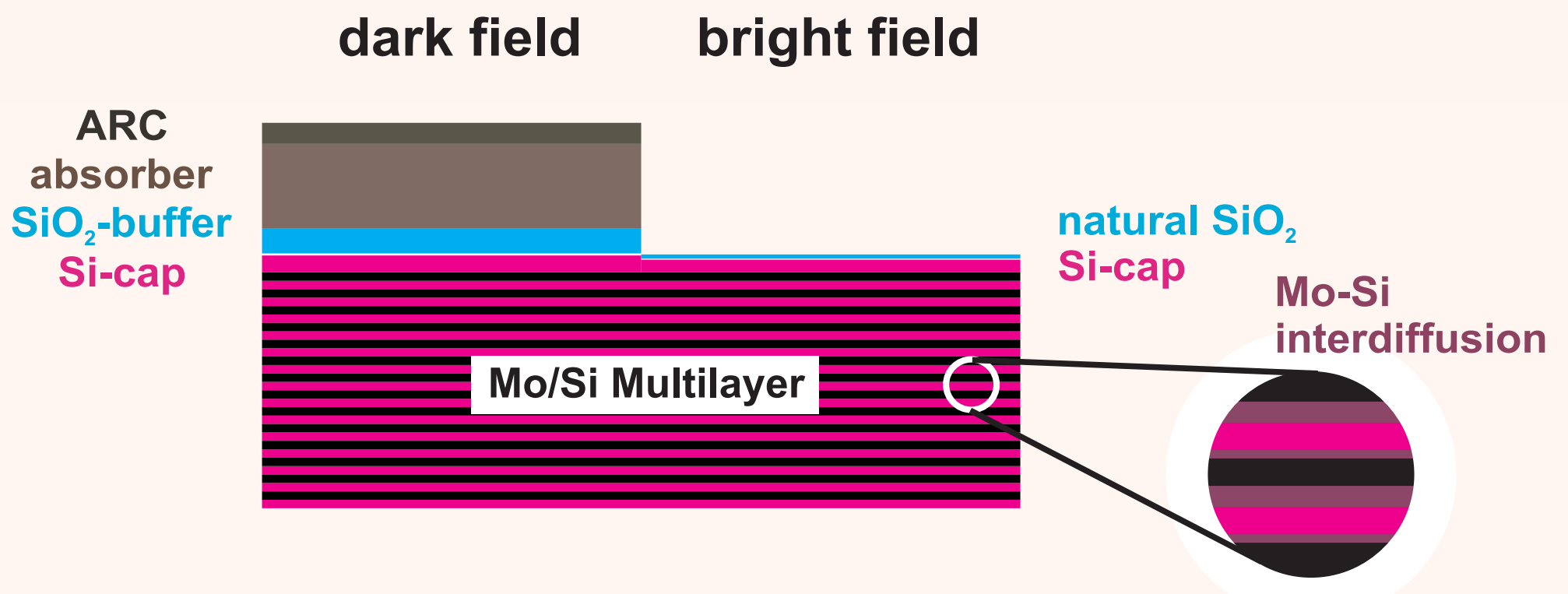
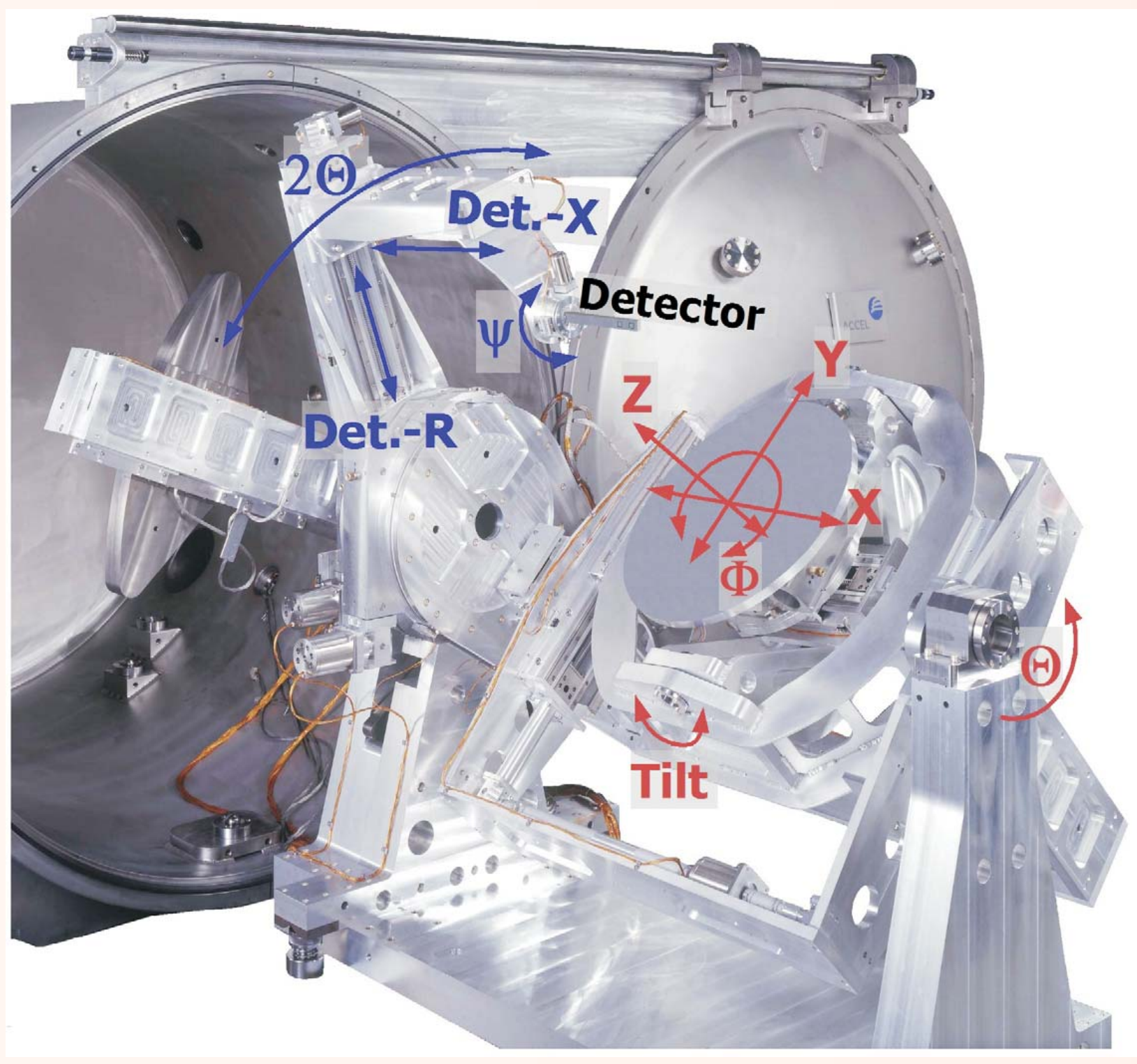
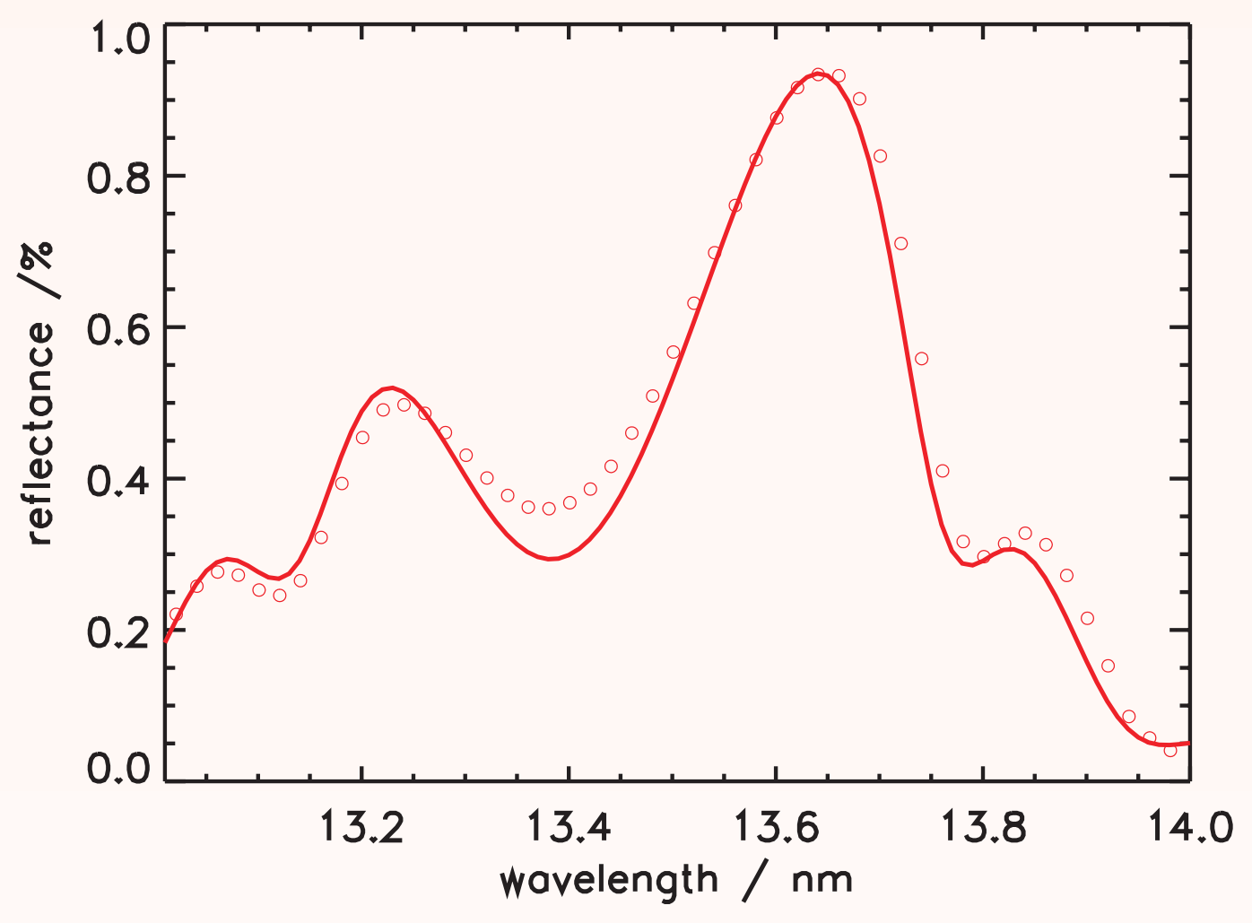
layer thickness determination using reflectometry



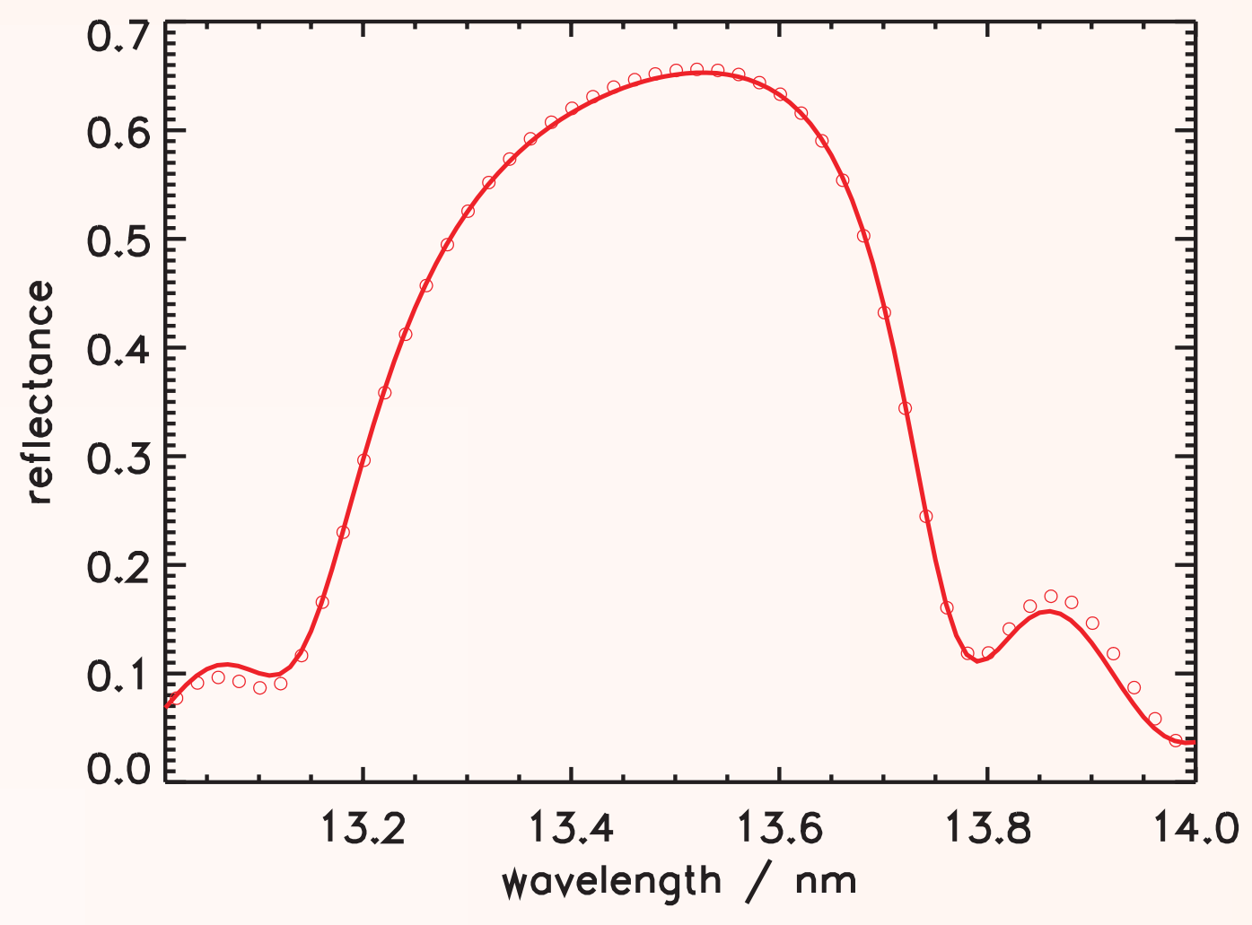
model for
EUV mask layer system:
interdiffusion layers in ML-stack included



Reflectometer mechanics outside vacuum chamber with motions indicated.



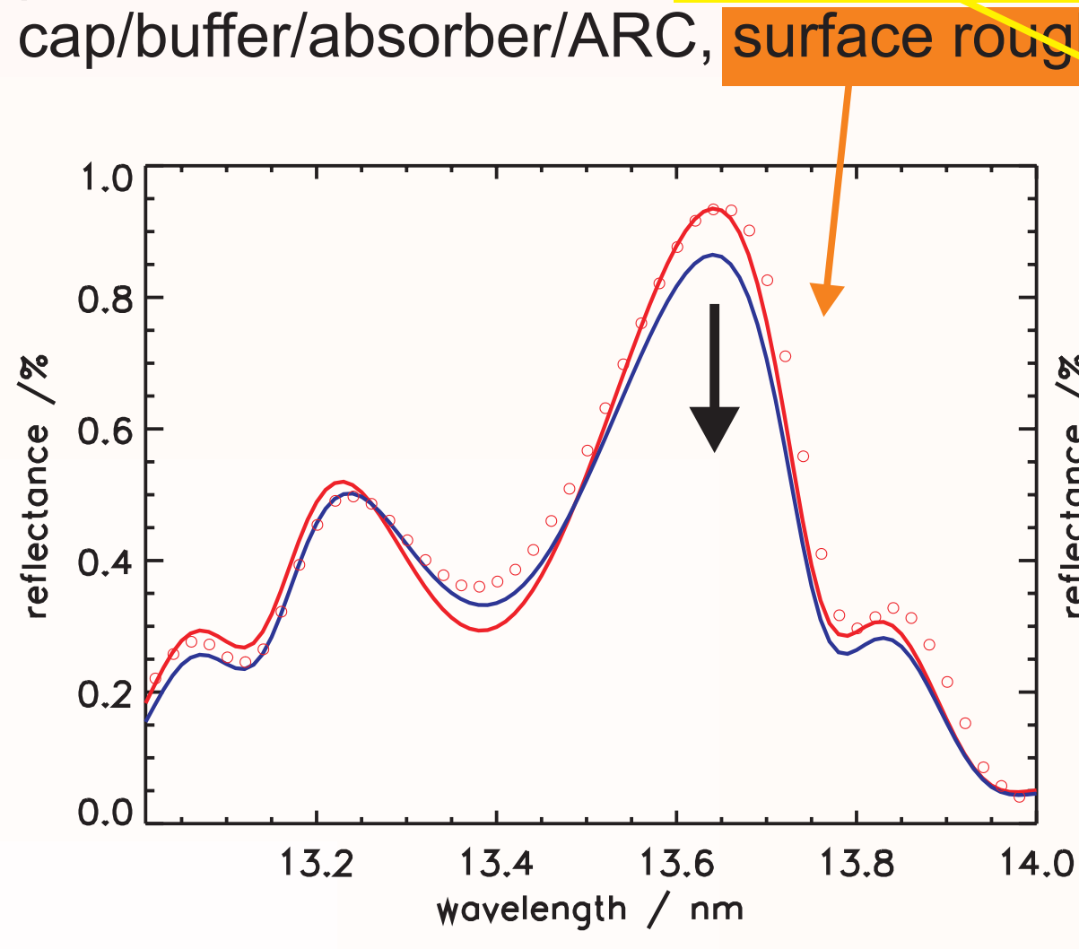
reflectance of absorber fields
parameters determined: total thickness of cap/buffer/absorber/ARC, surface roughness



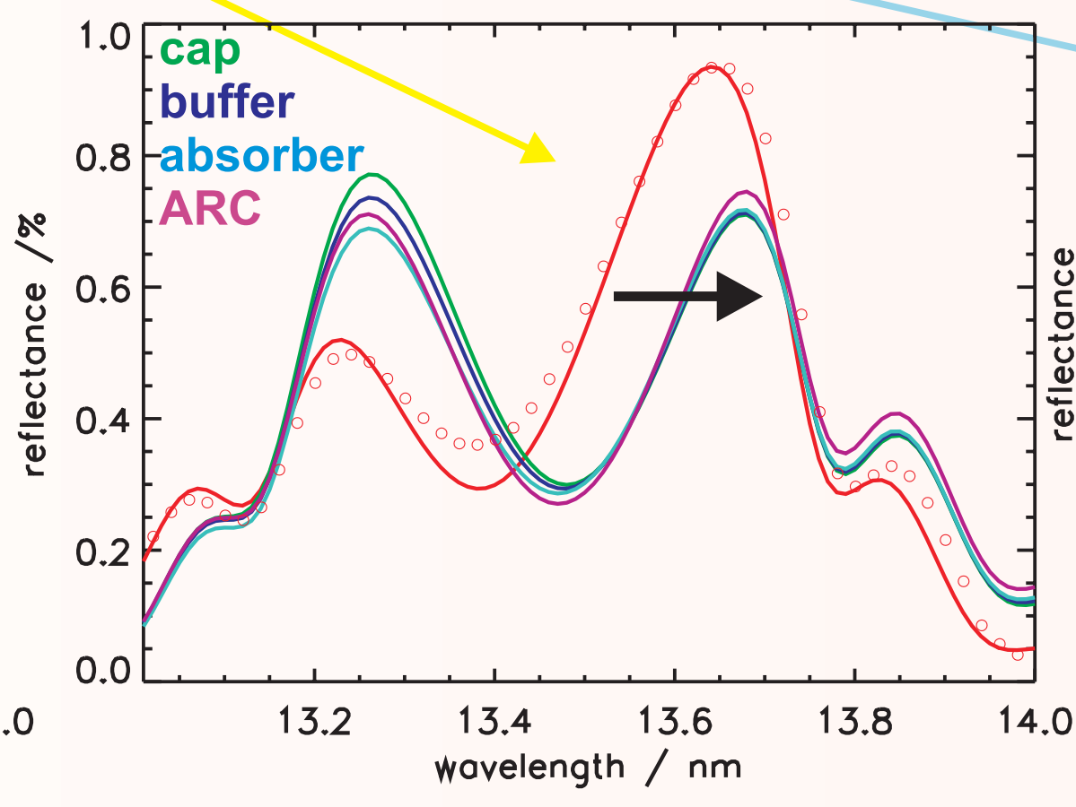
reflectance of bright fields
parameters determined: ML interdiffusion, roughness, cap thickness (incl. natural oxide)

results:

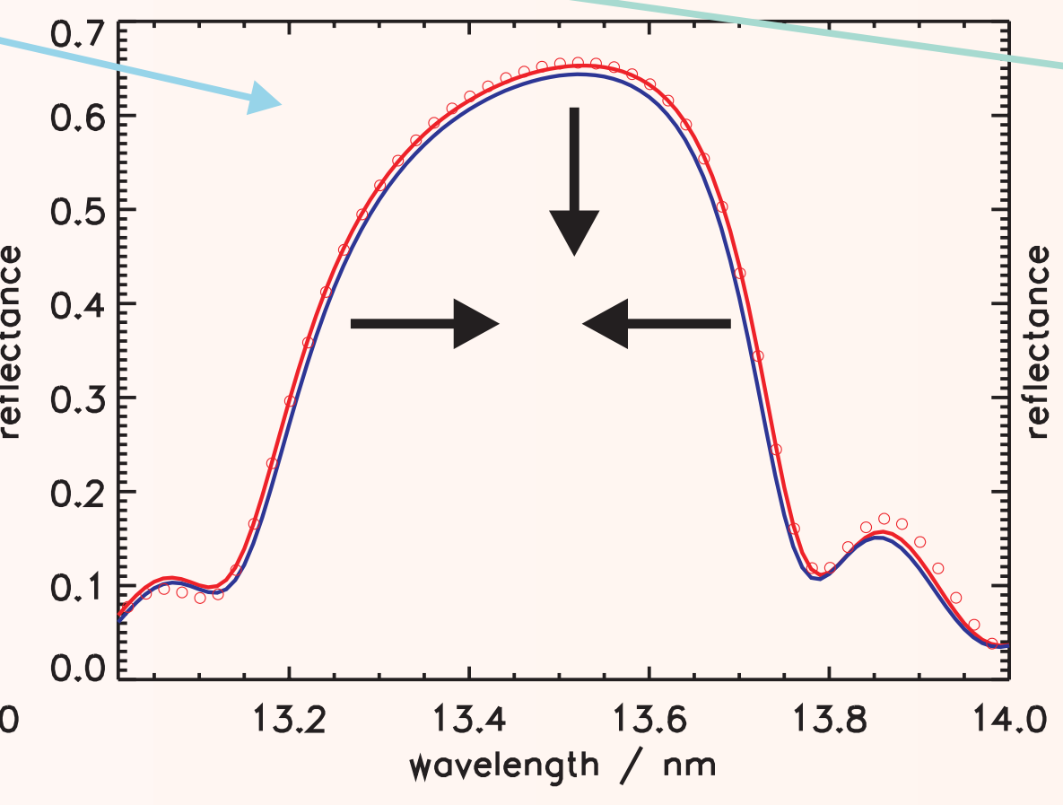
	Si-cap + SiO₂	total stack	surface roughness
bright field	12.6 nm	-	0.20 nm
dark field	-	87.5 nm	0.82 nm
line height	74.9 nm		



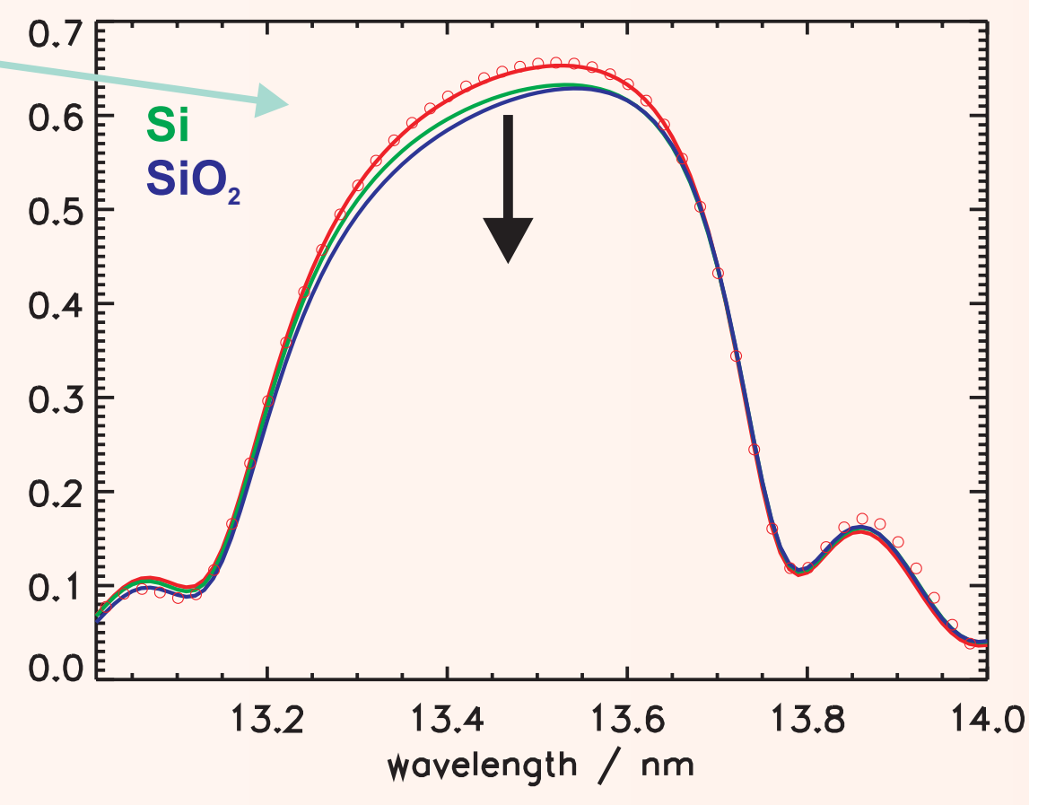
surface roughness reduces reflectance, no shift in phase (blue: roughness increased by 0.2 nm)



thickness of top layers shifts phase of spectral reflectance (lines: single layer thickness increased by 1 nm)

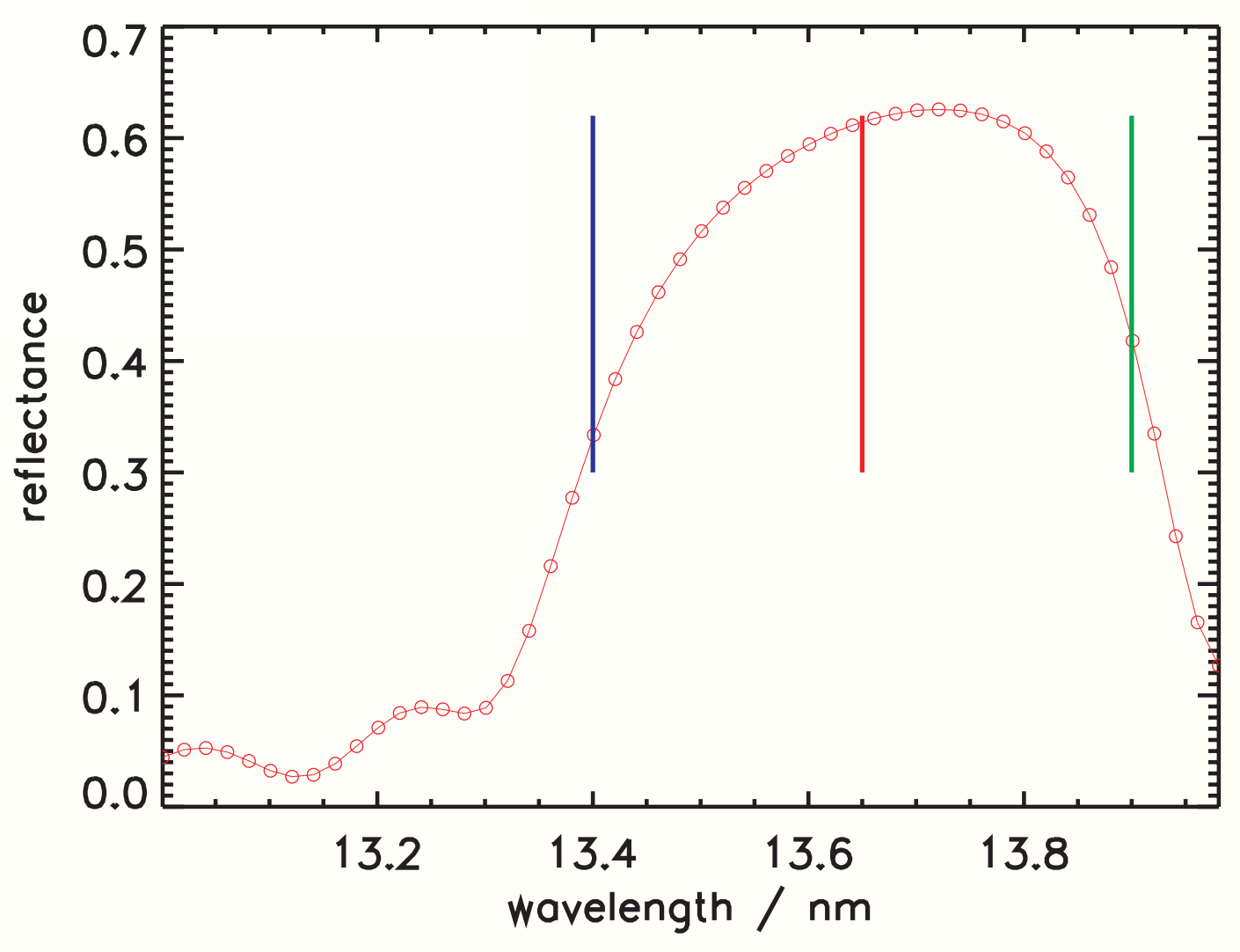


interface roughness, diffusion reduces peak reflectance and bandwidth (blue: roughness increased by 0.2 nm)

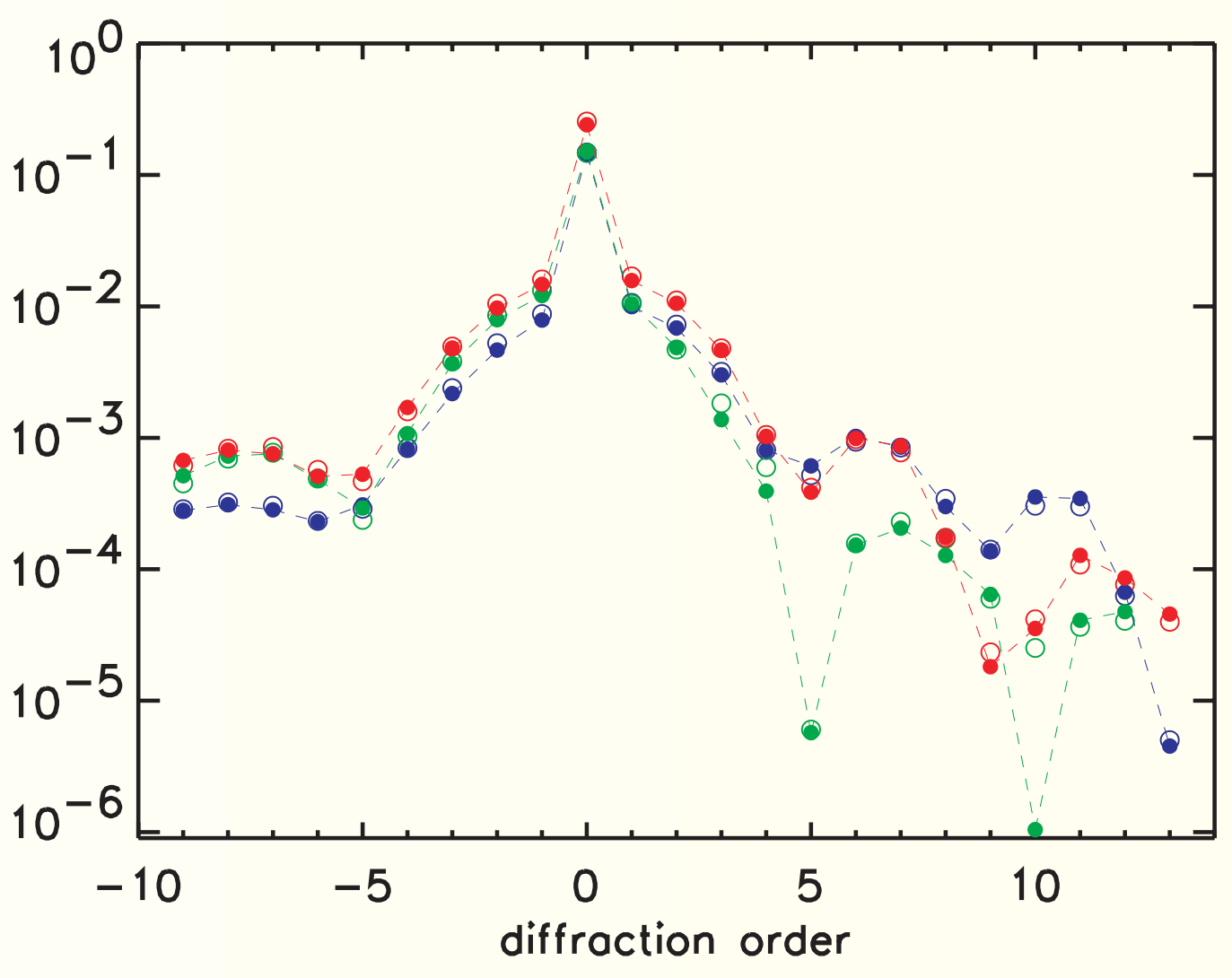


top layer thickness only reduces peak reflectance (lines: thickness increased by 1 nm)

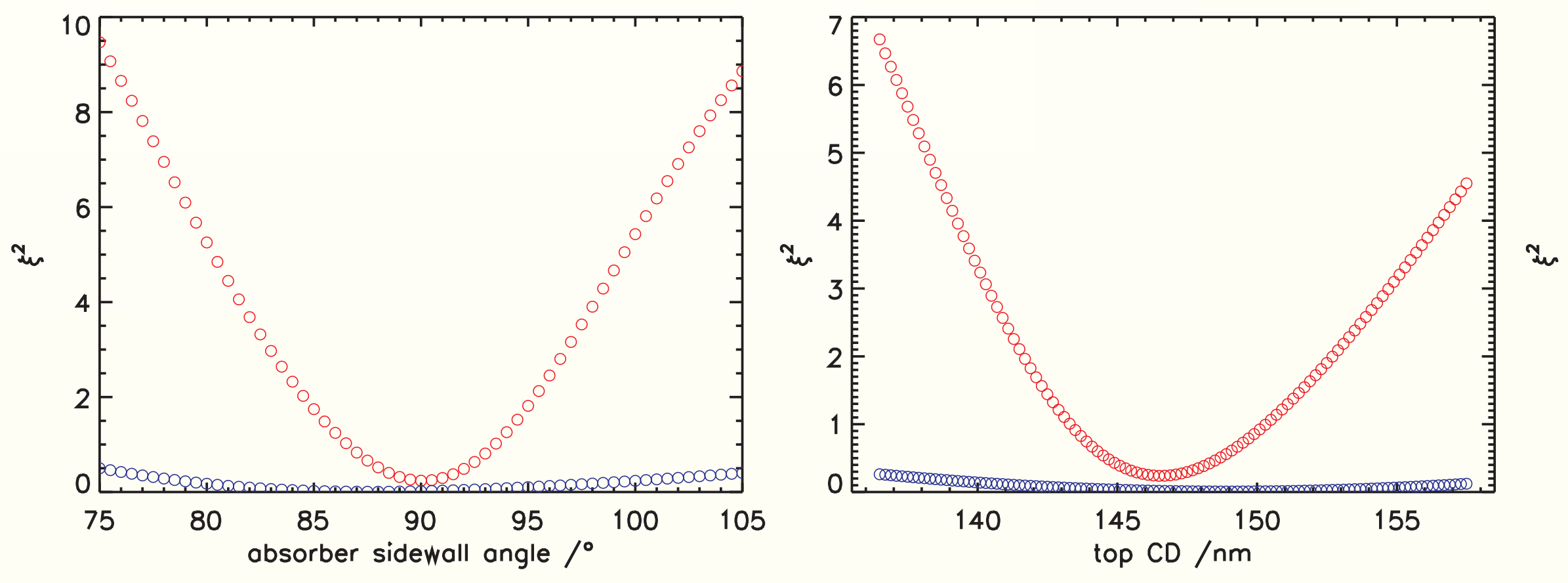
scatterometry experimental results



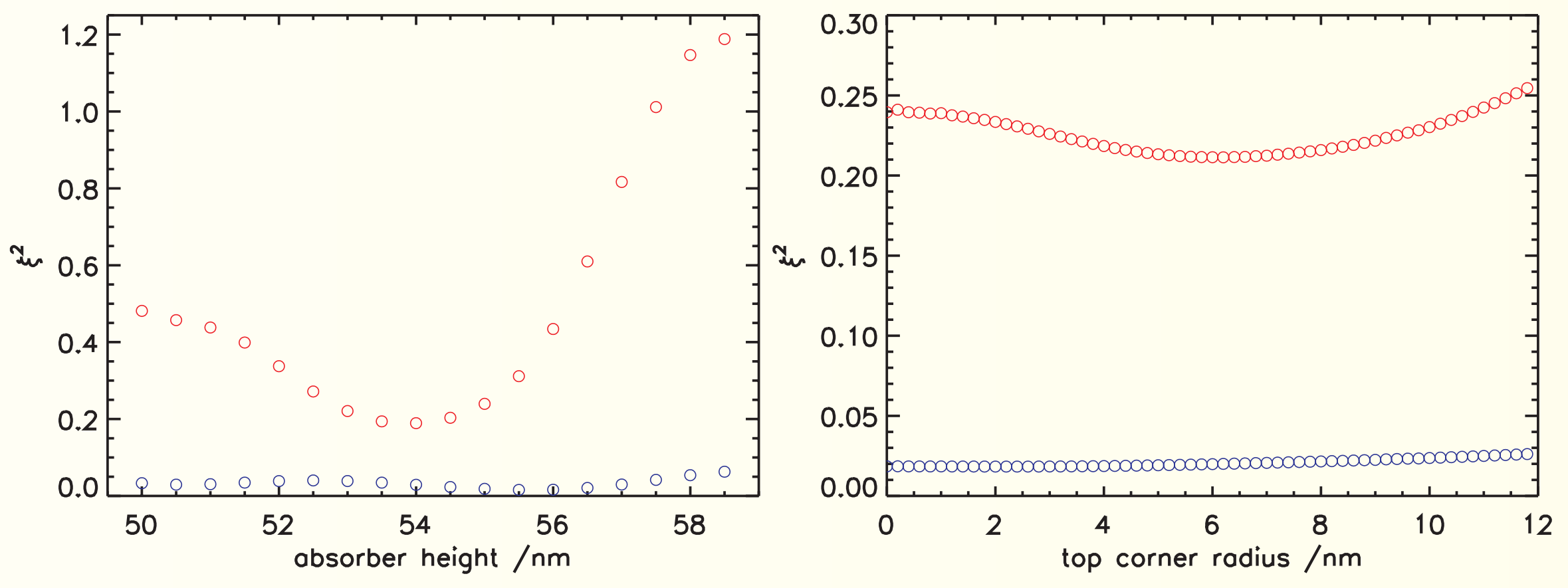
3 wavelengths (centre and left and right edge of the ML-peak) are used for scatterometry



Reflectance of -9th to 13th diffraction order at wavelengths of 13.4 nm, 13.65 nm and 13.9 nm. Experimental values (○) and simulated values (●) agree for almost all points simultaneously. The lines connect the simulated values and are only to guide the eye.



Deviation between experimental and simulated intensities as function of sidewall angle and top CD, using either 9 (blue) or 23 (red) orders of diffraction. Both parameters have significant impact on the diffraction. Using 23 orders of diffraction effectively improves the significance.



Deviation between experimental and simulated intensities as function of line height and top corner radius using either 9(blue) or 23(red) orders of diffraction. Both parameters have only minor impact on the diffraction. Only using 23 diffraction orders, parameter determination is possible.

results:

wavelength	top CD	sidewall angle	height(FEM)	height(reflect.)	corner radius
13.40 nm	145.7 nm	87.9°			6 nm
13.65 nm	146.5 nm	90°	75 nm	74.9 nm	6 nm
13.90 nm	146.5 nm	90°			6 nm

conclusion

We demonstrated that single wavelength EUV scatterometry in combination with FEM simulations is a viable method for an accurate and robust destruction free characterization of EUV masks. We compared experimental diffraction orders to FEM simulations. For the FEM simulations, the EUV mask is described with a finite number of geometrical parameters and then the best fitting values determined by minimizing the deviation of experimental and simulated data. The FEM method is well suited for the simulation of EUV masks since it allows computation of nearly arbitrary geometries, is very accurate and very fast as a precondition for the solution of the given inverse problem. We considered the top critical dimension, the sidewall angle, the height of the absorber lines, and the top corner radius as unknown parameters.
The search for the best fitting geometry at three different wavelengths gave nearly the same values for the top critical dimension and the absorber sidewall angle proving both robustness and accuracy of the method. Using as many diffraction orders as possible, effectively improved the significance of the results. The absorber corner radius and total stack height have only minor influence on the diffraction pattern and could only be estimated using all available diffraction orders. The stack height, however, can be determined unambiguously by reflectometry at absorber fields.
The combination of reflectometry at dark and bright test fields and scatterometry at lines&spaces provides full information on layer thicknesses, top CD, and sidewall angles.

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