Challenges for predictive EUV mask modeling

P. Evanschitzky, A. Erdmann
Fraunhofer IISB

Lithography Simulation

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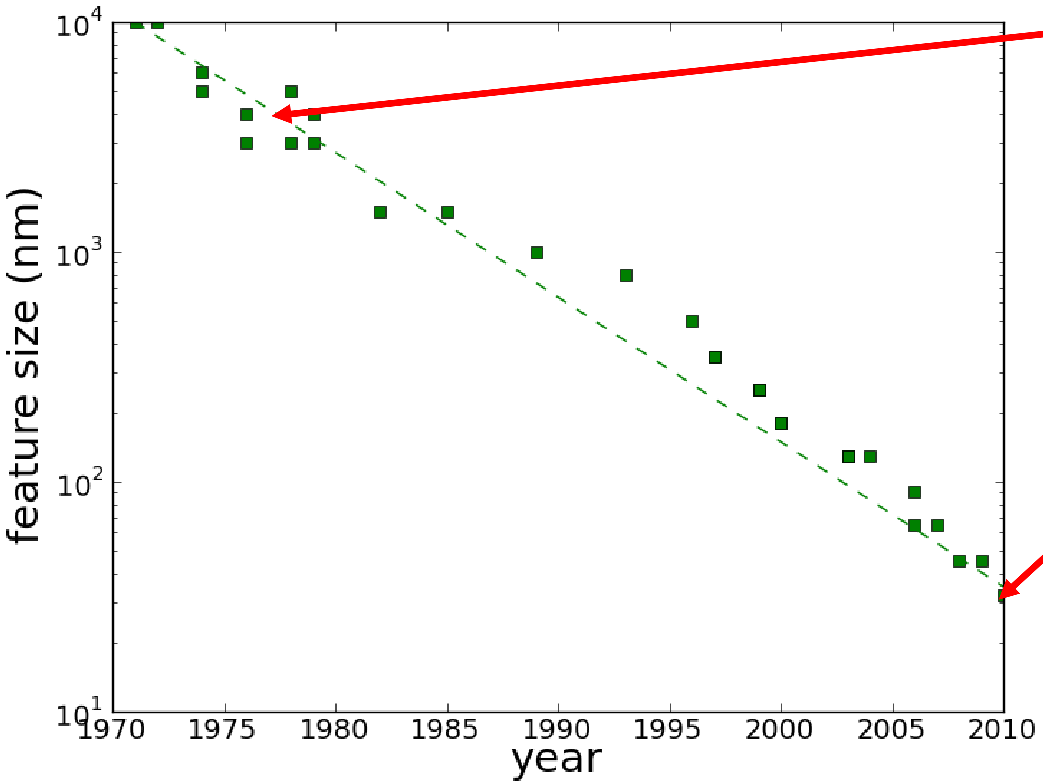
Outline

- EUV mask simulation challenges
- EUV mask simulation model
- Simulation consequences and potential solutions
  - 3D mask and material effects
  - Larger simulation area
  - Multilayer defects
  - EUV pellicle
- Conclusion

EUV mask simulation challenges

Feature size compared to illumination wavelength λ



First optical projection stepper:
λ = 436 nm

Feature size = 2 µm

Feature size / λ ~ 4.58

Optical projection scanner:
λ = 193 nm

Feature size = 36 nm

Feature size / λ ~ 0.18

EUV:
λ = 13.5 nm

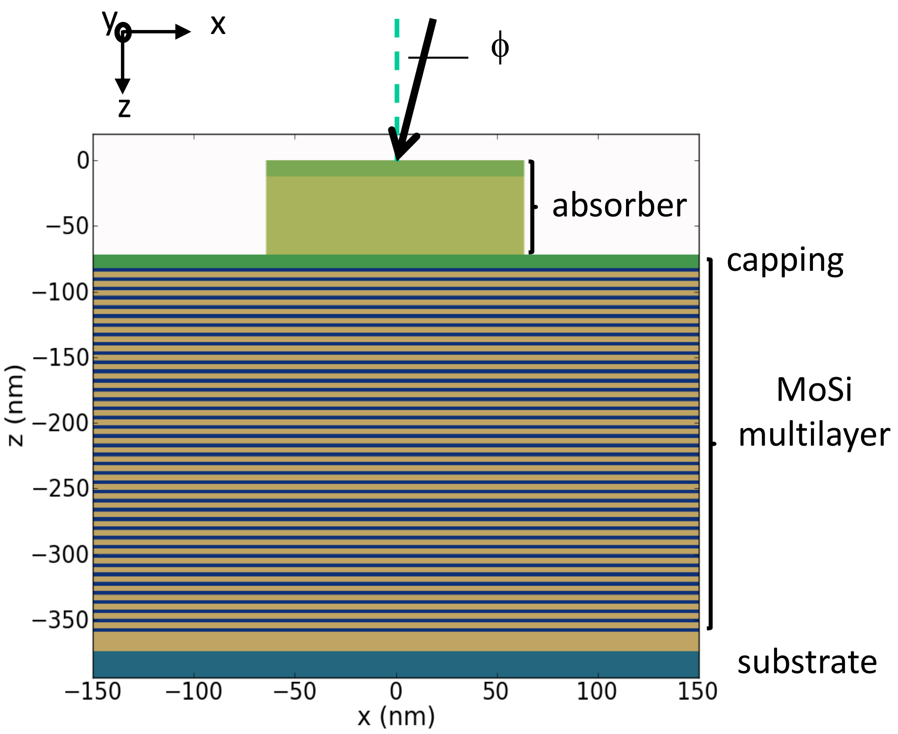
Feature size e.g. 10 nm

Feature size / λ ~ 0.74

Why EUV simulation is challenging ?

EUV mask simulation challenges

Why the EUV mask simulation is challenging ?



Thick absorber layer with oblique illumination

- Thickness currently ~ 4 x λ (at 193 nm ~ 0.25 x λ)
- Shadowing effects
- Deformation of the phase (aberration like effects)
- Material effects

Larger simulation areas with respect to the wavelength

- Currently period/λ ~ 6 (at 193 nm ~1.5)
- Properties defined over lager areas (e.g. roughness)
- Anamorphic system length scale doubling in one direction

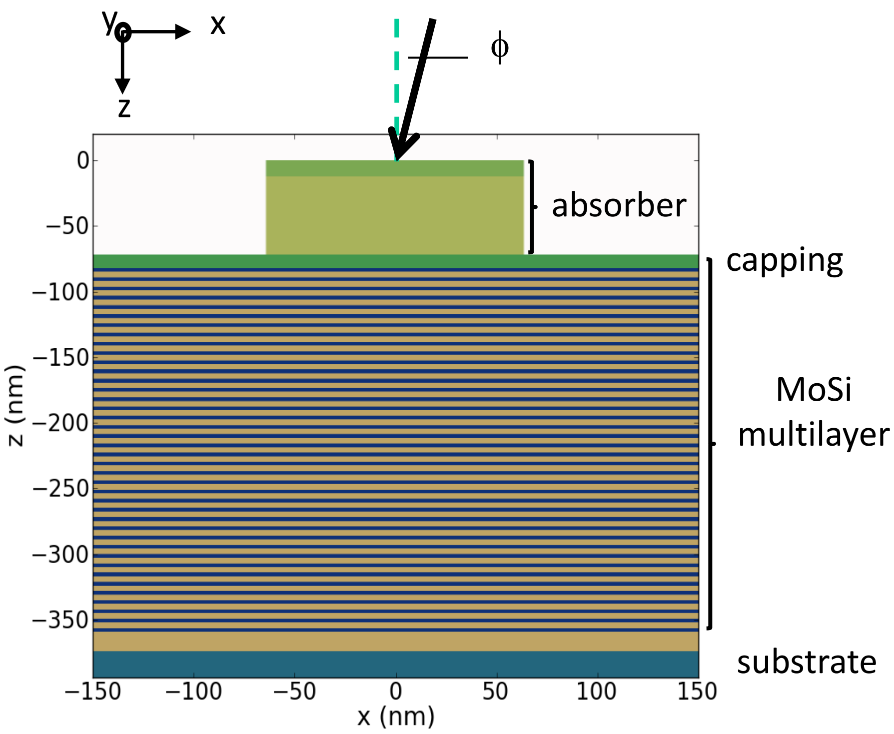
Multilayer is prone to defects

- Deformation of the planar layer system
- Significant modification of the reflected intensity and phase

Fast rigorous electromagnetic field modeling of larger areas required to cover all important effects

EUV mask simulation challenges

Why the EUV mask simulation is challenging ?



Pellicle

- Pellicle properties require the combination of rigorous mask diffraction simulation and Fourier optics

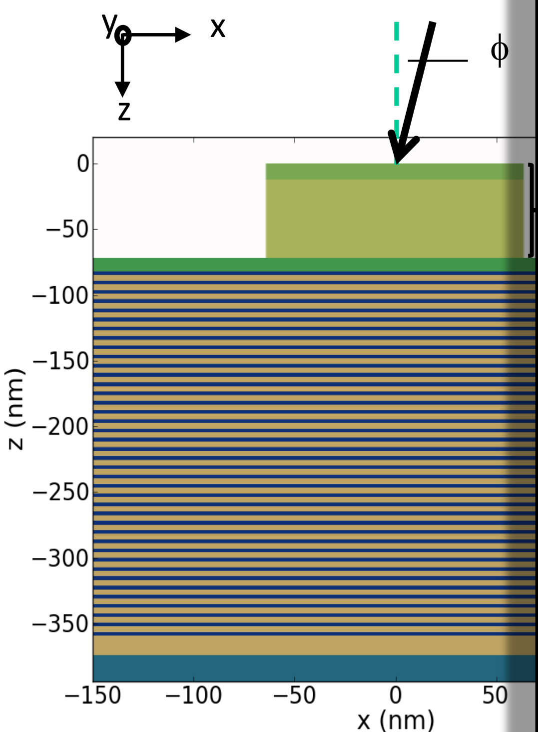
Source shape

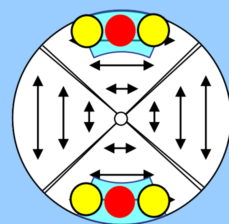
- A certain number (> 1) of rigorously computed illumination directions per image simulation required (No-Hopkins simulations)

Coupling of rigorous electromagnetic field modeling and image simulation required to cover all important effects

EUV mask simulation challenges

Why the EUV mask simulation is challenging ?





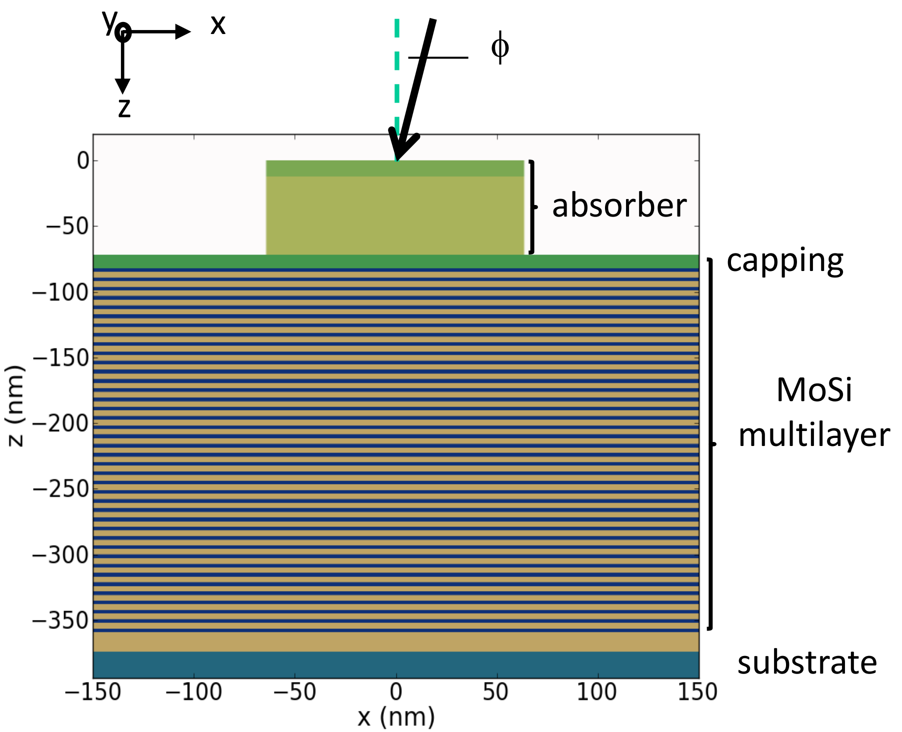
Source shape

Mask diffraction computation without Hopkins approach:

- Multiple rigorous mask spectrum simulations with the real illumination angles ⟶ (red dot)
- Mask Spectra of closely neighboring illumination points derived from the nearest computed spectra by shifting the spectra according to the slightly changed source point frequencies ⟶ (yellow dot)
- **A source dependent number of rigorously computed diffraction spectra is required to get sufficient accuracy → typically ~ 5 points per pole**

EUV mask simulation model

RCWA based mask diffraction simulation well suitable for EUV



$T \sim n \times M^3$ n = number of inhomogeneous layers (typically ~1)

$M = (k*2*b_x/\lambda + 1) \times (k*2*b_y/\lambda + 1)$ for 3D

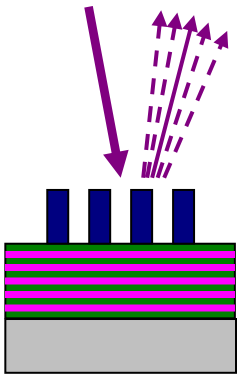
$b_{x/y}$ = mask size in x/y-direction

k ~ 0.5 for EUV (~3 for 193 nm)

1. Slicing of the mask (corresponds to mask geometry)
2. Description of the fields and of the material distributions with Fourier series (Δn small → only few Fourier orders required)
3. Computation of the electromagnetic spectrum inside each layer (slice) by defining and solving the eigenvalue problem resulting from the Maxwell equations (standard mathematical problem, significant computing time only for inhomogeneous layers, parallelization possible)
4. Coupling of the spectra of all layers according to the boundary conditions between the layers (fast coupling algorithm)
5. Computation of the resulting reflected, transmitted and internal spectra

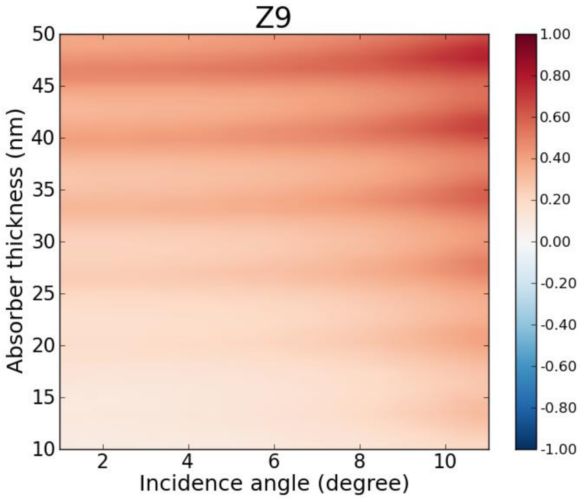
Thick absorber - 3D mask and material effects

Mask diffraction analysis



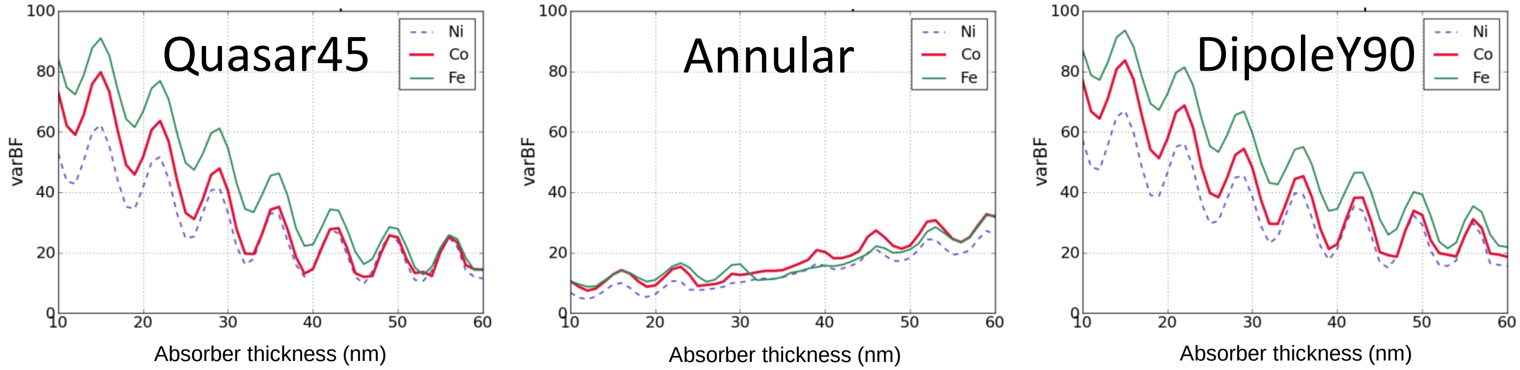
Extraction of phase (and intensity) of orders

Quantification of virtual wavefront by Zernikes and offsets



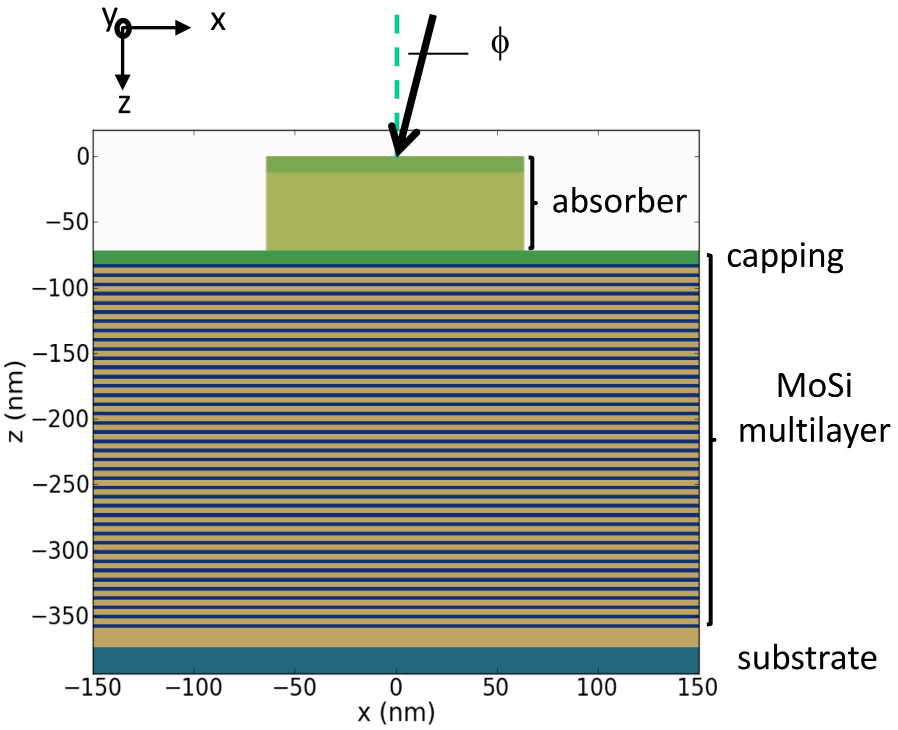
Aerial Image analysis

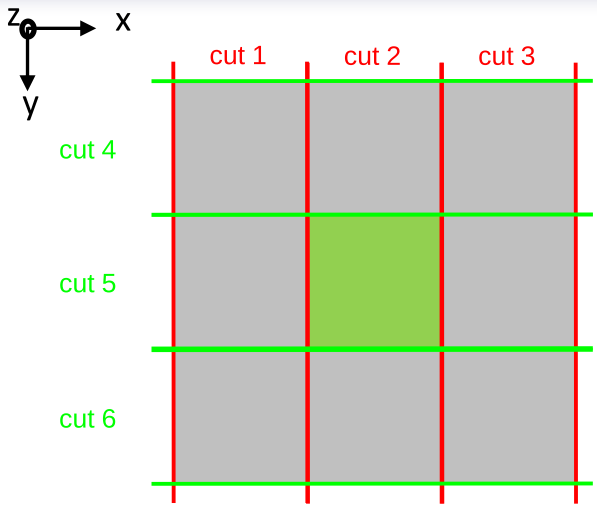
Exemplarily best focus variation (varBF) over pitch for different illuminations and absorber materials



Larger simulation area

Decomposition technique - Model

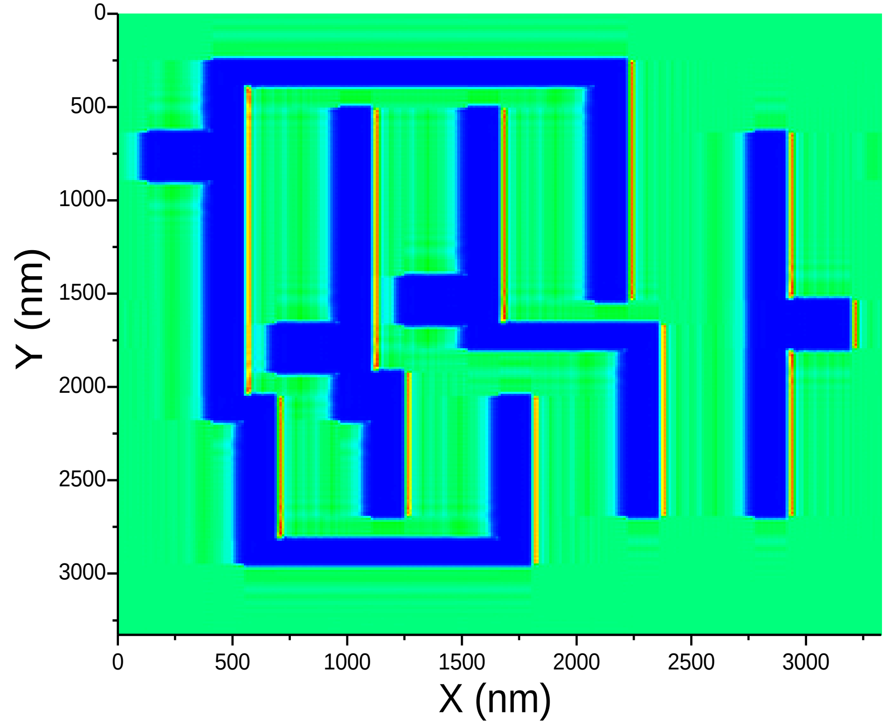




- Split-up of the mask in 2D cuts (here exemplarily cut 1 – cut 6)
- Independent rigorous 2D/1D computation of the cuts/cut overlap areas (parallelization possible)
- Composition of the individual cut/cut overlap area results (for RCWA in the frequency domain for better performance)
- Introduction of an error → in case of standard masks acceptable, to be tested case by case for advanced mask concepts

Larger simulation area

Decomposition technique - Speedup



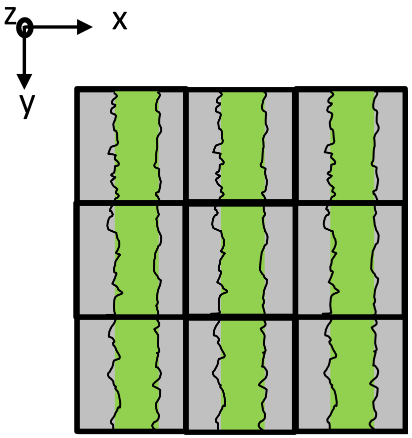
Near field simulation of an EUV-mask
Size: 250λ×250λ×50λ

Simulation times

- Full 3D: 400 days (estimation)
- Decomposition: 250 s
- Parallelized Decomposition: 10 s (27 CPU)

Larger simulation area

Field stitching – Model (overview, currently under development)



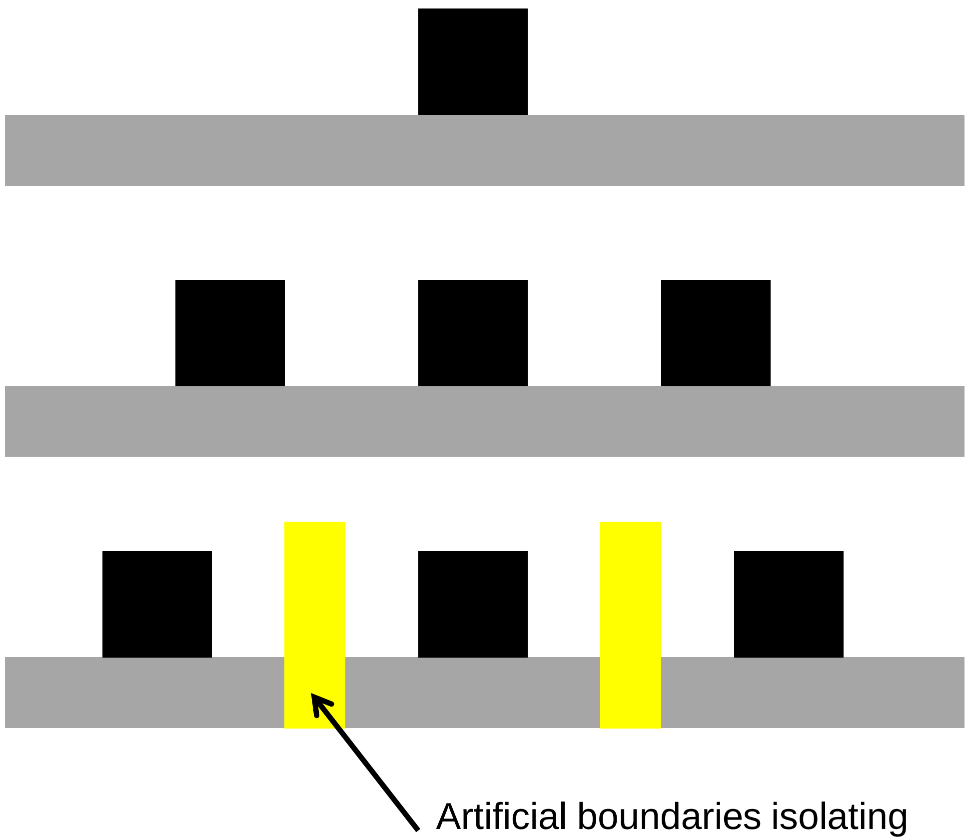
Dense lines/spaces with overlaid roughness

Subdivision of the simulation area in subcells, here exemplarily 3 x 3 subcells (n = 3)

- Subdivision of the area to be simulated into subcells
- Independent 3D simulations of the subcells
- Composition of the subcells by stitching the fields
- Very efficient for RCWA based models: Significant speedup due to time scaling behavior, e.g. ~ 20 x faster for n = 3

Larger simulation area

Isolated boundaries - Model



Isolated feature with large pitch → desired result, relatively slow

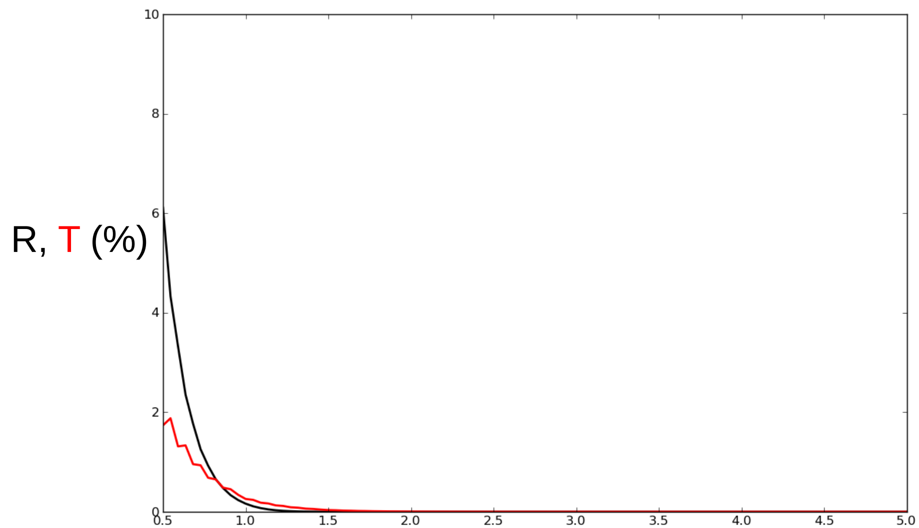
Dense features with small pitch → different result compared to iso feature, fast

Dense feature with small pitch + additional boundaries → same result compared to iso feature, relatively fast

Larger simulation area

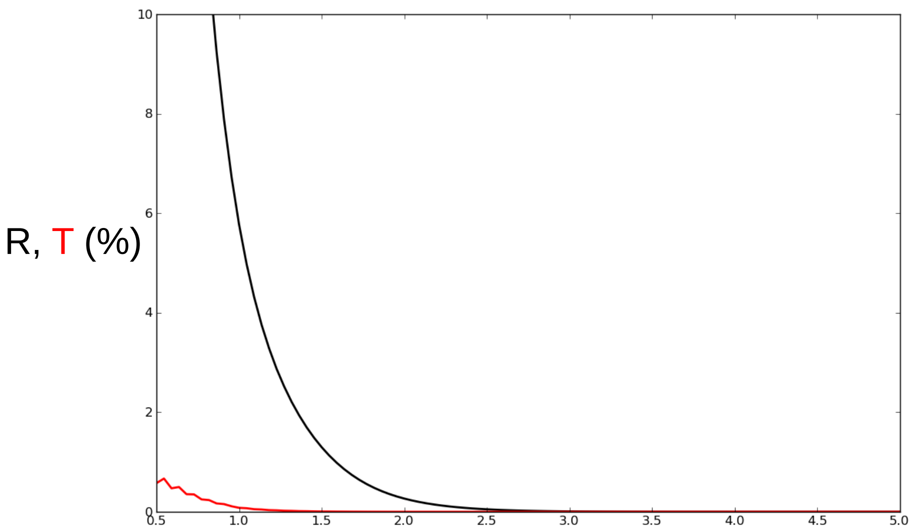
Isolated boundaries – Reflection/transmission properties

Reflection (black curve) and transmission (red curve) of the artificial boundary layer for different layer thicknesses and illumination angles



Layer thicknesses (multiple of wavelength)

0 degree incidence



Layer thicknesses (multiple of wavelength)

70 degree incidence

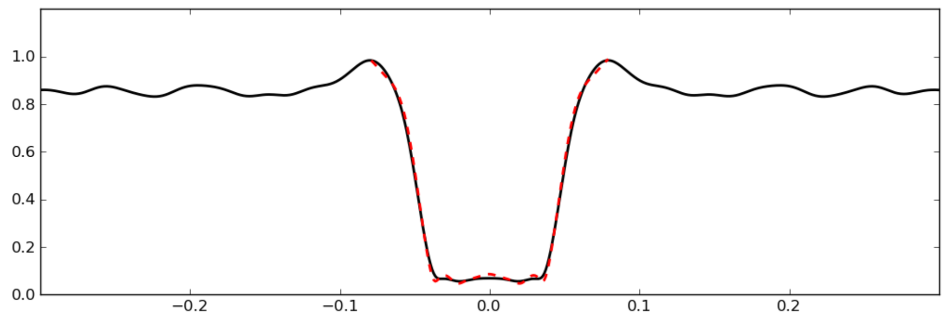
Artificial boundary layer thickness ~ 2 x wavelength → sufficient isolation of neighboring features

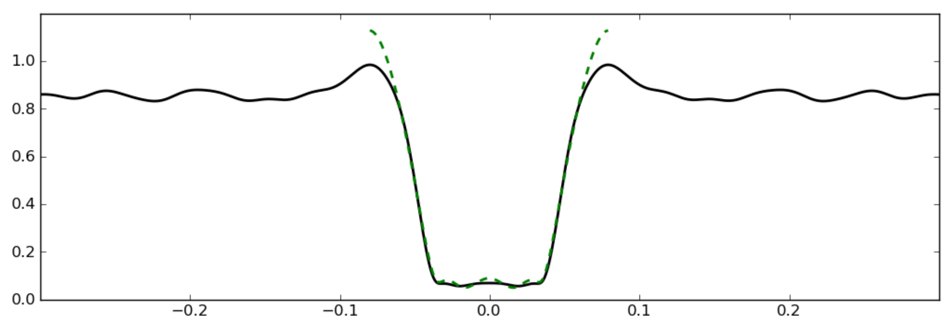
Larger simulation area

Isolated boundaries - Example

20 nm iso line (4x), illumination 13.5 nm

- Black curve = reference computation with 2 µm pitch
- Green curve = dense feature
- Red curve = dense feature + isolated boundaries





- Good functionality of the boundary model
- Introduction of many inhomogeneous layers in the ML part
- Optimization of the isolated ML part ongoing to reduce the overall computation time

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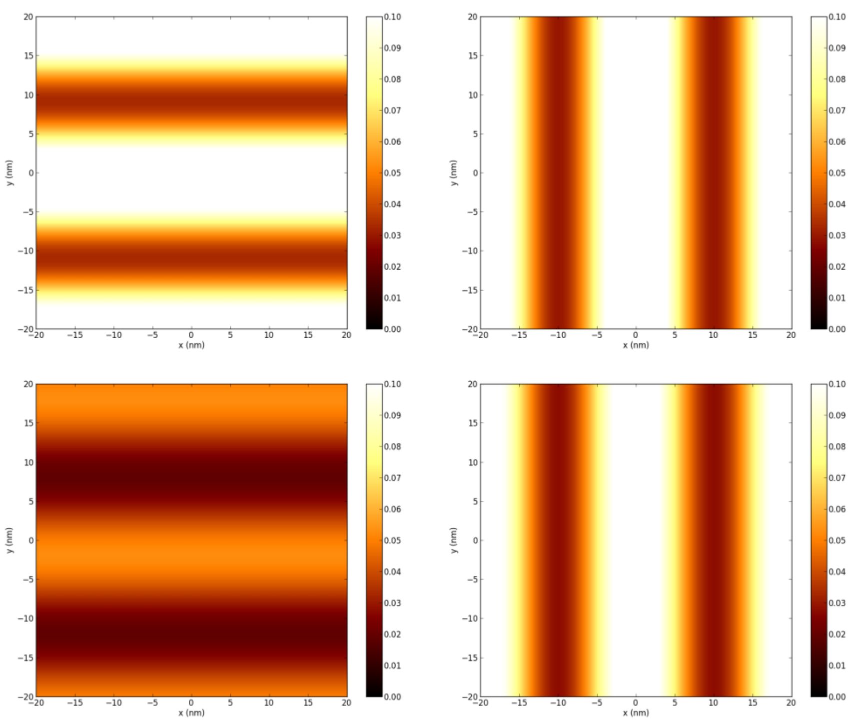
Anamorphic imaging

Reduction 4/4 vs. 4/8 (anamorphic system)
10 nm horizontal / vertical dense lines, NA 0.55, annular illumination, aerial images

4/8

4/4



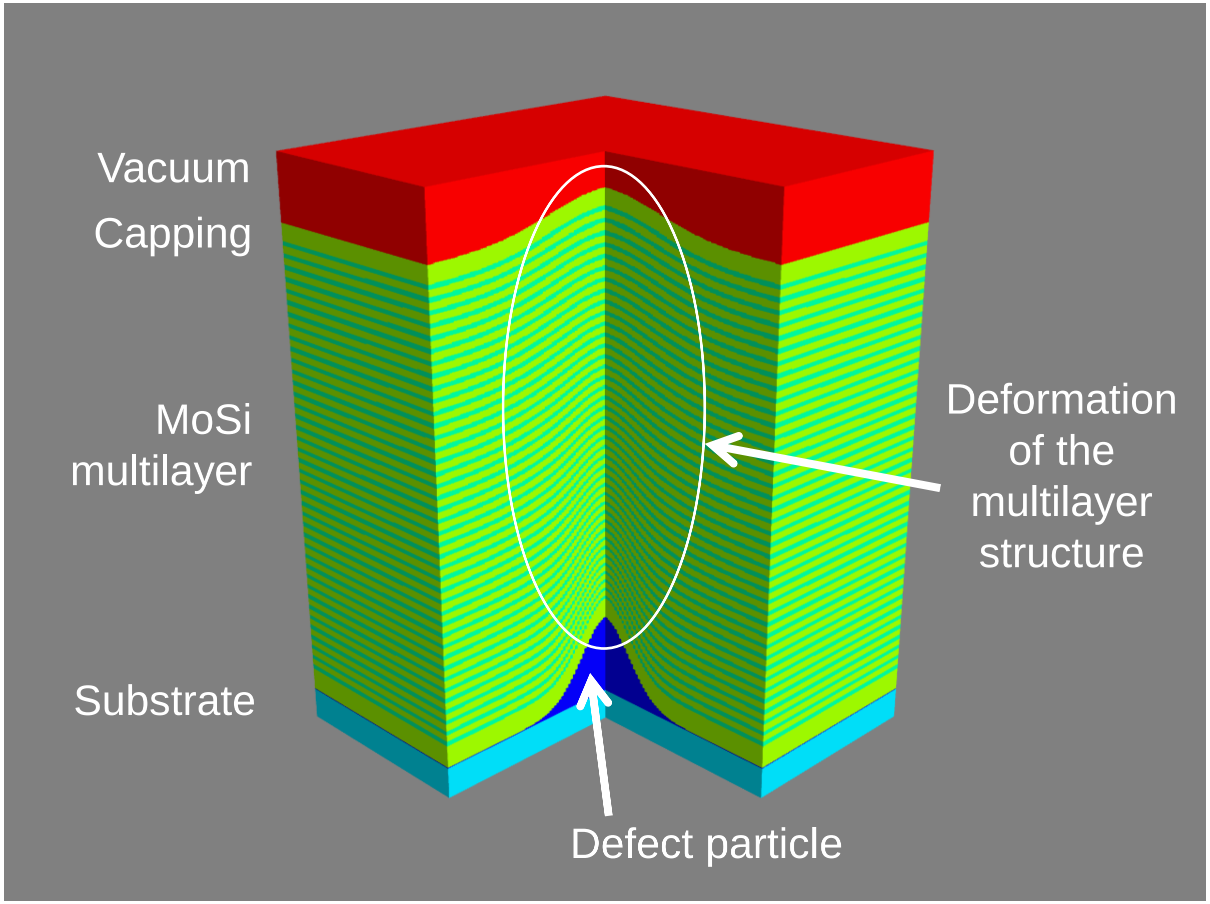
High contrast of the 4/8 systems similar to a 8/8 system independent from line orientation

→ Detailed investigations show that the 4/8 anamorphic system shows in general a similar imaging performance compared to a 8/8 system

Significant contrast loss of the 4/4 system for horizontal lines

Multilayer defects

Deformed defective multilayer



Defect caused deformation of the planar multilayer structure requires the rigorous 3D simulation of the whole multilayer

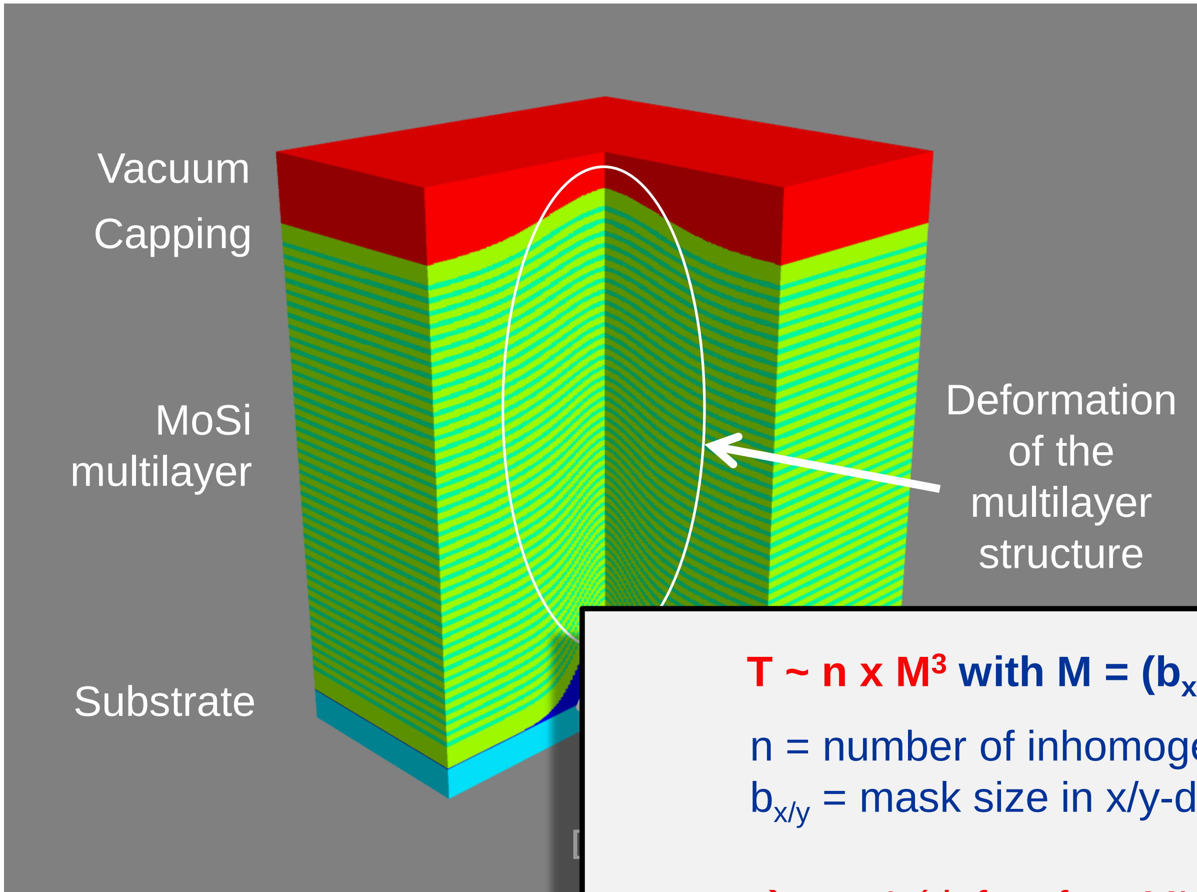
→ Very time-consuming

→ E.g. 640 nm x 640 nm mask area with defect on 4 x 2.8 GHz CPU takes about 50 hours (~2 minutes without defect)

→ 3D simulation of a defective EUV multilayer is currently one of the most challenging parts of the whole simulation flow

Multilayer defects

Deformed defective multilayer



Defect caused deformation of the planar multilayer structure requires the rigorous 3D simulation of the whole multilayer

→ Very time-consuming

→ E.g. 640 nm x 640 nm mask area with defect on 4 x 2.8 GHz CPU takes about 50 hours (~2

$T \sim n \times M^3$ with $M = (b_x/\lambda + 1) \times (b_y/\lambda + 1)$ for 3D

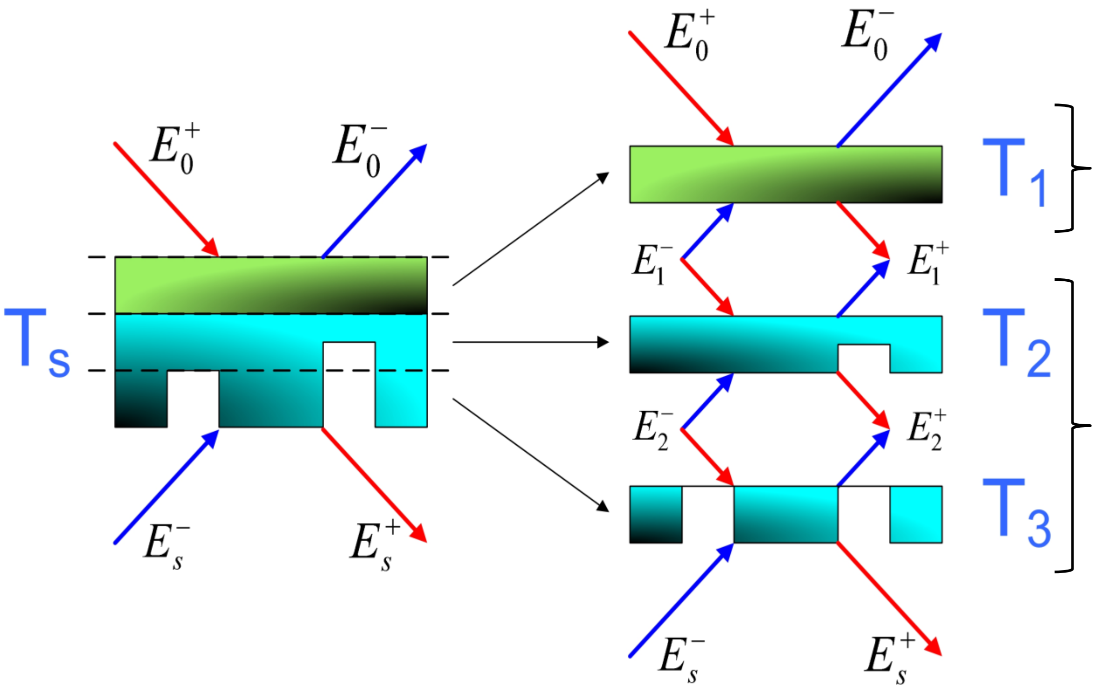
n = number of inhomogeneous layers
$b_{x/y}$ = mask size in x/y-direction

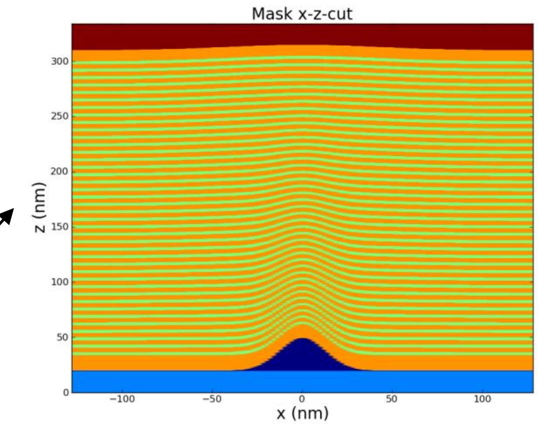
→ n ~ 1 (defect free ML with absorber)

→ n ~ 2000 (defective ML)

Multilayer defects

Defect data base

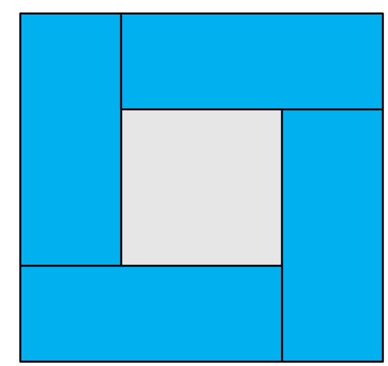




"Off line" computation of the defective ML and storage of the results in a data base

T_s = mask (including ML defect) to be computed

$T_{1,2,3}$ = split-up of the mask into independent parts



"On demand" computation of the non-ML parts and recombination with the stored defective ML results

→ Simulation time of typical absorber structures with defective ML in the range of a few minutes

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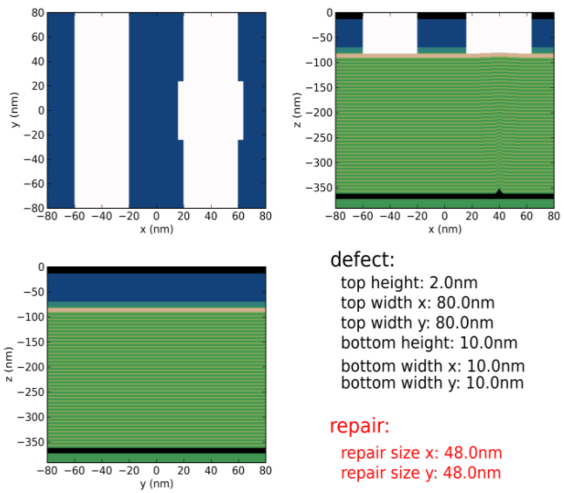
Multilayer defects

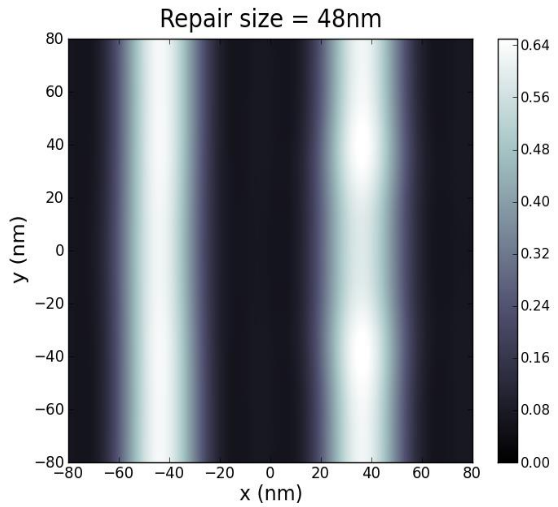
Modeling and optimization of repair strategies

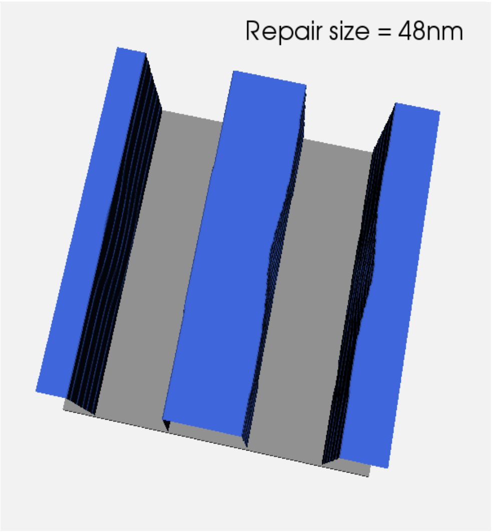
Mask layout

Aerial image

Resist profile







Mask: 40nm dense L/S
Optics: NA=0.25, λ=13.6nm, σ=0.5
Calibrated resist
Defect: top 2/80nm, bottom: 10/10nm

- Good repair at best focus
- How about through-focus?

EUV pellicle

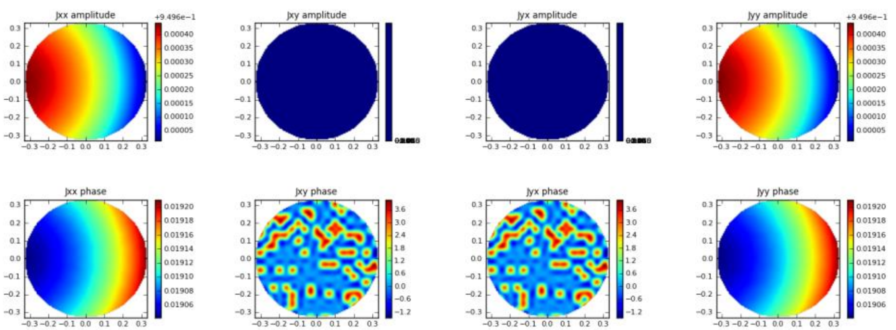
Combination of rigorous EMF modeling and Fourier optics

Spectrum extraction plane

Pellicle with
particle on top

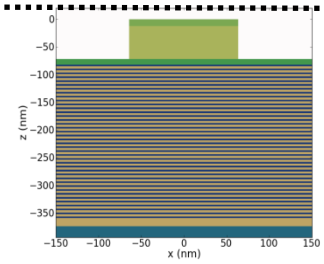
Rigorous simulation of particle diffraction

Application of a defocus to the individual diffraction spectra



Jones pupil representation of the pellicle including pellicle tilt (rigorous simulation of tilt very time consuming)

Object plane

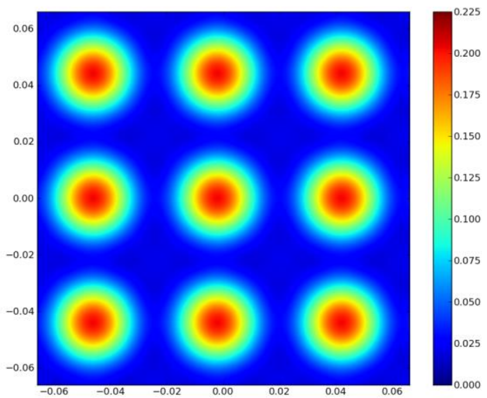


Rigorous simulation of mask diffraction

EUV pellicle

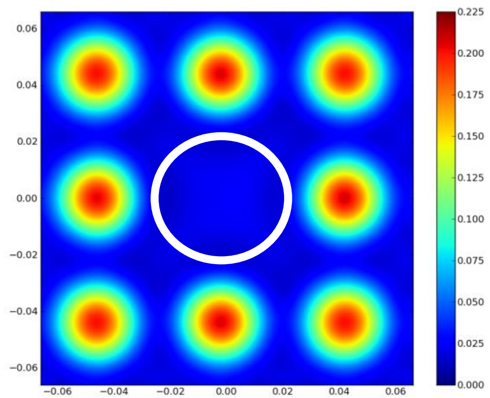
Basic example – Pellicle with particle

22 nm dense contacts with pellicle, aerial images



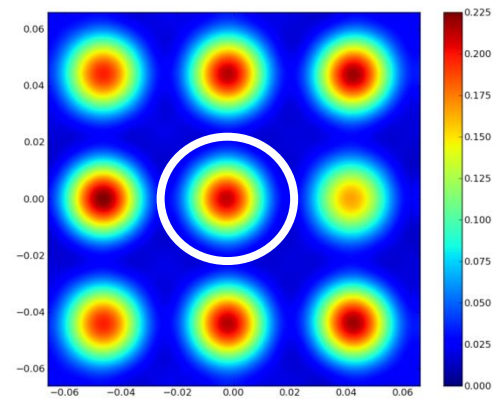
Pellicle 3 mm above the mask

→ Expected intensity reduction comparted to a system without pellicle



Pellicle with particle (white circle in the picture) right above the mask

→ Expected printing of the particle



Pellicle with particle (white circle in the picture) 3 mm above the mask

→ Particle out of focus, significantly reduced printing impact (simulation of real isolated particle under development)

Conclusion

- Thick absorbers with different materials and oblique illumination, typically larger simulation areas compared to the wavelength and multilayer defects require a fast rigorous 3D mask diffraction modeling

- Specific model extensions like a decomposition technique, field stitching, isolated boundaries and a ML defect model data base are required to simulate important effects in a reasonable time

- Pellicles and advanced illumination source shapes require a specific coupling of rigorous EMF simulations and image simulations to simulate important effects with sufficient accuracy

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All simulations were performed with Dr.LiTHO: www.drlitho.com