Characterization and Mitigation of 3D Mask Effects in EUV Lithography

Andreas Erdmann[1], Dongbo Xu[1], Peter Evanschitzky[1],
Vu Luong[2,3], Vicky Philipsen[2], Eric Hendrickx[2]

[1]Fraunhofer IISB, Schottkystr. 10, 91058 Erlangen, Germany
[2]imec, Kapeldreef 75, B-3001 Leuven, Belgium
[3]KULeuven, MTM Department, 3001 Leuven, Belgium

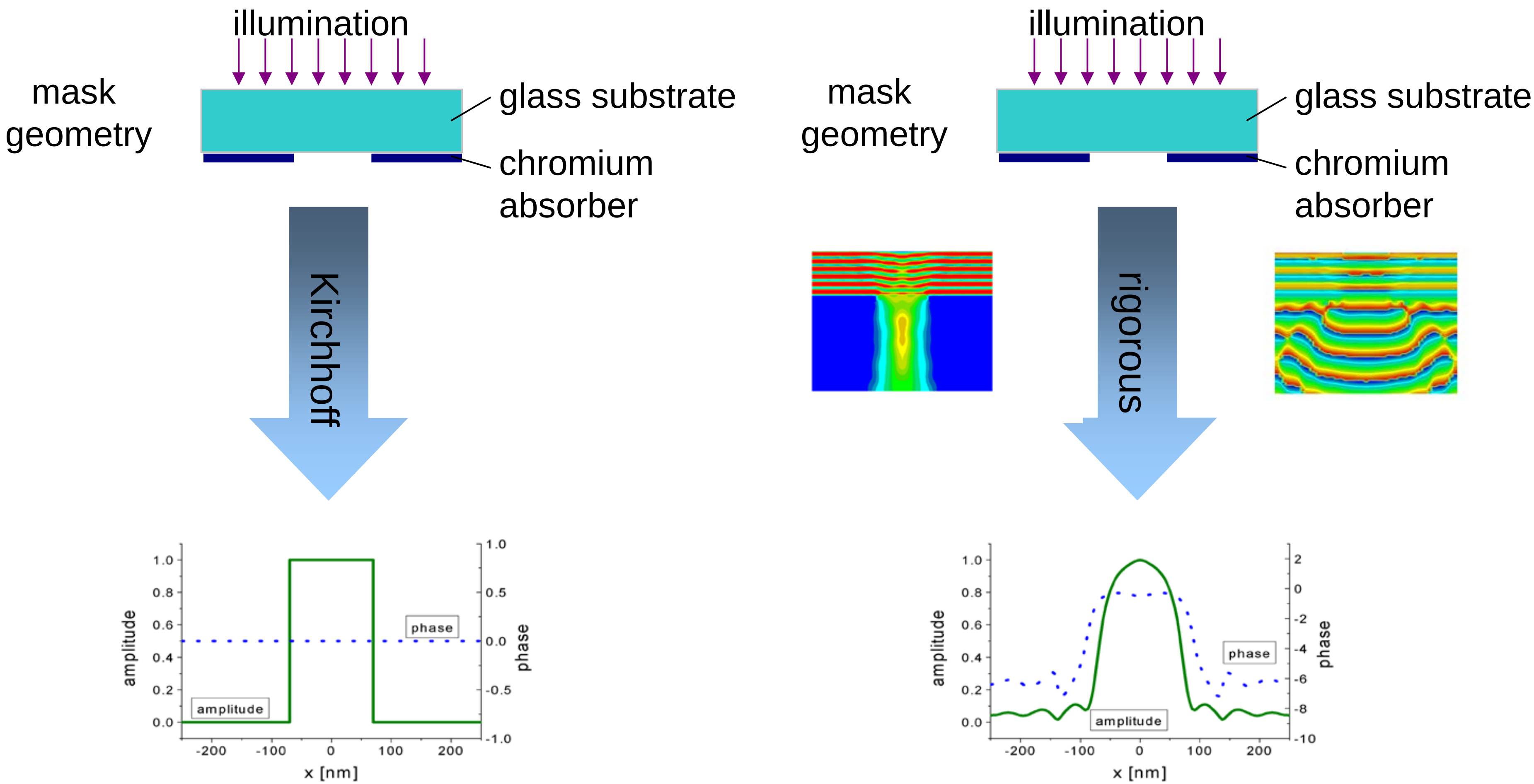
Lithography Simulation

Fraunhofer IISB

Outline

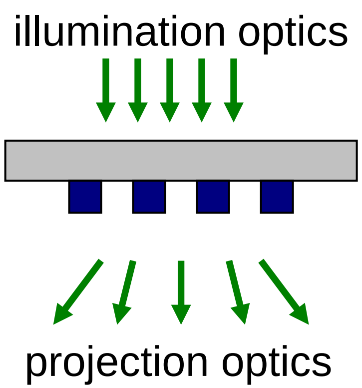
- Introduction
- Mask 3D effects in EUV
  - Feature orientation and shadowing
  - Contrast fading
  - Phase deformation and best focus shifts
  - Double images and absorber thickness swings
- Mitigation Strategies
  - Alternative mask stacks (etched multilayers, buried shifters, …)
  - Absorber material and thickness
  - Asymmetric illumination
- Outlook at larger NA systems
- Conclusions and outlook

Introduction: Mask Models for Lithography



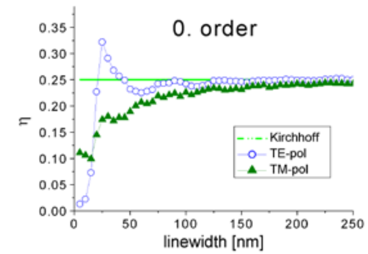
- ➢ rigorous mask models required to describe state-of-the-art lithography

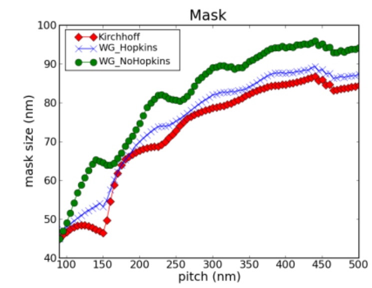
Introduction: 3D Mask Effects in DUV Lithography



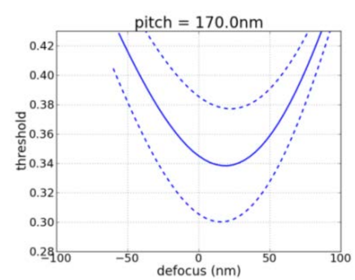
- transmissive
- absorber features are small and thin compared to wavelength
- large contrast of optical properties (n/k)
- symmetric illumination

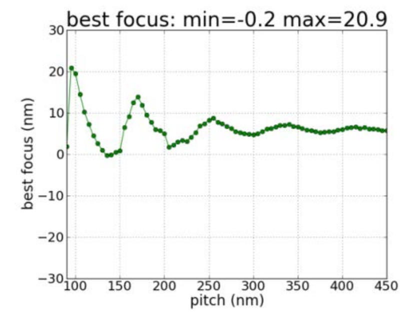
➢ significant impact on OPC and polarization performance



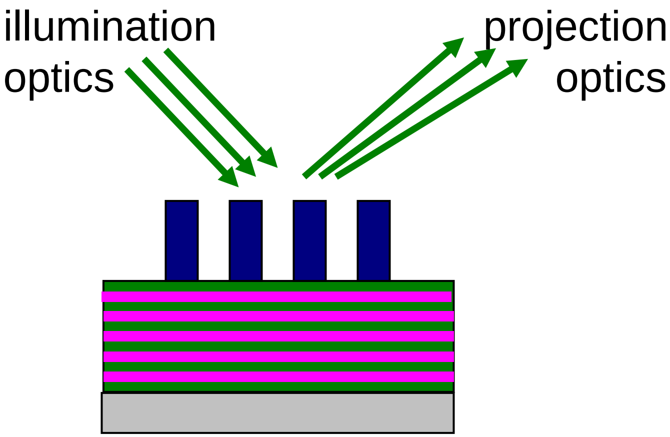


➢ mask-induced best focus shifts and aberration like effects





Introduction: Peculiarities of EUV Masks



- reflective
- absorber thick compared to wavelength
- small contrast of n/k
- off-axis illumination
- multilayers

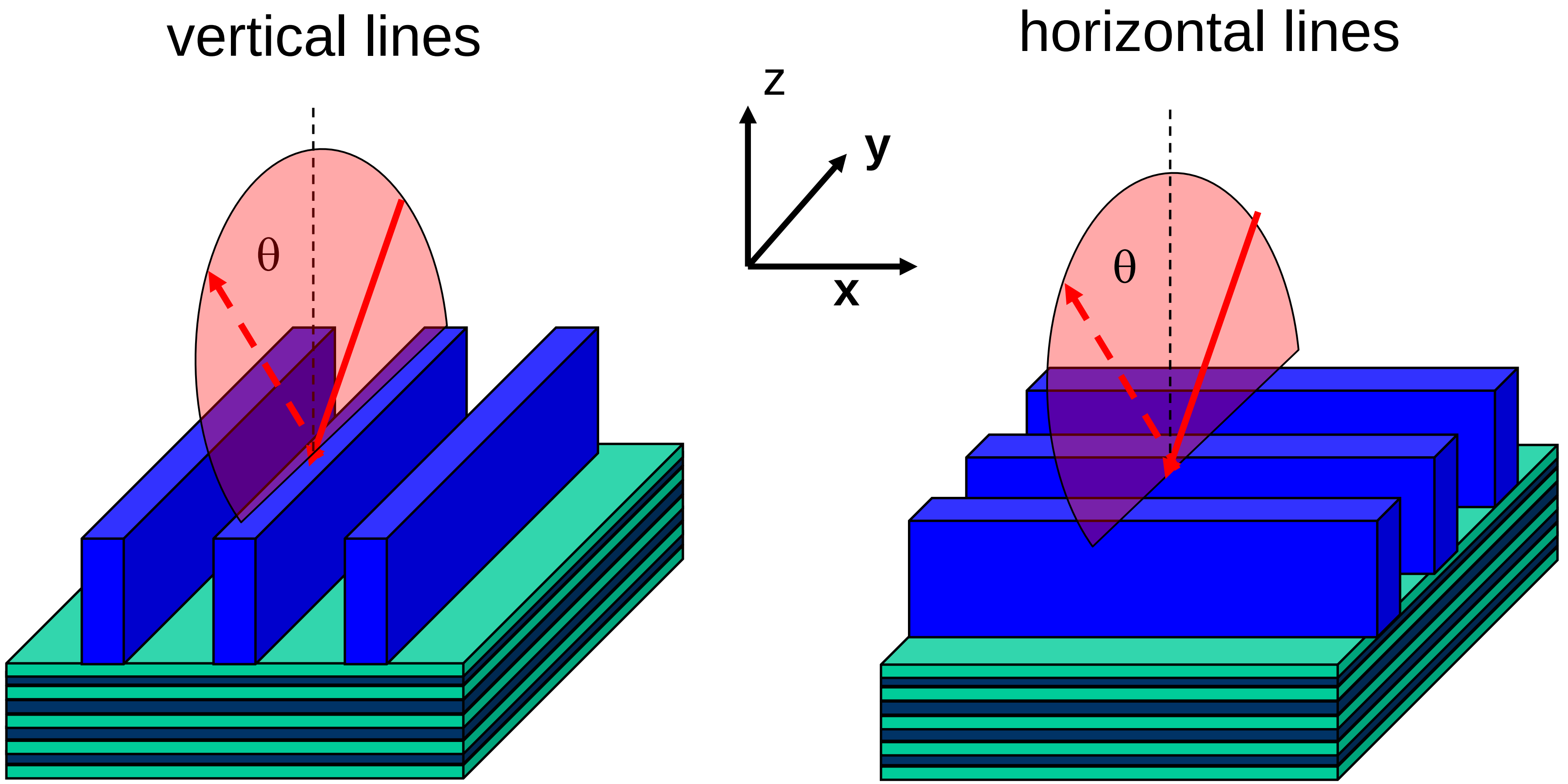
?

Outline

- Introduction
- Mask 3D effects in EUV
  - Feature orientation and shadowing
  - Contrast fading
  - Phase deformation and best focus shifts
  - Double images and absorber thickness swings
- Mitigation Strategies
  - Alternative mask stacks (etched multilayers, buried shifters, …)
  - Absorber material and thickness
  - Asymmetric illumination
- Outlook at larger NA systems
- Conclusions and outlook

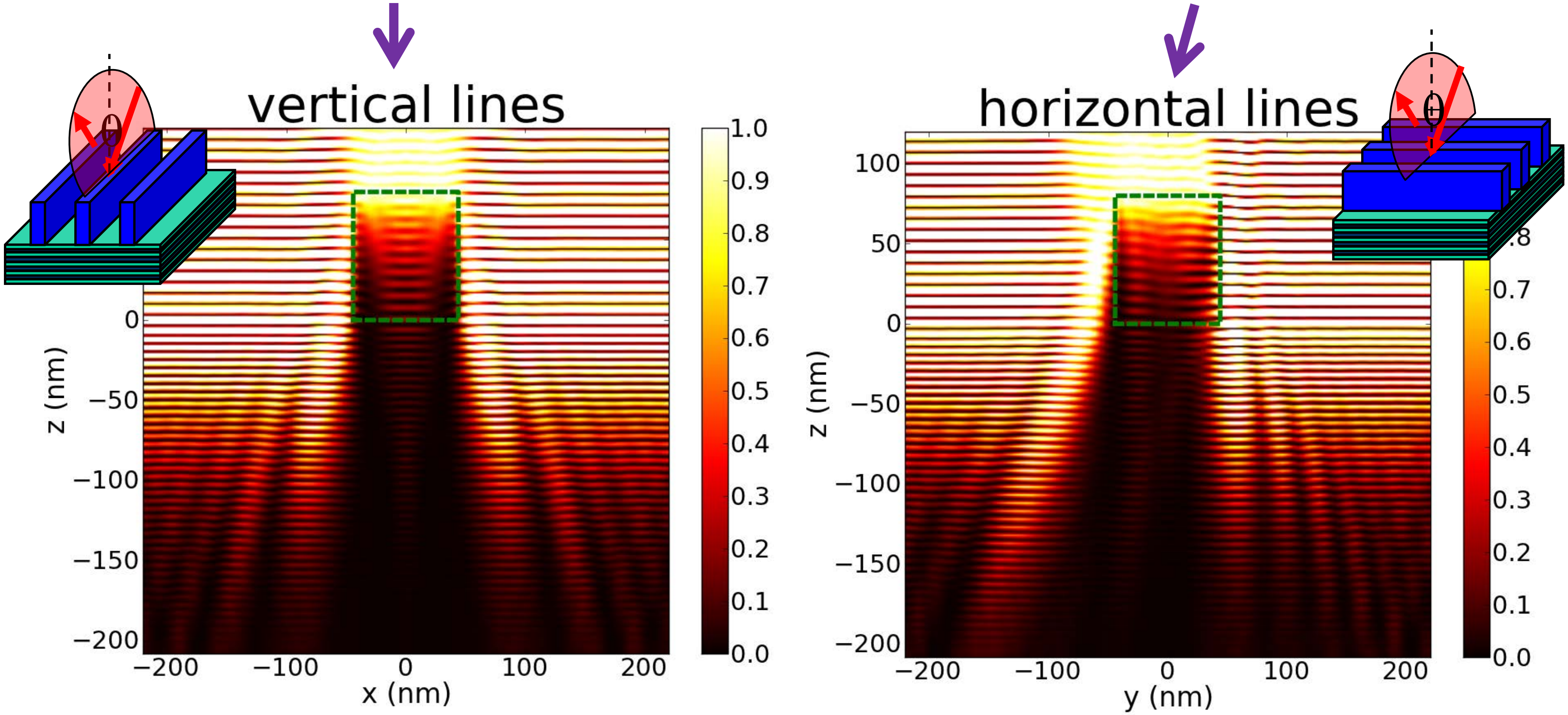
Feature Orientation & Shadowing

Naming conventions



Feature Orientation & Shadowing

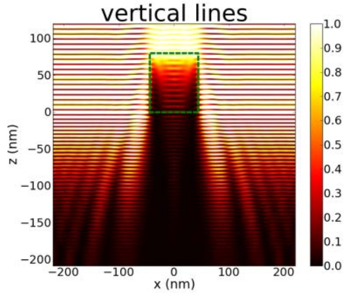
Near field plots

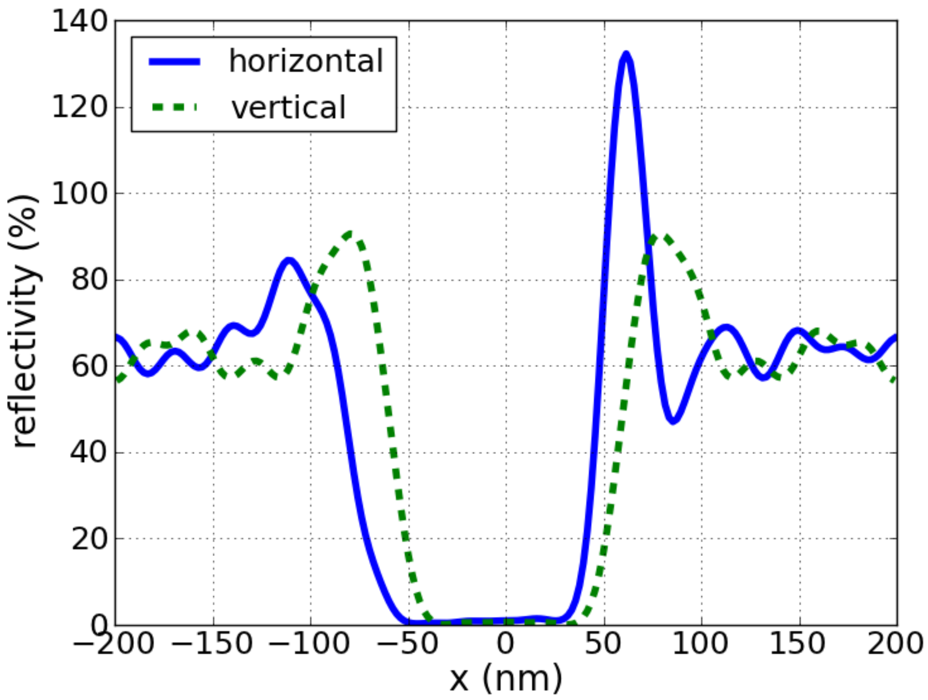


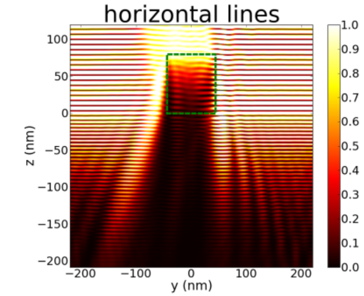
- intensity decays rapidly inside multilayer
- asymmetric shadowing for horizontal lines

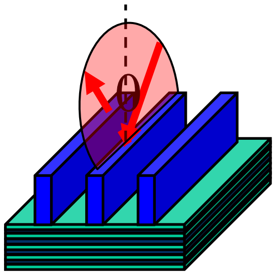
Feature Orientation & Shadowing

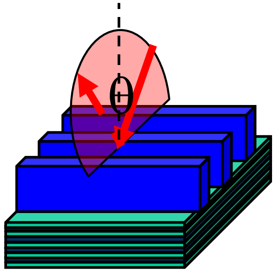
Reflected near fields







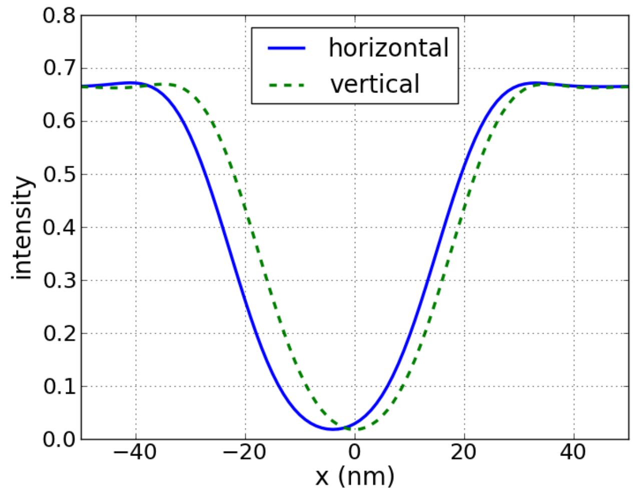


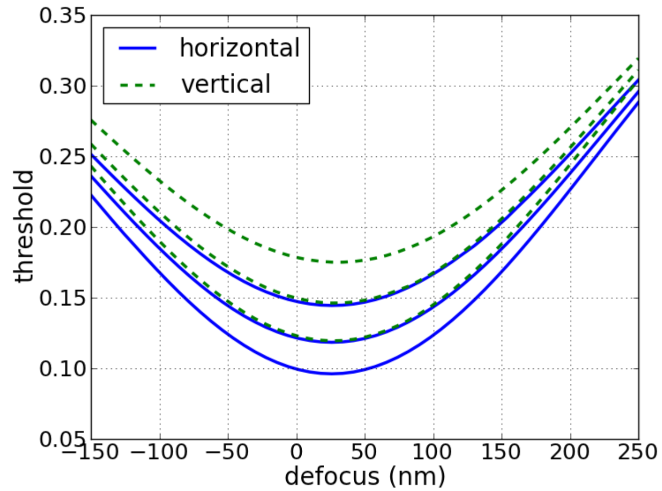


- ➢ asymmetric shadowing for horizontal lines

Feature Orientation & Shadowing

Aerial images & process windows



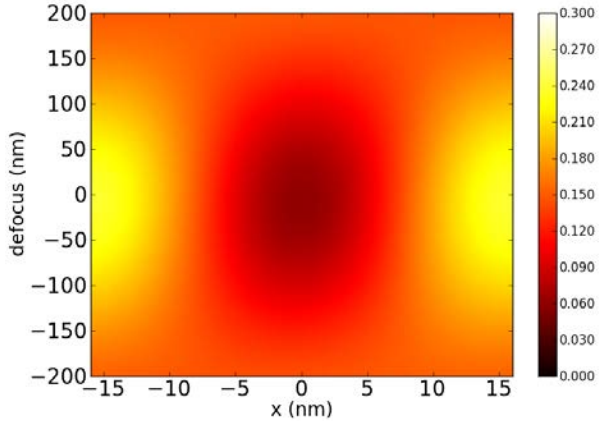


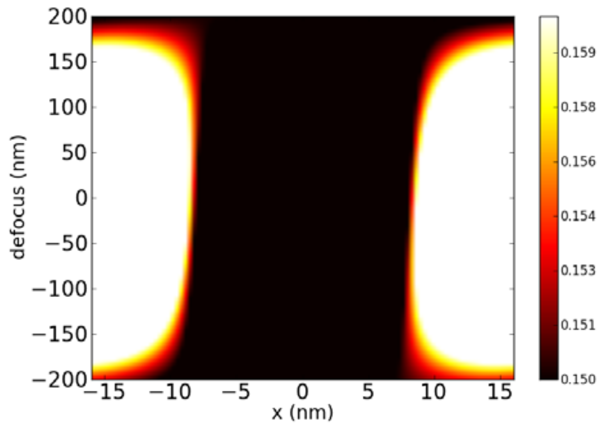
- position shift for horizontal lines
  → can be compensated by vertical shift of the mask or by OPC
- shift of process windows along threshold/dose axis
  → can be compensated by OPC
- these effects depend on illumination, slit position, feature size/pitch!

Feature Orientation & Shadowing

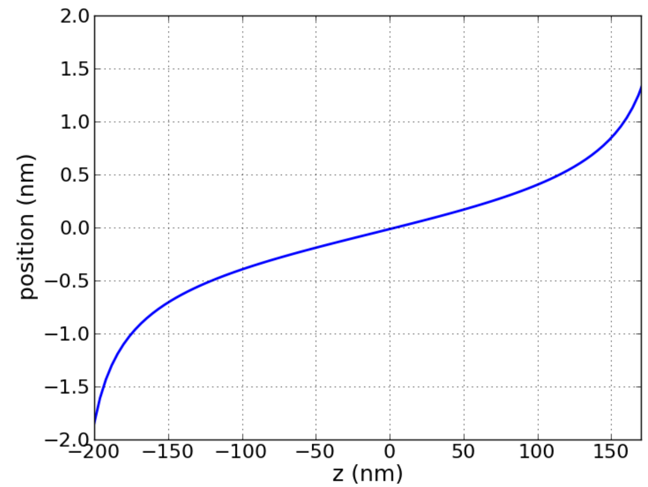
Imaging versus focus: Telecentricity effects

extraction of "footprint"





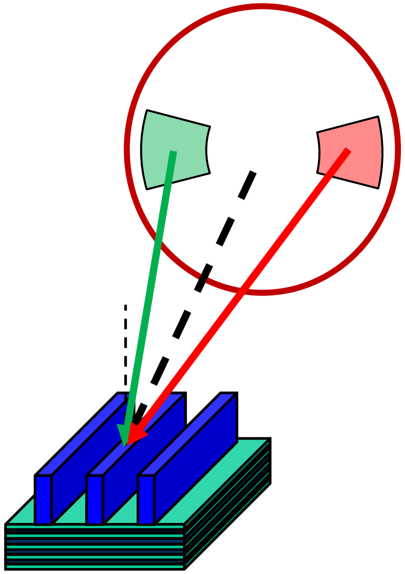
feature position versus focus

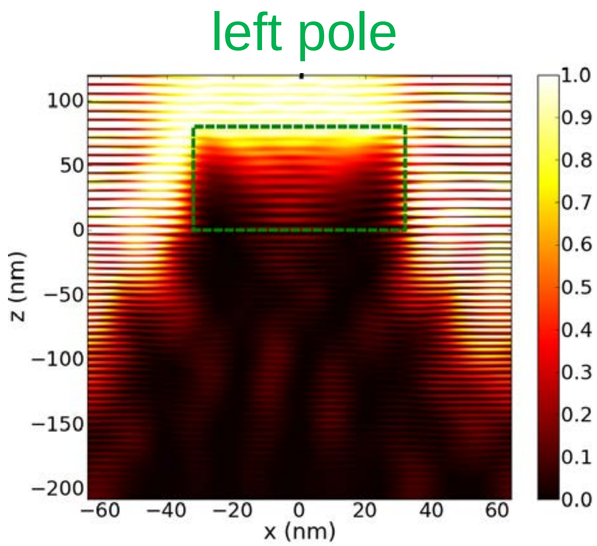


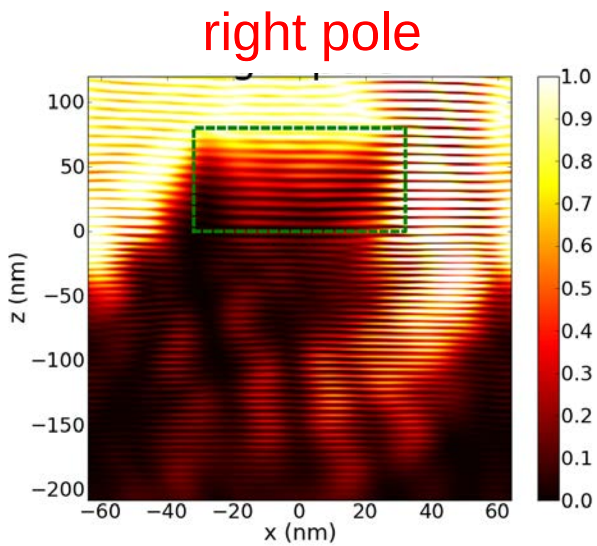
- horizontal features experience telecentricity errors of several nm/micrometer (mrad)

Contrast Fading

Variation of illumination direction over illumination pupil







- right pole experiences more pronounced shadowing

Contrast Fading

Through focus images of a horizontal dense line for a dipole

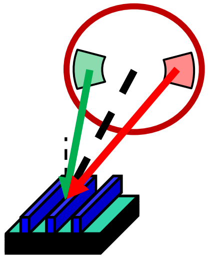


image right pole

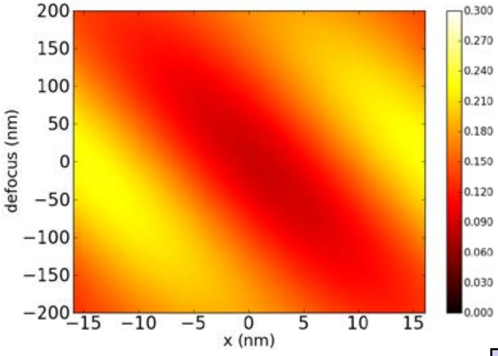


image left pole

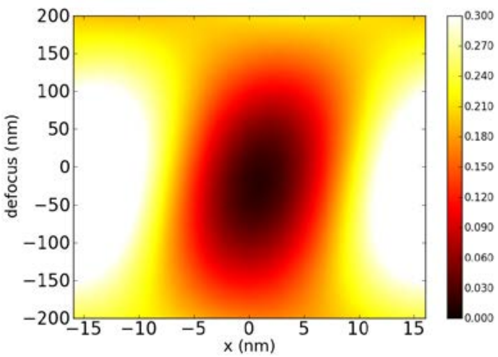
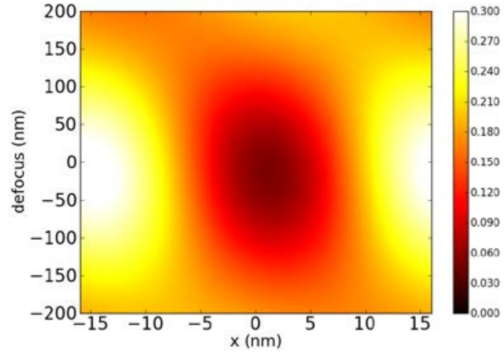
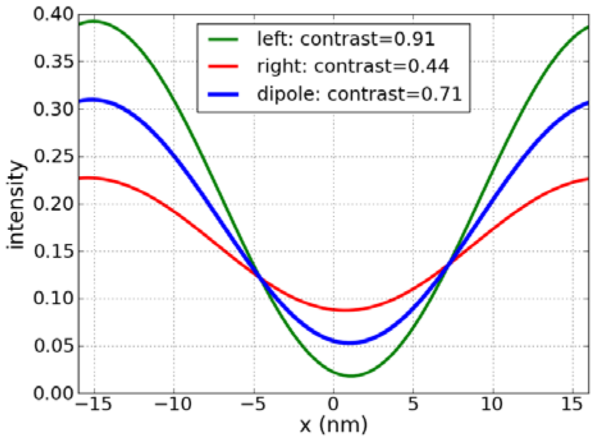


image dipole



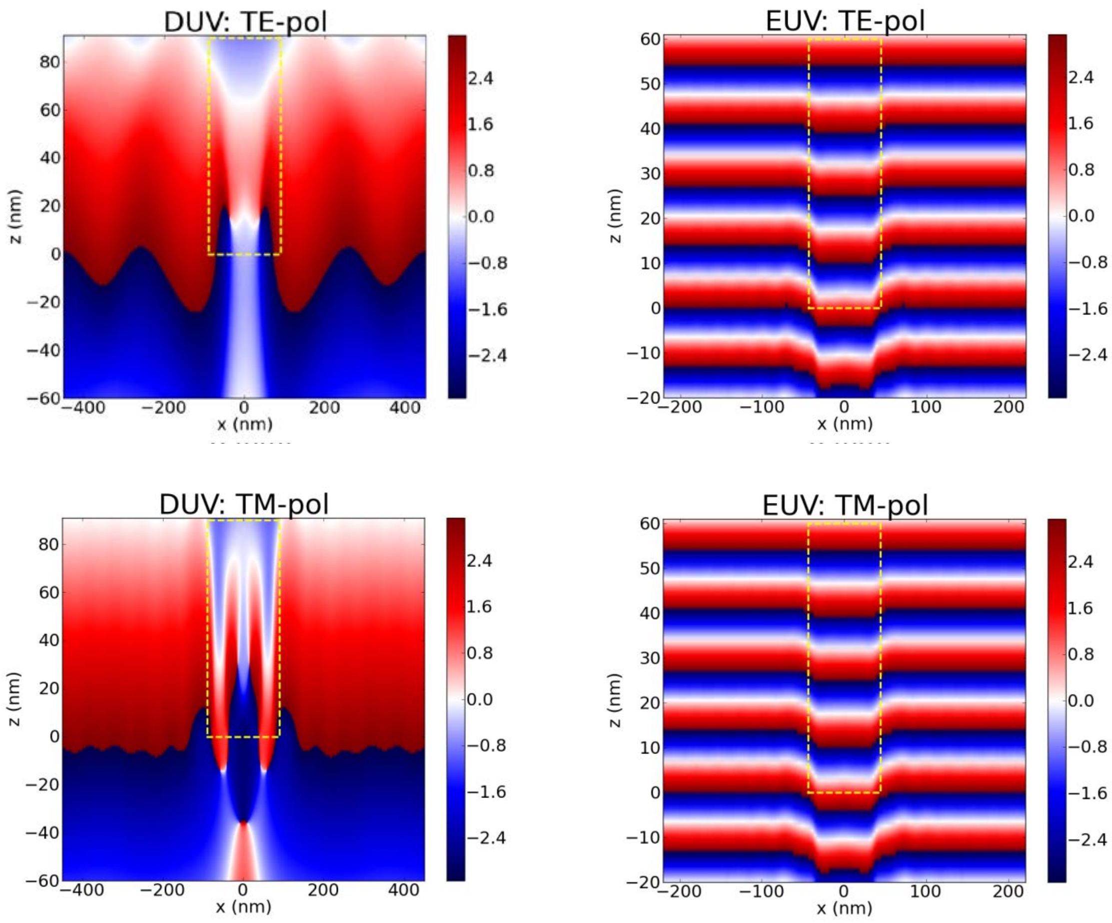
cross sections



- ➢ significant contrast loss

Phase Deformation & Best-focus Shifts

Light transmission through chromium absorbers

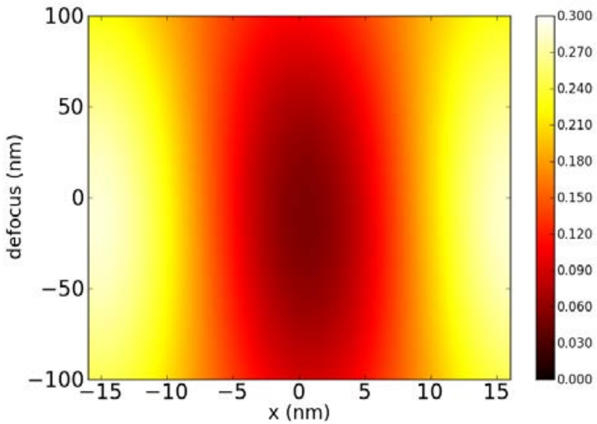


- DUV: 4×45nm wide 90nm thick absorber
- EUV: 4×16nm wide 60nm thick absorber
- Phase deformation for DUV and EUV
- Impact of polarization for DUV only

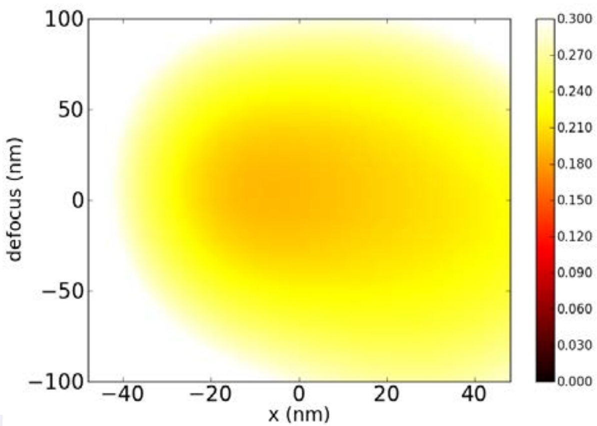
Phase Deformation & Best-focus Shifts

Through focus images of horizontal lines

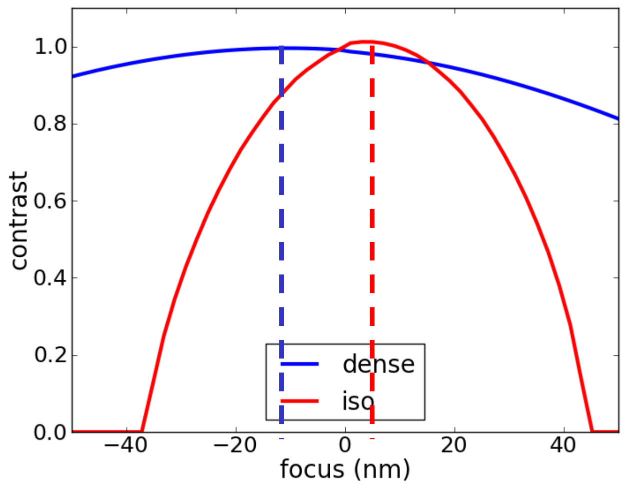
dense



iso



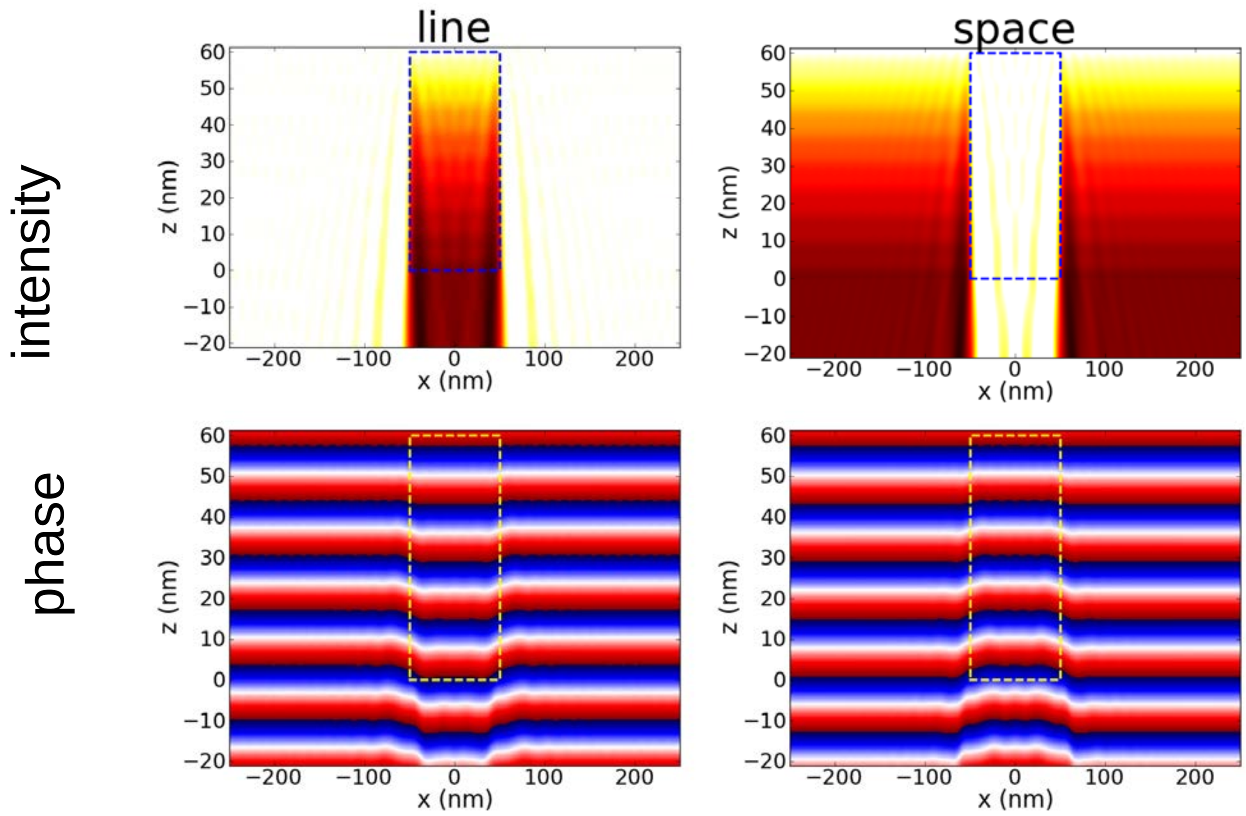
Local contrast versus focus



- significant best focus shift between iso and dense

Phase Deformation & Best-focus Shifts

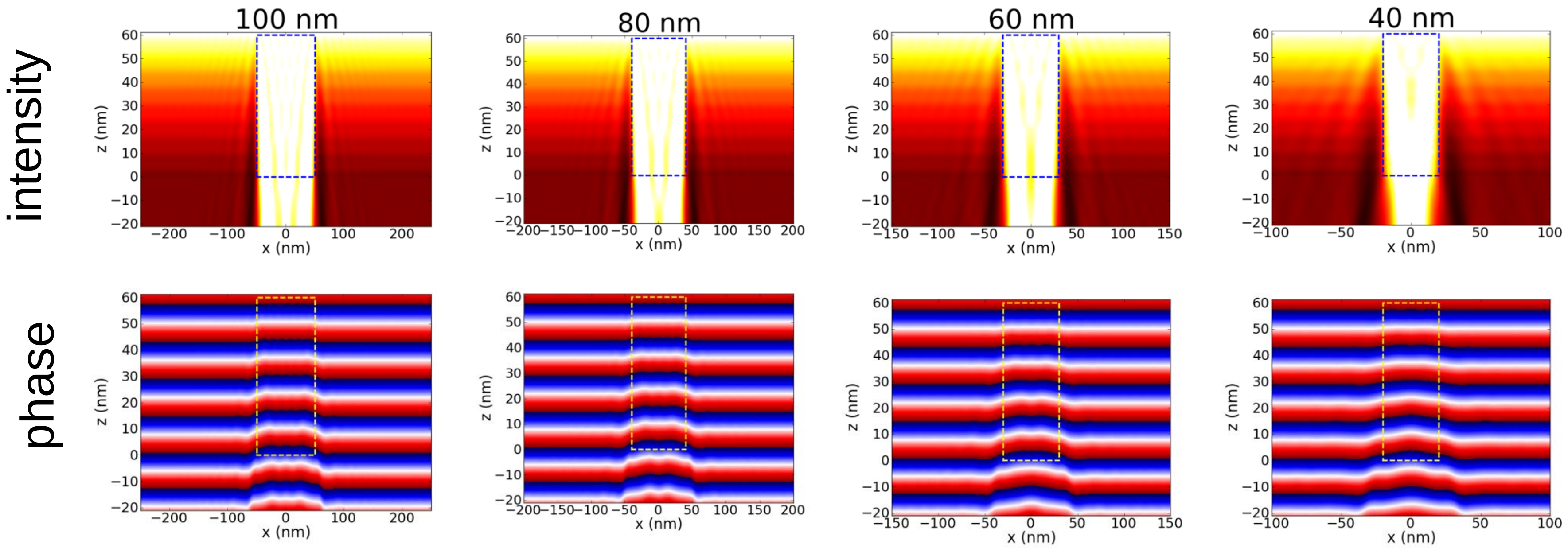
Impact of feature tone



- dark and bright features experience opposite phase deformation and best focus shifts

Phase Deformation & Best-focus Shifts

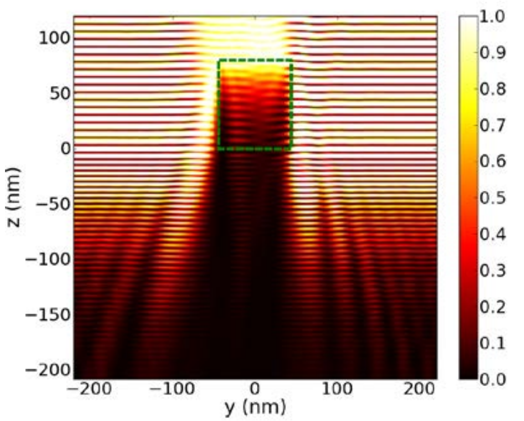
Impact of feature size: Spaces



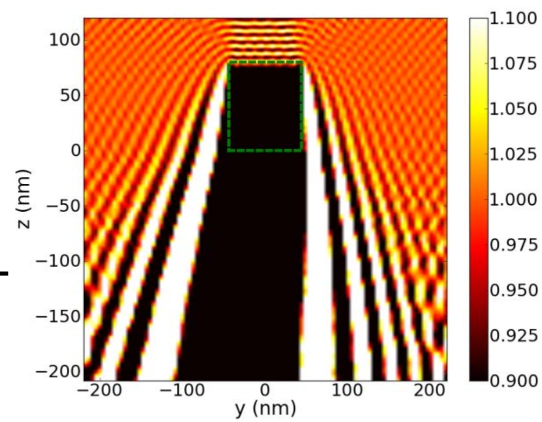
- ➢ larger features experience more phase deformation
- ➢ how about impact on 8× direction in anamorphic systems?

Near field plots with/without multilayer

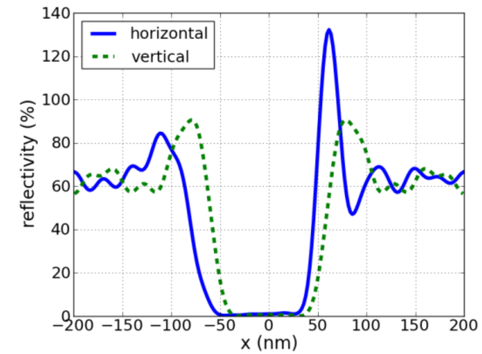
with ML

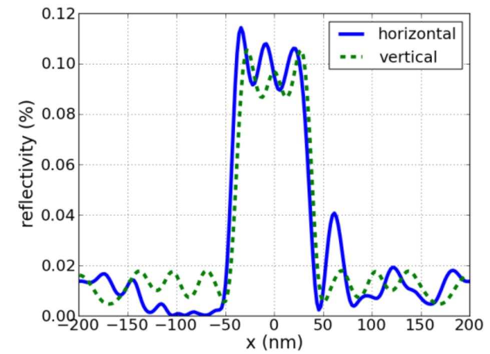


without ML



reflected light



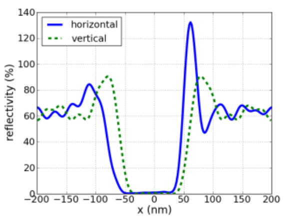


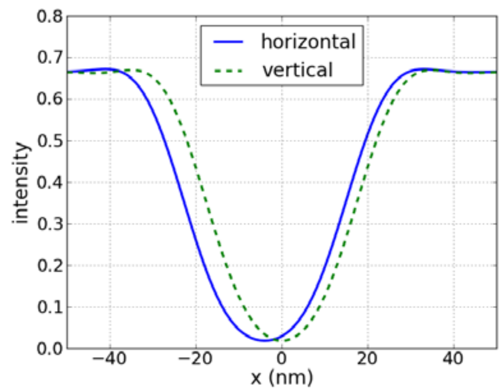
"Double Images" and Absorber Thickness Swings

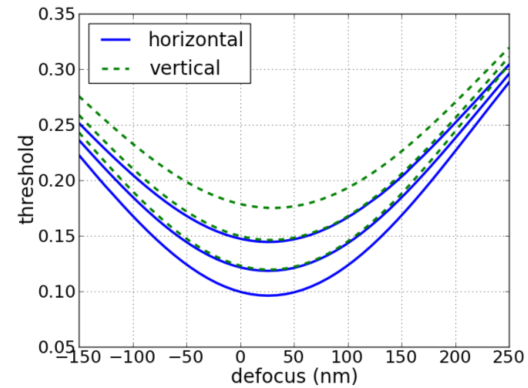
image cross section

process window

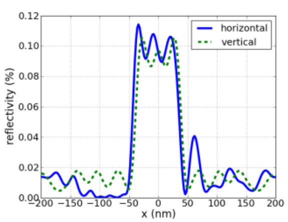
with multilayer

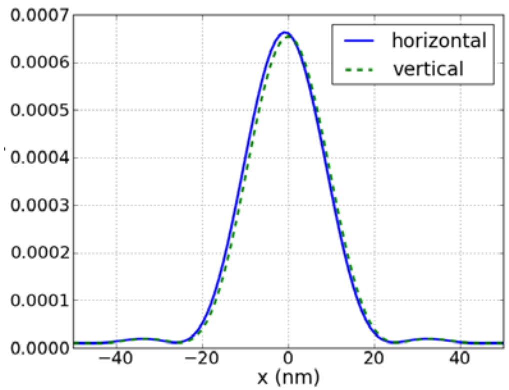


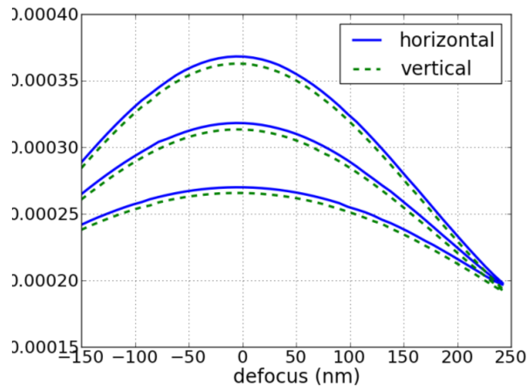




without multilayer



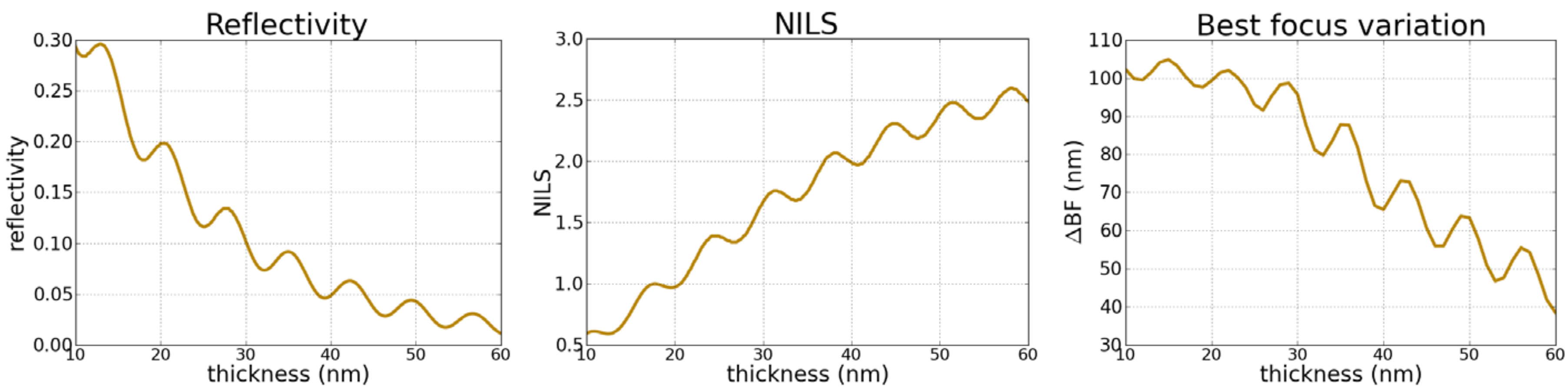




- ➢ top reflection causes contrast inverted image with shifted best focus

“Double Images” and Absorber Thickness Swings

Lithography metrics versus thickness



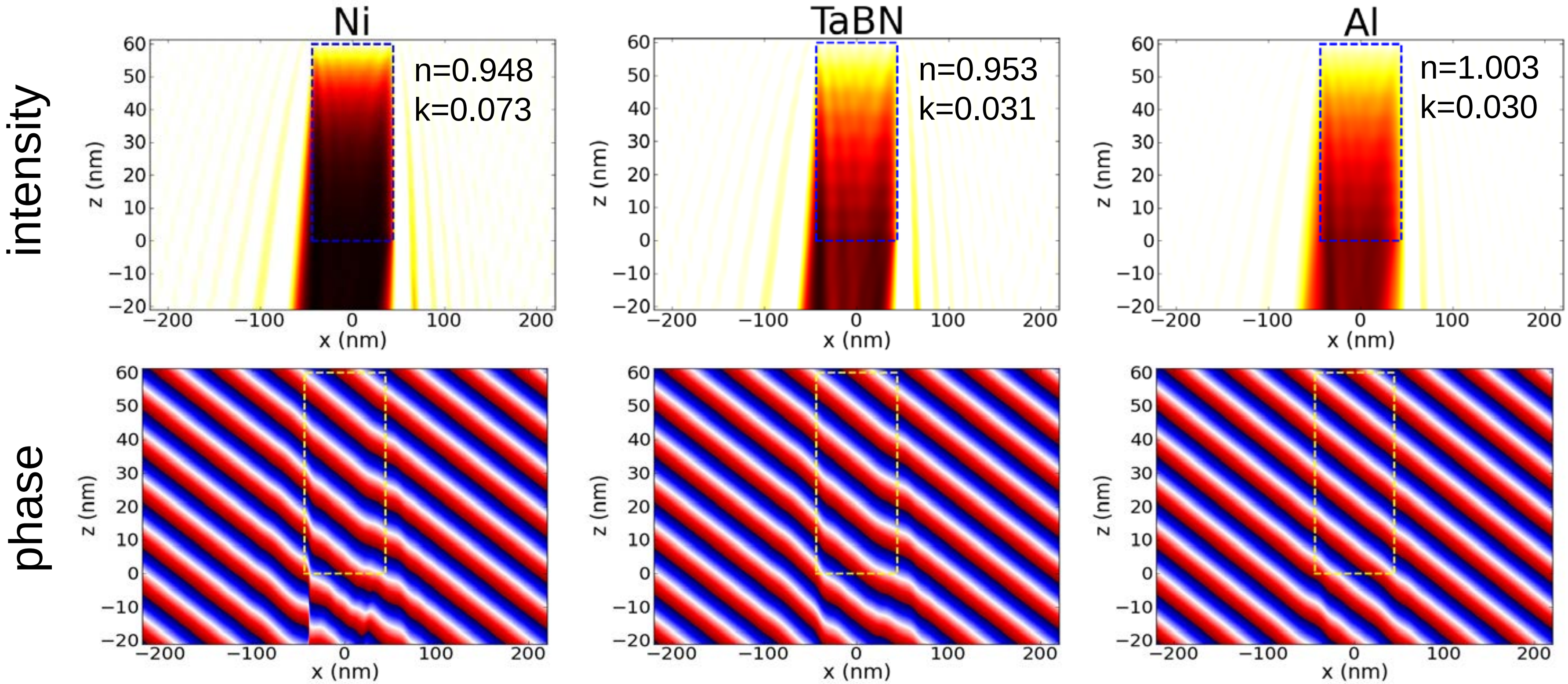
- coherent superposition of images causes swing of litho-metrics versus absorber thickness

Outline

- Introduction
- Mask 3D effects in EUV
  - Feature orientation and shadowing
  - Contrast fading
  - Phase deformation and best focus shifts
  - Double images and absorber thickness swings
- Mitigation Strategies
  - Alternative mask stacks (etched multilayers, buried shifters, …)
  - Absorber material and thickness
  - Asymmetric illumination
- Outlook at larger NA systems
- Conclusions and outlook

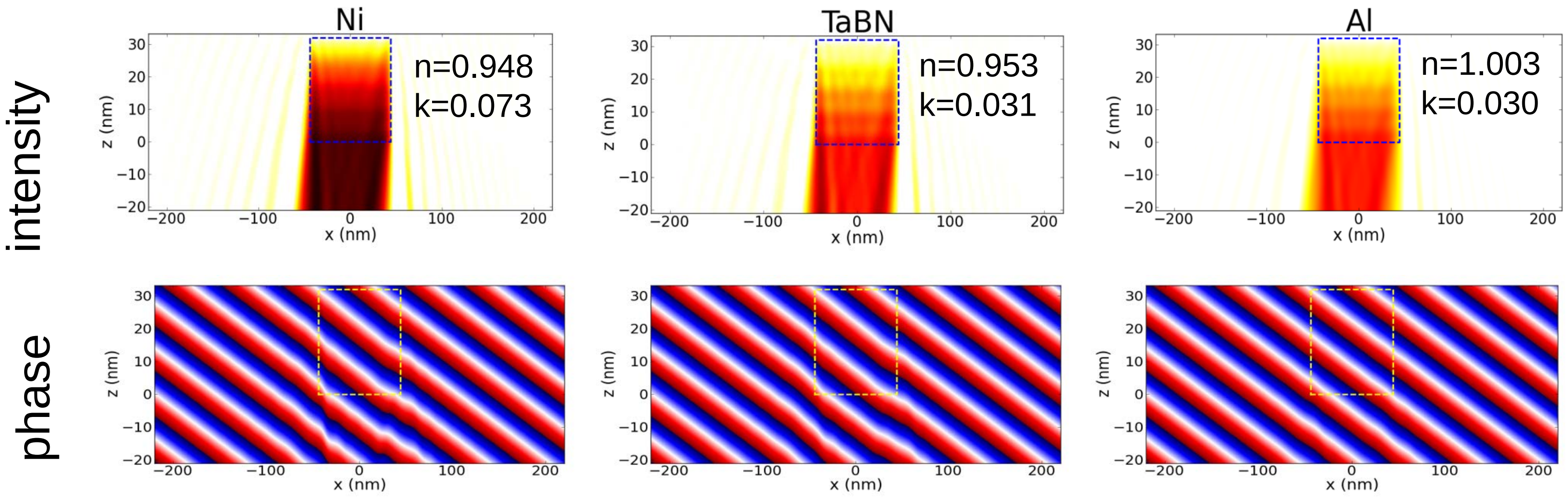
Absorber Material & Height

Near field plots without multilayer



- reduction of phase deformation for Al (n~1.0)

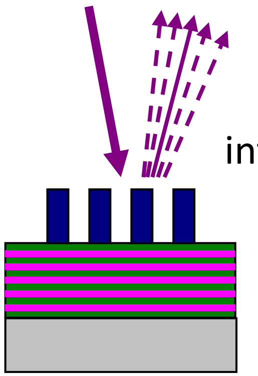
Near field plots for reduced absorber thickness



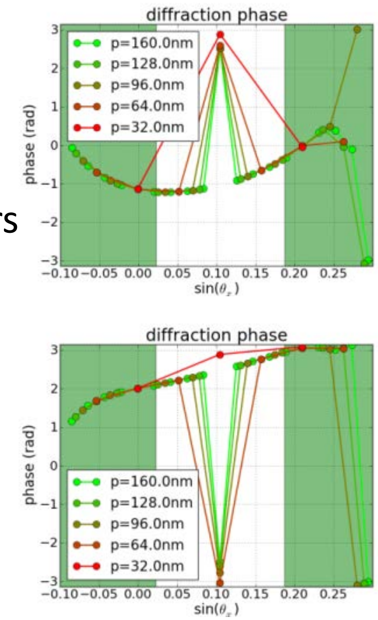
- larger extinction materials, such as Ni enable thinner absorber with high contrast and small phase deformation
- thinner TaBN and Al suffer from pronounced contrast loss

Absorber Material & Height

Material characterization by mask diffraction analysis



extraction of phase (and intensity) of orders



quantification of virtual wavefront by Zernikes and offsets

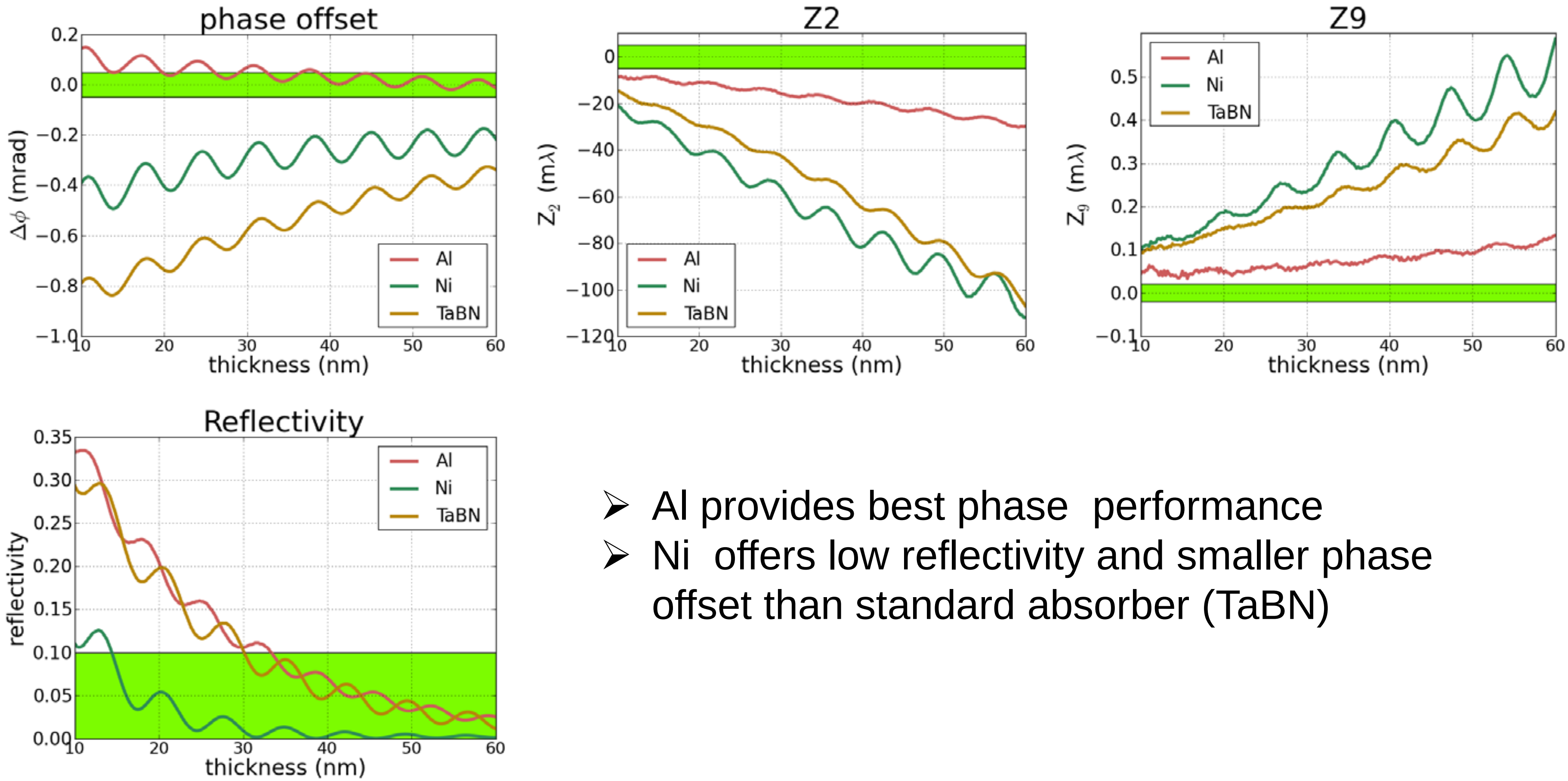
aberration type	Z (in mλ)
x-tilt	74
defocus	100
first order ast.	-155
x-coma	-32
spherical	13
sec. order ast.	-31

see: A.Erdmann et al., J. Micro/Nanolith. MEMS MOEMS, 15 (2016), 021205.

- mask absorber induced deformation of the wavefront can be characterized by few numbers

Absorber Material & Height

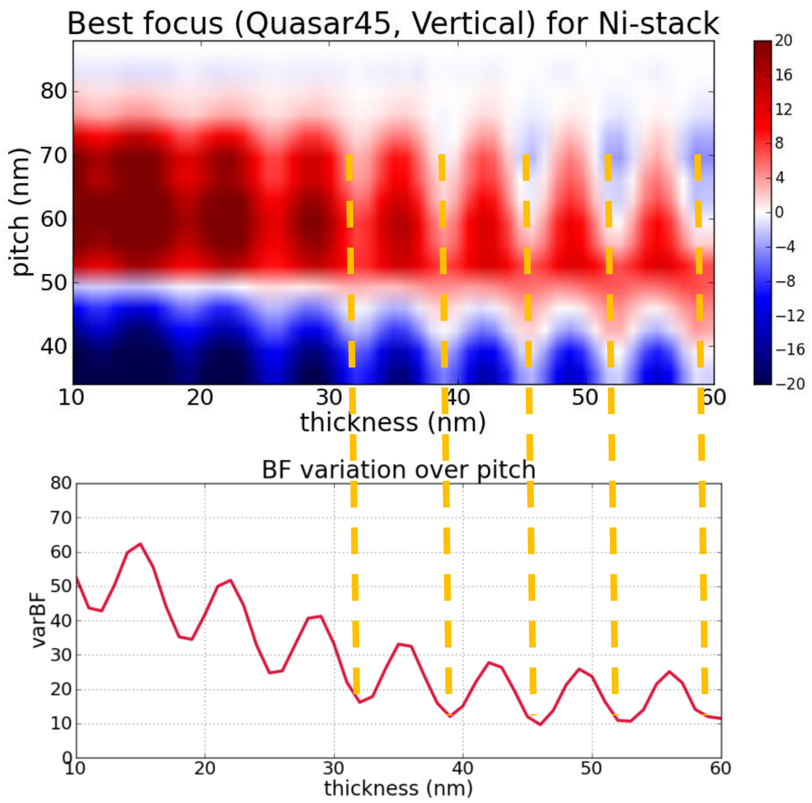
Material characterization by mask diffraction analysis



- Al provides best phase performance
- Ni offers low reflectivity and smaller phase offset than standard absorber (TaBN)

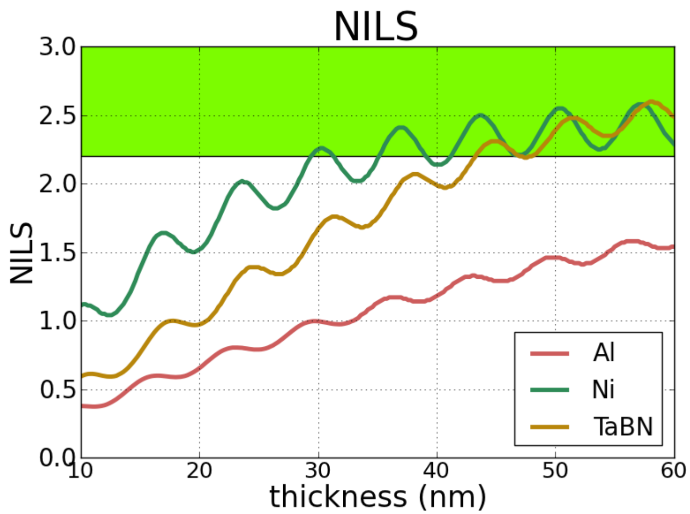
Material characterization by image analysis

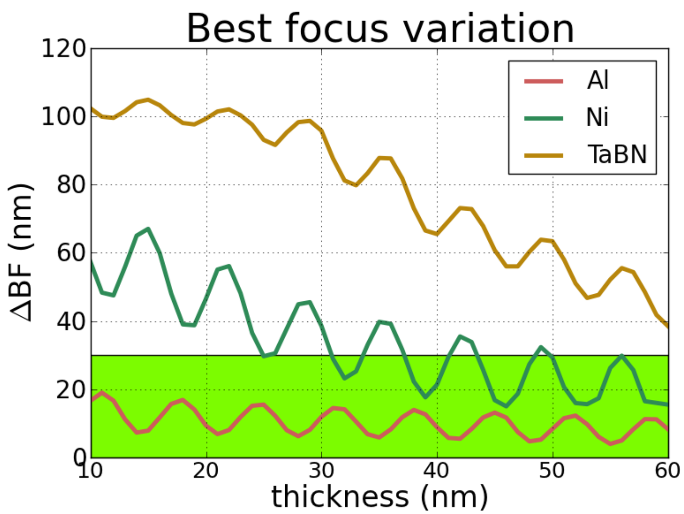
- computation of best focus (BF) versus pitch and absorber thickness
- extraction of range of BF variation versus absorber thickness
- resulting swing-behavior can be correlated with swing-behavior of reflectivity & Zernikes
- identification of optimum absorber thickness for given material properties
- characteristic curves depend also from illumination shape



Absorber Material & Height

Material characterization by image analysis for Dipole



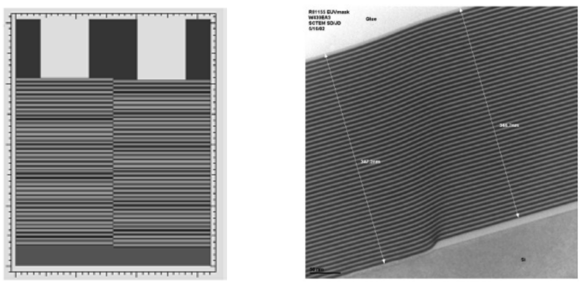


- Ni and Al can reduce best focus shift over the complete pitch range from 32nm-100nm to 20nm
- Al suffers from poor NILS
- selection of thickness is important to reduce BF-shift
- see presentation of Vicky Philipsen (imec) for further details

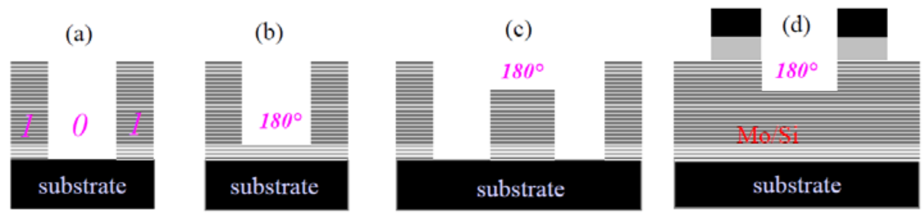
Alternative (Etched) Mask Stacks

Selected proposals from literature

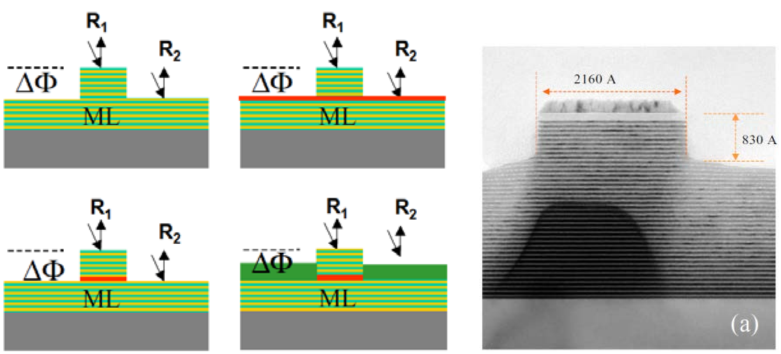
*P.Y. Yan, Proc. SPIE, **2002**, 4889, 1099*



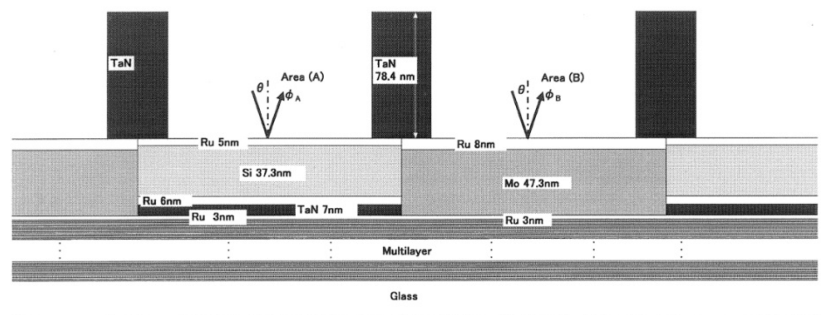
*Y. Deng, B. Fontaine, H. Levinson, A. Neureuther: Proc. SPIE, **2003**, 5037, 30*



S. Han, E. Weisbrod, Q. Xie, P. Mangat, S. Hector, W. Dauksher, W. J.: *Proc. SPIE,* **2003**, *5037*, 314



M. Sugawara, M., A. Chiba, I. Nishiyama: *Proc. SPIE,* **2003**, *5037*, 850



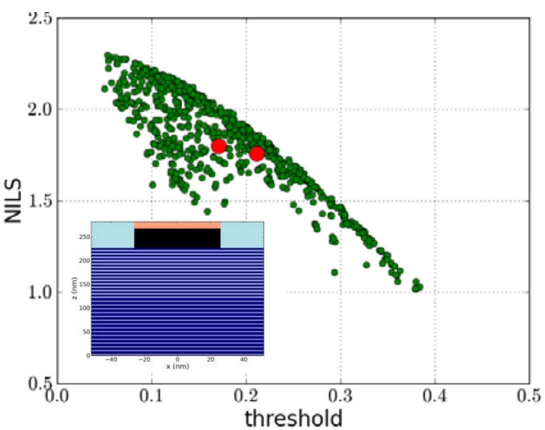
Alternative (Etched) Mask Stacks

Multi-objective optimization of alternative mask-stacks

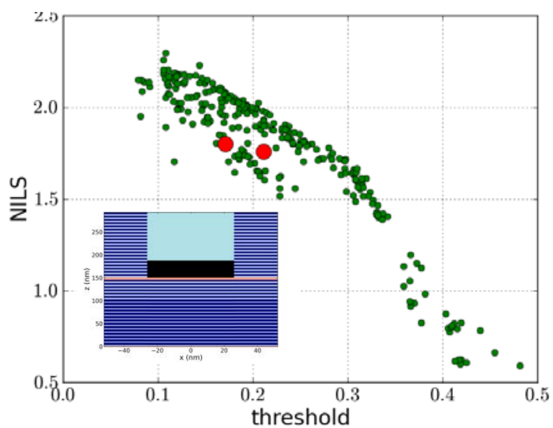
Objectives: max. NILS, max. reflectivity/threshold, min. telecentricity error, min best-focus variation through pitch

Variables: multilayer stack, absorber thickness, etch depth, mask bias

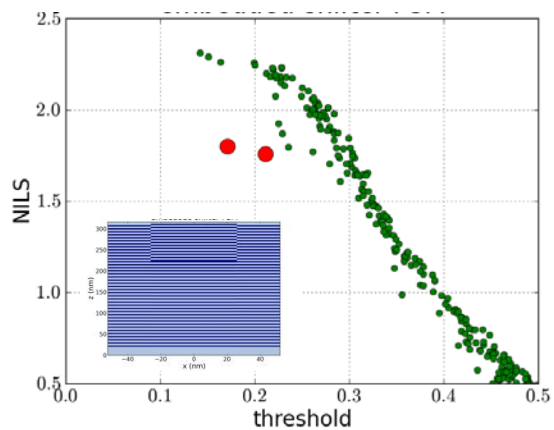
standard BIM



etched AttPSM



embedded shifter PSM

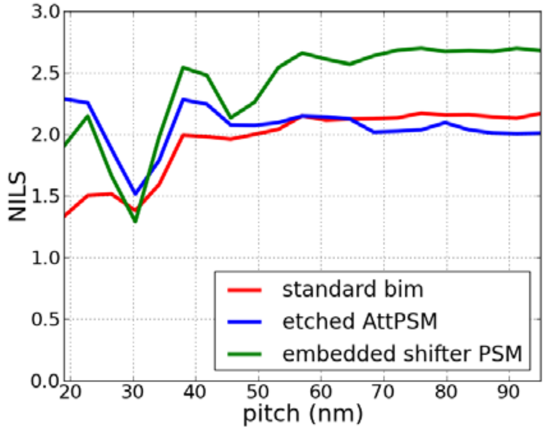


binary reference stacks from literature

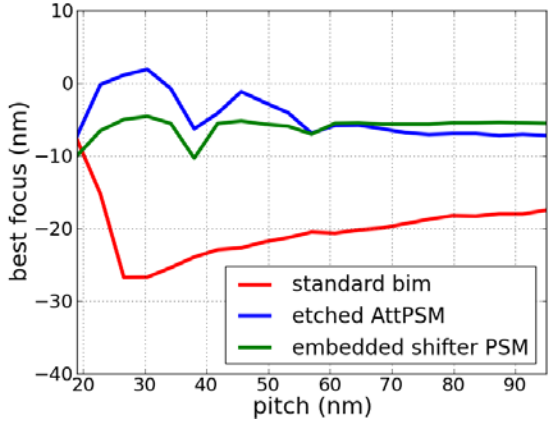
- etched and embedded PSM can provide a better compromise between high contrast and reflectivity/threshold

Imaging performance of optimized mask-stacks

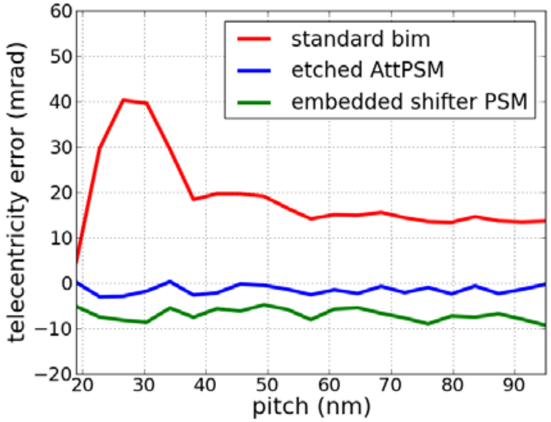
NILS



best focus



telecentricity error

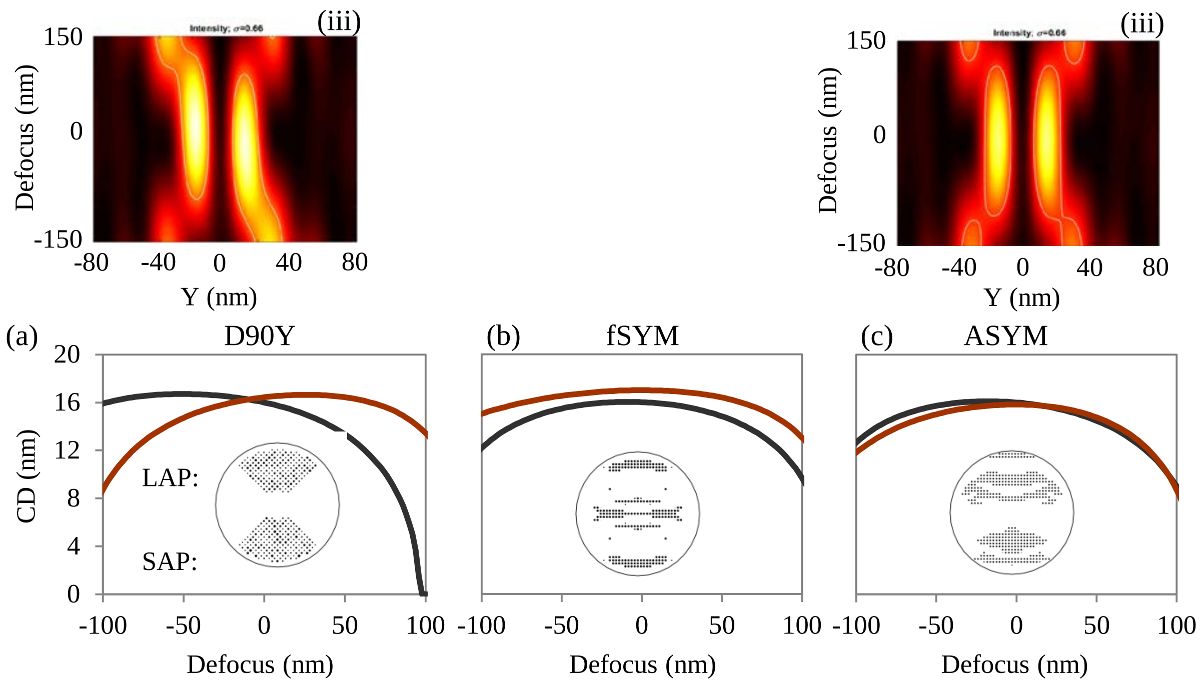


- etched AttPSM and embedded AttPSM can provide better imaging performance than standard binary masks
- not considered: mask making and inspection

A. Erdmann et. al: Proc SPIE 8679 (2013) 86791Q

Source Optimization

Application of asymmetric sources to balance diffraction orders and resulting best-focus and contrast of dark field two-bars

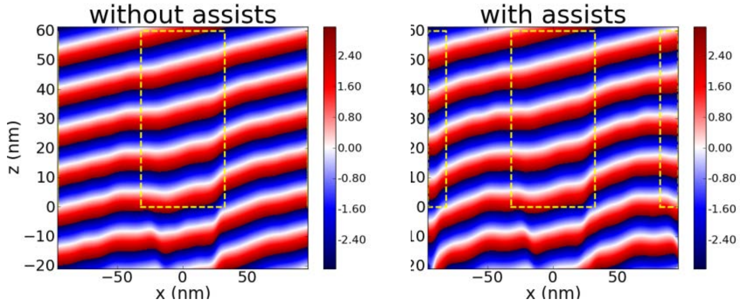


T. Last, L. de Winter,
P. van Adrichem,
J. Finders: EMLC 2016

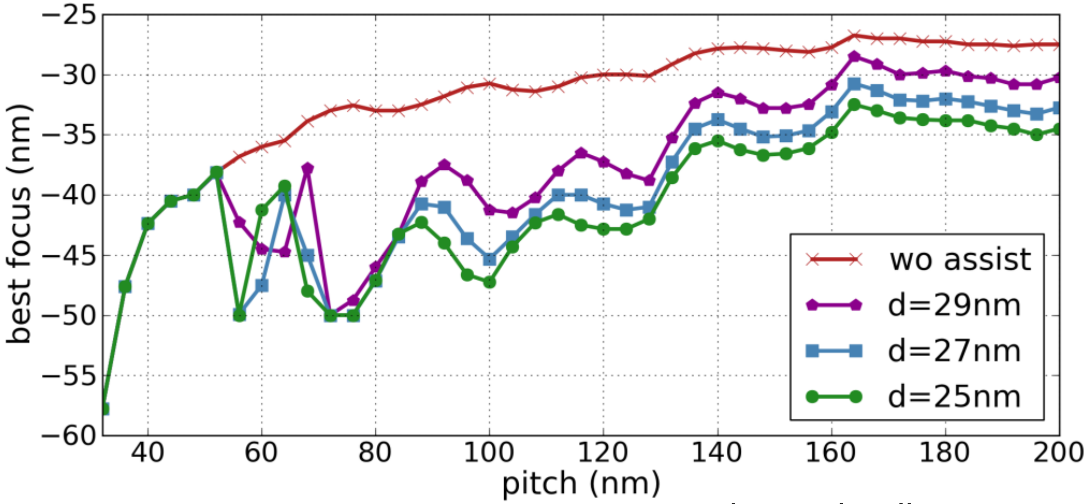
➢ see presentation of Lieve Van Look (imec) for detailed discussions

Impact of Assist Features

near field



best focus



d – assist distance

- optimized assist features mitigate best-focus shift versus pitch
- asymmetric assists provide an additional degree of freedom

- *M. Burkhardt et al.: Proc. SPIE, **2015**, 9422, 94220X*
- *S. Hsu et al.: Proc. SPIE, **2015**, 9422, 94221I*
- *I. Mochi et al.: Proc. SPIE, **2016**, 9776, 97761S-97761S-17*

Outline

- Introduction
- Mask 3D effects in EUV
  - Feature orientation and shadowing
  - Contrast fading
  - Phase deformation and best focus shifts
  - Double images and absorber thickness swings
- Mitigation Strategies
  - Alternative mask stacks (etched multilayers, buried shifters, …)
  - Absorber material and thickness
  - Asymmetric illumination
- **Outlook at larger NA systems**
- Conclusions and outlook

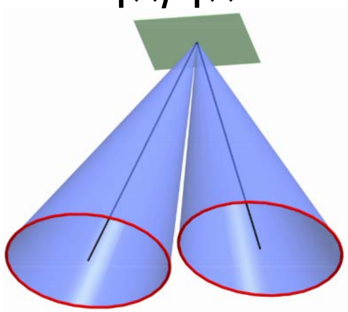
Larger NA Systems

Optical design options for NA > 0.33

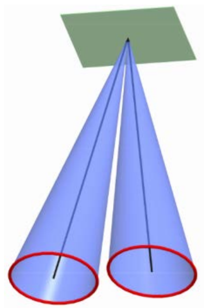
reticle-side angles

*S. Migura, B. Kneer, J. Neumann, W. Kaiser, J. van Schoot: Proc. SPIE, **2015**, 9661, 96610T*

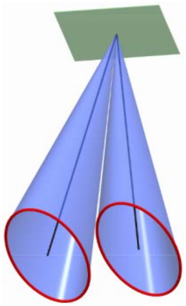
4×/4×



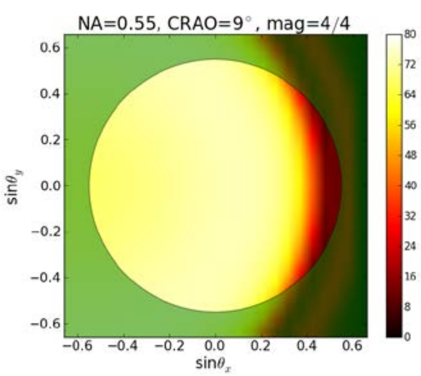
8×/8×

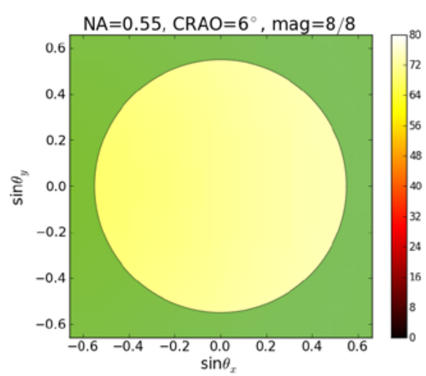


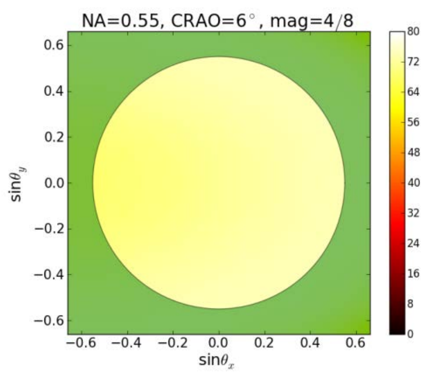
4×/8×



multilayer-reflectivity over range of incidence inside NA



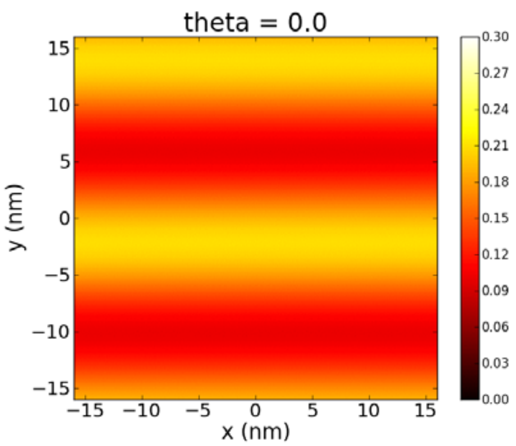




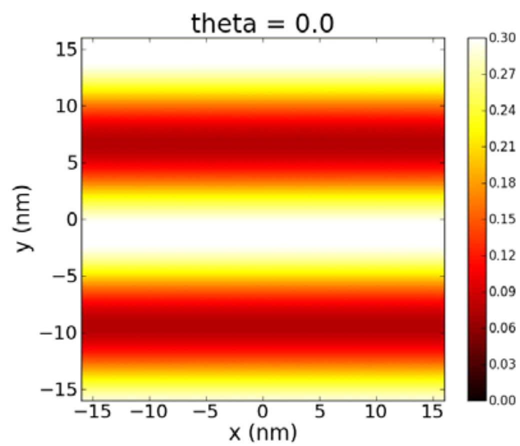
Larger NA Systems

Imaging of dense lines/spaces versus rotation angle

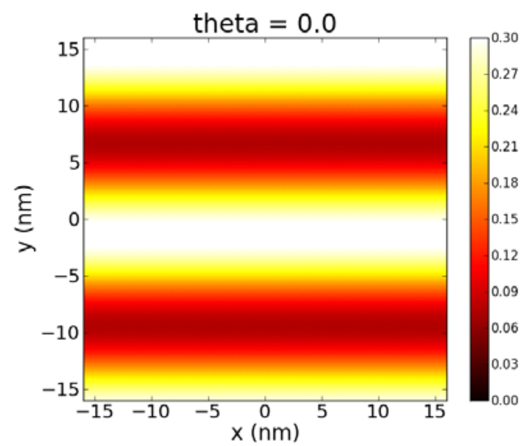
4×/4×



8×/8×



4×/8×



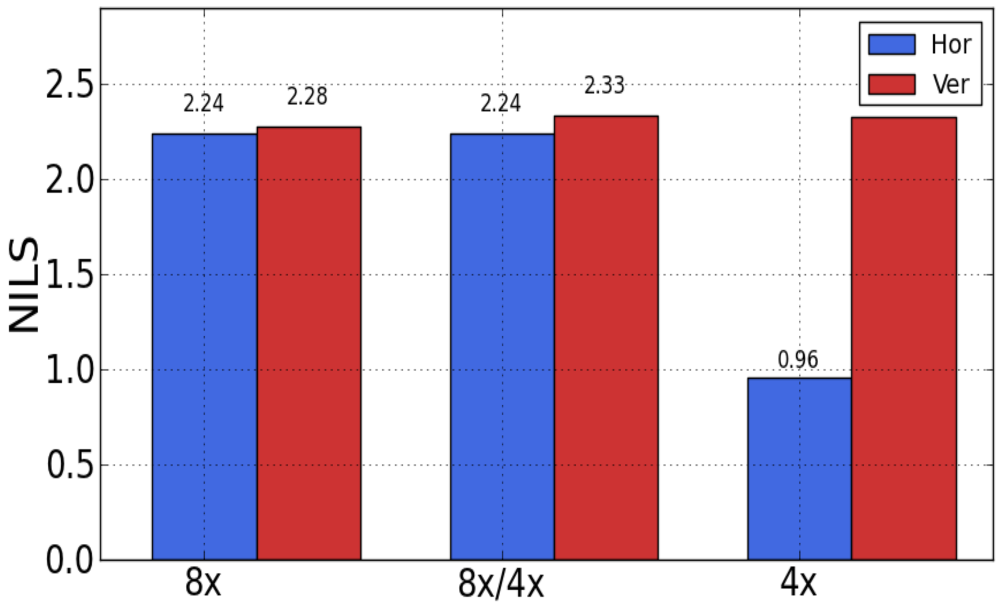
theta: azimuthal angle: 0° for vertical, 90° for horizontal

- significant contrast loss of hor. spaces for 4×/4×
- 4×/8× and 8×/8× show very similar performance

Larger NA Systems

Comparison of lithographic performance for design options

dense line/space patterns



illumination
- λ=13.5nm
- unpolarized
- CRAO: 9° / 6°
- Leafshape

pupil
- NA=0.52
- 20% central obscuration

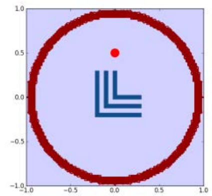
mask
- *8 nm lines/spaces*
- *stack: V. Philipsen et al.: Proc. SPIE, **2013**, 8886, 88860B*

➢ 4×/8× and 8×/8× show very similar performance

Larger NA Systems

Comparison of lithographic performance for design options

elbow patterns

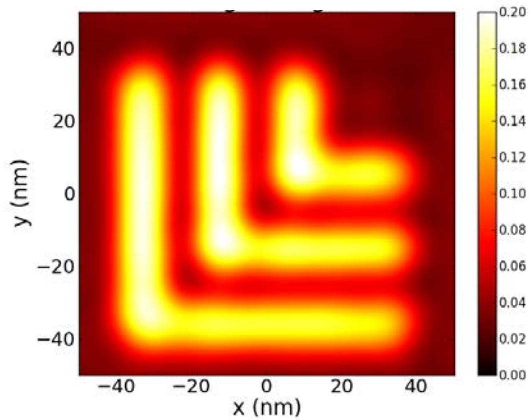


illumination
- λ=13.5nm
- unpolarized
- CRAO: 9° / 6°
- Annular

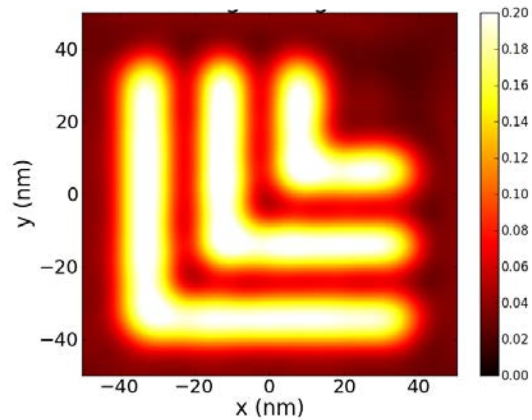
pupil
- NA=0.52
- 20% central obscuration

mask
- 10 nm spaces
- stack: *V. Philipsen et al.: Proc. SPIE, **2013**, 8886, 88860B*

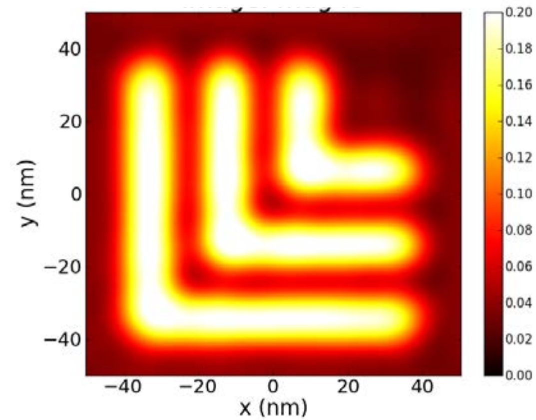
4×/4×



8×/8×



4×/8×



➢ 4×/8× and 8×/8× show very similar performance

Conclusions

- 3D mask effects need to be considered in the design of EUV systems, masks and OPC:
  - Orientation dependence: shadowing and contrast fading
  - Phase deformation: Focus shifts
  - “Double images”: absorber thickness swings
- Mitigation strategies
  - Illumination shapes and assists
  - Optimization of absorber material & height
  - Alternative (etched multilayer) stacks
- Anamorphic imaging systems enable larger NA systems with manageable 3D mask effects

Acknowledgements

- This project has received funding from the Electronic Component Systems for European Leadership Undertaking under grant agreement number 662338. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Netherlands, France, Belgium, Germany, Czech Republic, Austria, Hungary, Israel.

- Jens Timo Neumann and Paul Gräupner (Zeiss SMT) for their support and many technical discussions

- Thorsten Last (ASML) for sharing figures on the source impact

- All simulations were performed with the Fraunhofer IISB lithography simulator Dr.LiTHO