Benefits of Mask3D effects in high-NA and hyper-NA EUV lithography

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Fraunhofer-Institut für Integrierte Systeme und Bauelemente-technologie IISB

Dr. LiTHO Lithography Simulation

Can 3D masks outperform Kirchhoff-type masks?

SPIE Advanced Lithography 2025

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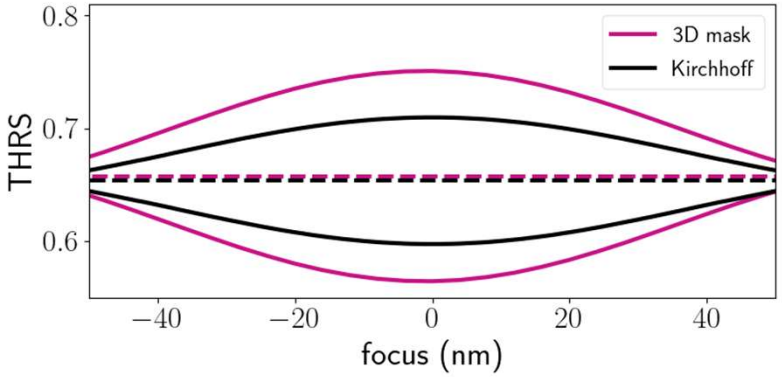
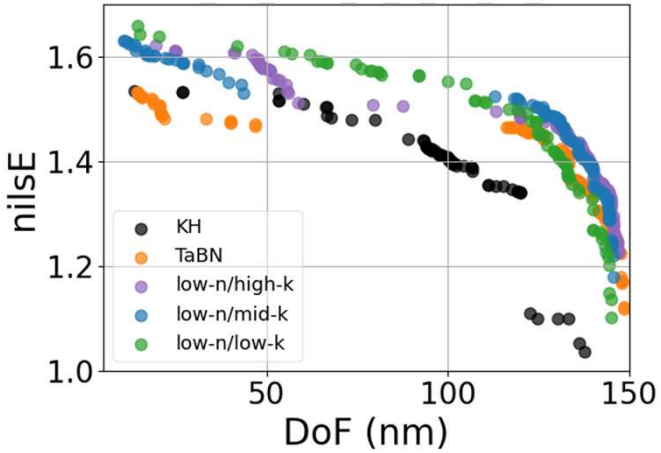
- **target: 4.5 nm** vertical L/S, **pitch = 9 nm**
- **NA = 0.85**, 4×/8×
- 3D mask: low-n/low-k
- polarized pencil dipole at telecentric setting



Today's presentation

- Ver L/S: **targets = 12/16 nm, pitches = 24/48 nm**
- **NA = 0.55**, 4×/8×
- 3D mask: different flavors
- unpolarized pencil dipole



DoF : depth of focus
KH: Kirchhoff
NILS : Normalized Image Log Slope
THRS : Threshold-to-size
nilsE : NILS Efficiency = NILS x $THRS^{½}$

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Key claims (this work, 2026)

- With rigorous SMO + Split-Pupil (SP), **3D masks outperform Kirchhoff** (KH) for vertical L/S at pitches 24/48 nm (NA=0.55), achieving higher nilsE at comparable or larger DoF.
- **Mechanism:** low-n absorbers guide light → **tighter near-field peaks + stronger coupling into in-NA** orders; SP offsets contrast loss by restoring telecentricity.
- **Bright-field masks** show weaker benefits due to **sidelobe constraints** under defocus.
- At **hyper-NA**, low-n/low-k 3D absorbers provide the largest gains; **with SP, optimal source becomes largely model-independent** (enables predictive source optimization using KH, then rigorous refinement).

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Outline

- Introduction: Kirchhoff and (rigorous) 3D mask models
- Optimization of achievable performance of Kirchhoff and 3D mask for a specific double-pitch use case
- Exploration of root causes by analysis of near field, far fields and images
- What happens for other mask materials, pitch combinations, feature orientations, tonalities and NAs?
- Conclusions and outlook

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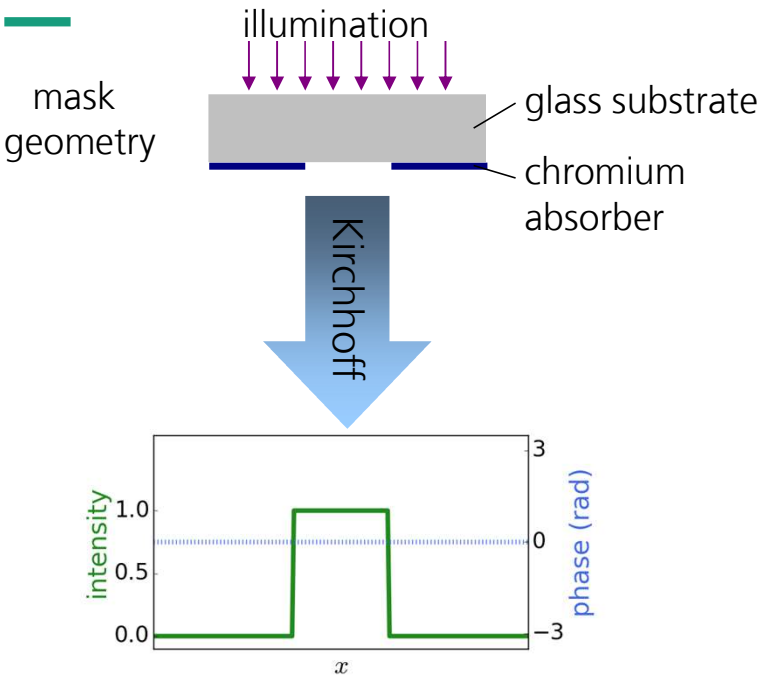
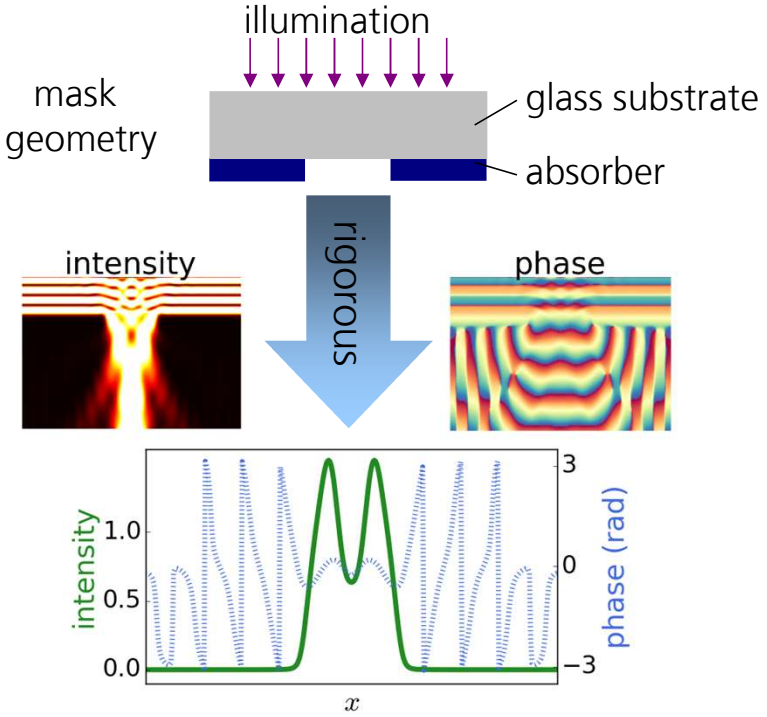
Kirchhoff-type and rigorous 3D mask modeling: DUV



- Parameters: transmission, phase
- Diffraction characteristics independent from illumination direction



- Parameters:
  - Optical properties: n/k
  - Geometry: thickness, shape
- Diffraction characteristics depend on illumination direction

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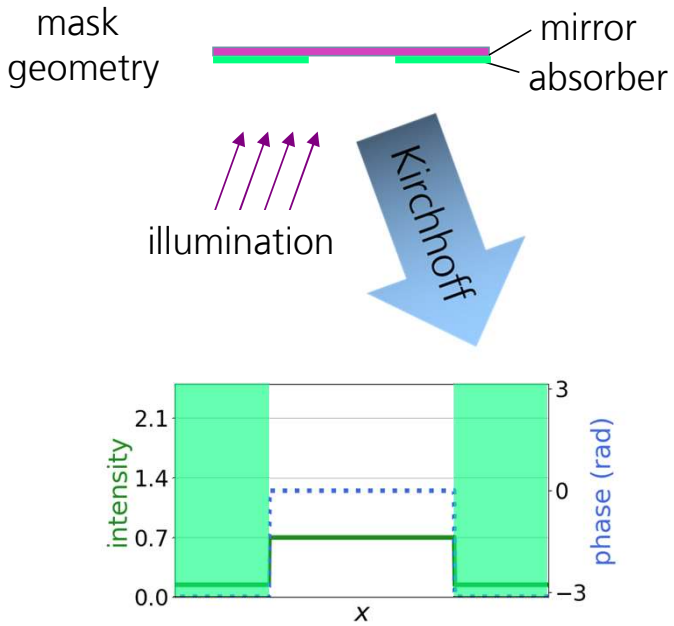
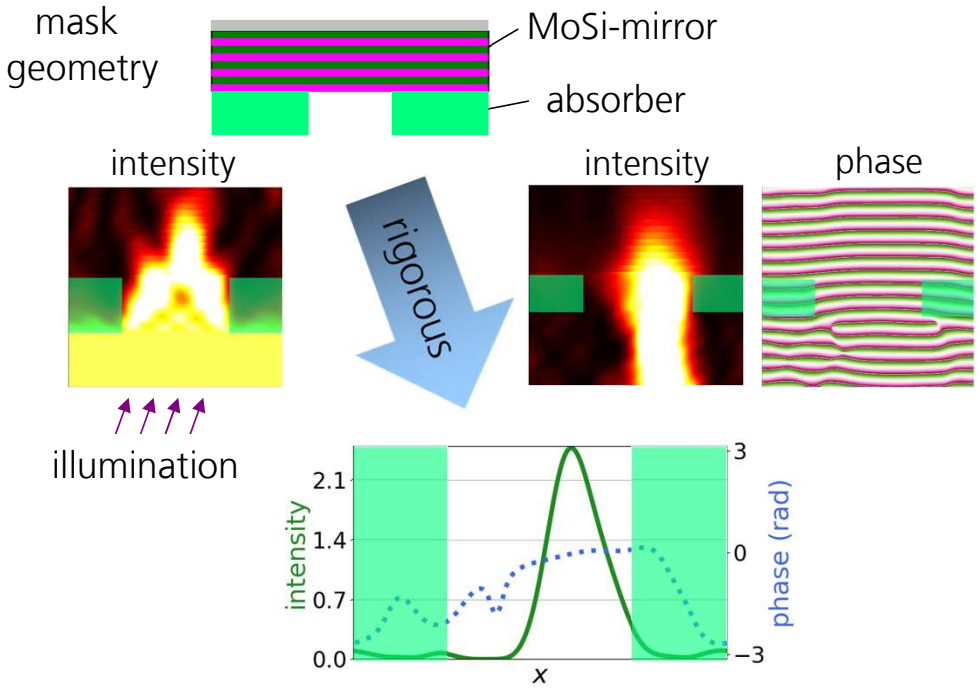
Kirchhoff-type and rigorous 3D mask modeling: EUV



- Parameters: transmission, phase
- Diffraction characteristics independent from illumination direction

Note: no double diffraction



- Parameters:
  - Optical properties: n/k
  - Geometry: thickness, shape, multilayer
- Diffraction characteristics depend strongly on illumination direction

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Simulation settings and strategy

Vertical L/S with two pitches on a dark field mask

Settings:

- **NA = 0.55**, 4×/8×, CRAO = 5.4°
- Vertical L/S: targets: 12/24 nm, **pitch = 24/48 nm**
- Unpolarized illumination: pencil, PFR = 10%
- Mask:
  - **Kirchhoff** (without double diffraction):
    - Fixed clear reflectivity: $r_F = 0.7$, $\phi_F = 0°$
    - Attenuated PSM with var r_B and $\phi_B = 180°$
  - **M3D**:
    - Low-n, mid-k (n = 0.9, k = 0.04) with var. thickness
    - Basic Mo/Si: 40 bilayers of 3.0 nm Mo & 4.0 nm Si, 2.0 nm Ru capping
- Mask tonality: Dark Field / Bright Field
- Exposure options:
  - SE: single exposure
  - SP: split pupil exposure

Variables:

- **Mask**
  - Bias for both pitches, assist size
  - M3D: thickness: 20nm – 80nm
    KH: absorber reflectivity: 0. – 0.5
- **Source**: pencil position σ_{pencil}
- Exposure: focus, **SP: mask shift**

Objectives:

- Print features with highest effective NILS: **nilsE** & **DoF**
- Compare performance for different assumptions on mask

Boundary conditions:

- No mask rules
- No resist effects (blur, etc.)
- Exclude sidelobe printing inside PW

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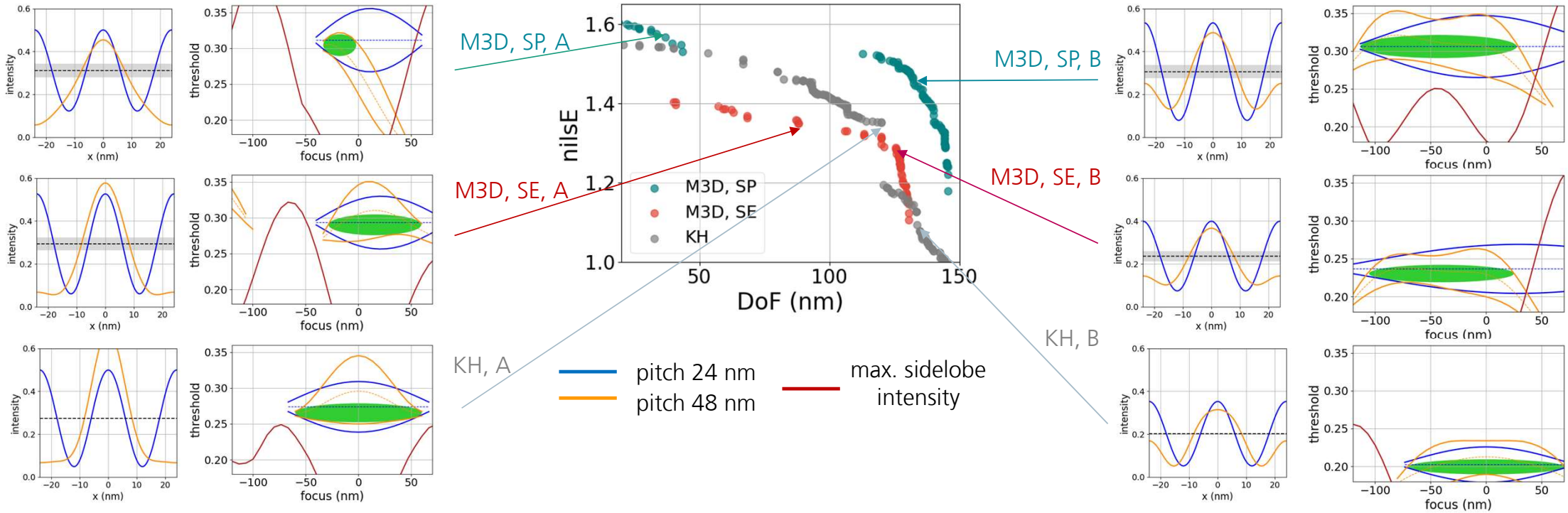
Results for vertical L/S, dark field mask, pitches: 24/48nm

- Variables: bias (for both pitches), assist size, absorber thickness (reflectivity), σ_{penc}, focus, mask shift (for SP)
- Mask absorber: low-n/mid-k

Pareto data and selected cross sections and process windows



- Tradeoff between achievable nilsE and DoF for all absorber options
- M3D with split pupil exposure (SP) outperforms Kirchhoff (KH) mask

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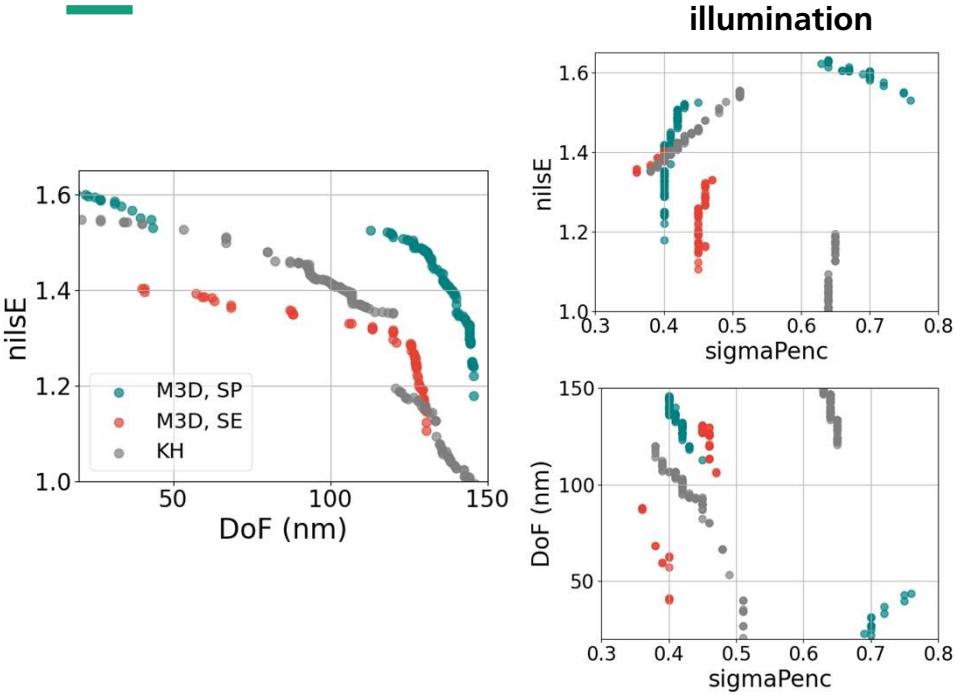
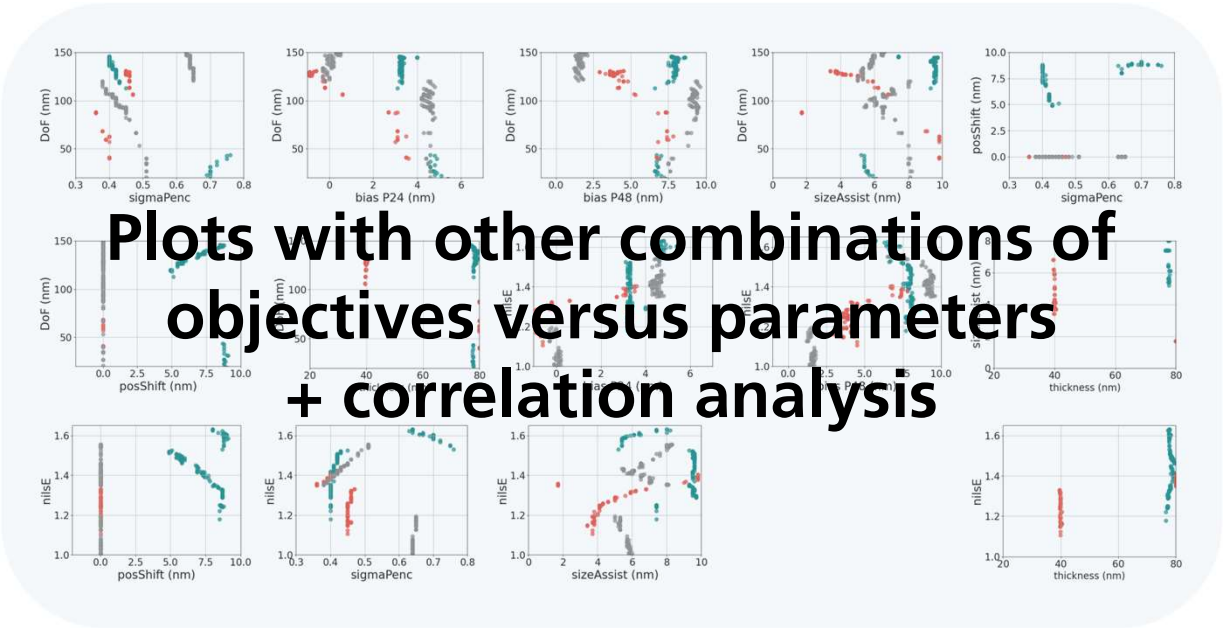
Results for vertical L/S, dark field mask, pitches: 24/48nm

- Variables: bias (for both pitches), assist size, absorber thickness (reflectivity), σ_{penc}, focus, mask shift (for SP)
- Mask absorber: low-n/mid-k

Which settings provide this performance: more Pareto plots





Plots with other combinations of objectives versus parameters + correlation analysis

- Across all absorber types, solutions fall into two regimes: lower-σ and higher-σ.
- M3D + SP enables larger bias and assist features, yielding high nilsE and large DoF -> impacts OPC strategy!
- For KH, large-DoF solutions are limited by small bias, resulting in low nilsE.
- SP supports thick absorbers while maintaining large DoF.

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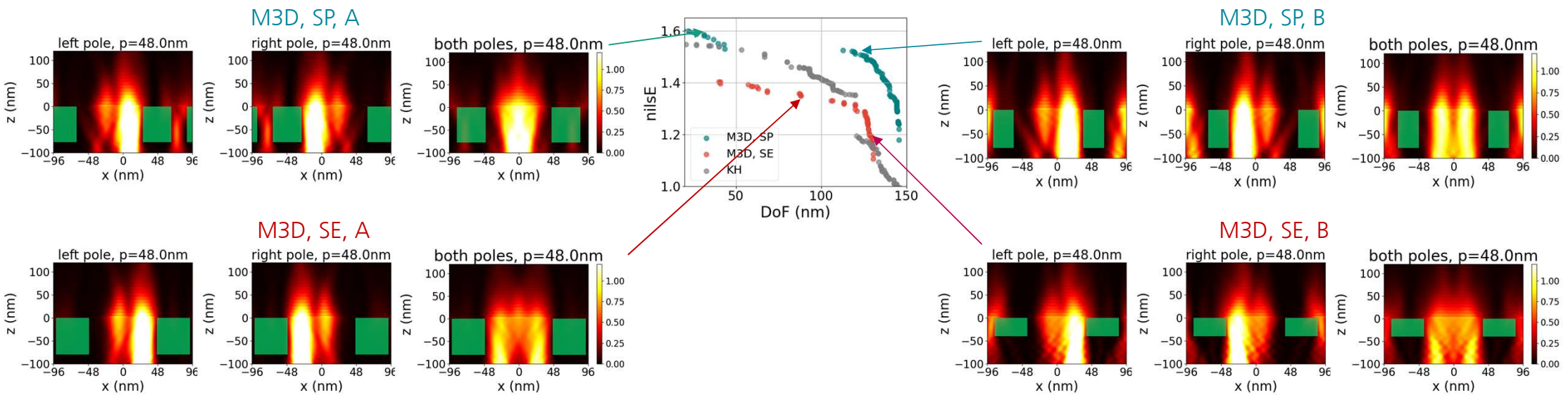
Root causes: light guiding in low-n absorber

Near Field: Intensity maps (low-n/mid-k absorber, pitch 48 nm, Dark Field mask)



- Asymmetric distribution of reflected light inside absorber openings (mode excitation by oblique incidence)
- Wafer shift in SP mitigates contrast loss in superposed near fields
- Higher DoF solutions exhibit larger assist features with more transmitted light
- SP enables larger assist features

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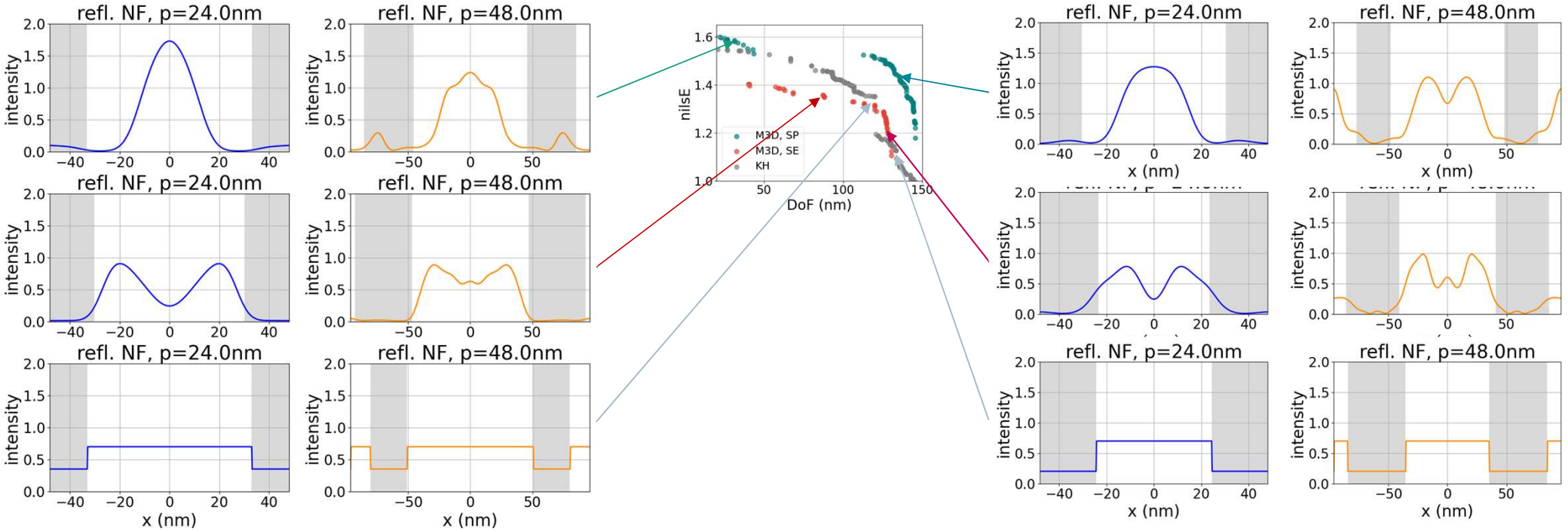
Root causes: narrower intensity peaks in reflected light

Near Field: Intensity at absorber height (low-n/mid-k absorber, pitch 24/48 nm, Dark Field mask)



- M3D enables higher intensity peaks
- M3D, SP provides highest and best localized intensity peaks inside the absorber-free area of the mask
- SP supports larger biasing without contrast loss and large non-printing assists features

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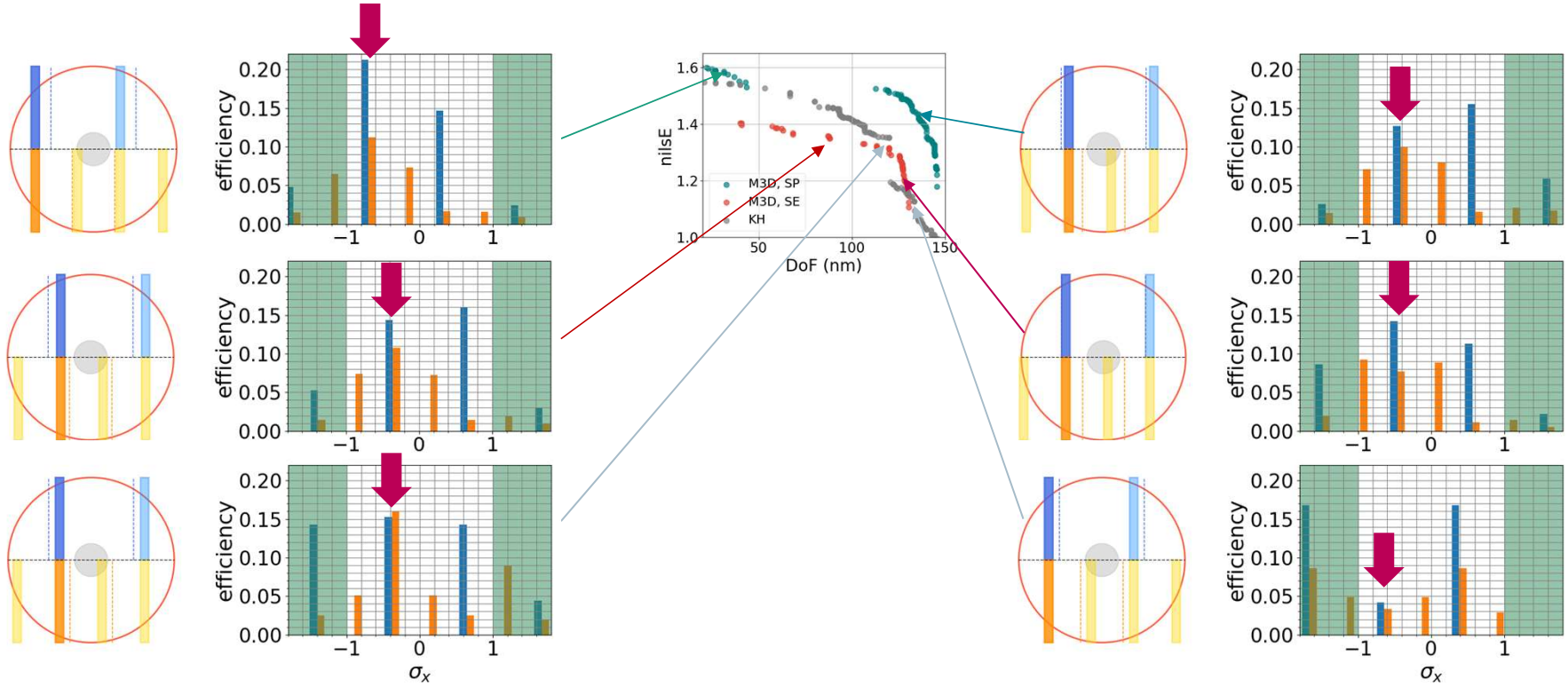
Root causes: more intensity of diffraction orders inside NA

Far Field: pupil plots and diffraction orders (low-n/mid-k absorber, pitch 24/48 nm, Dark Field mask)



- KH masks lose significant amount of light to out-of-NA diffraction orders (olive background)
- High-DoF designs place less intensity in the 0th order, especially at 48 nm pitch

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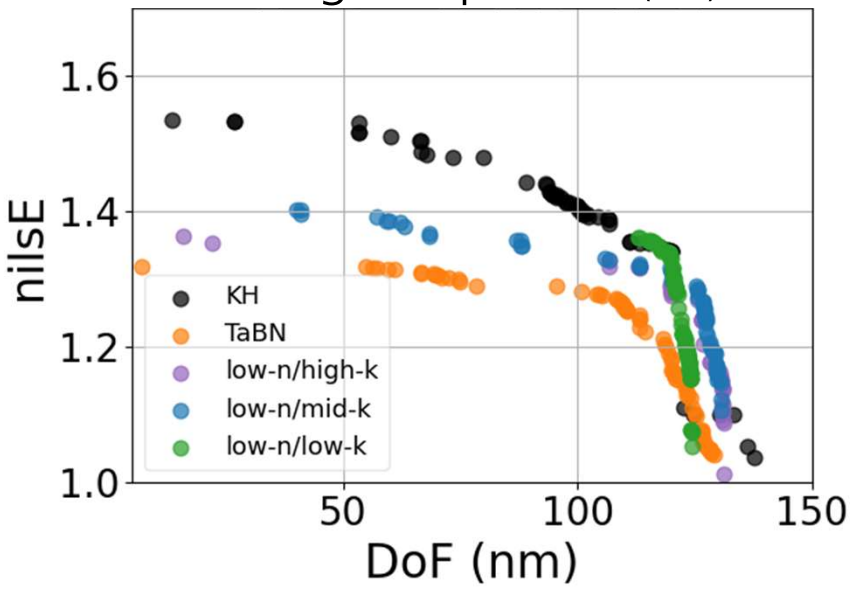
- NA=0.55
- Pitch= 24nm/48nm, target = 12nm/16nm
- Orientation: vertical
- Tonality: dark field

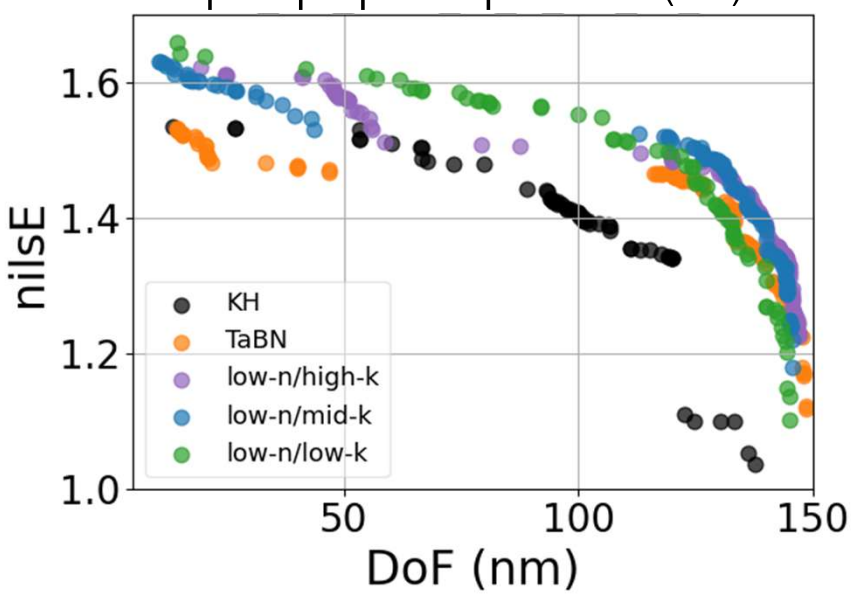
Other use cases

Impact of **absorber material**

Single exposure (SE)



Split pupil exposure (SP)



- TaBN underperforms relative to other mask types.
- Low-n masks deliver DoF comparable to Kirchhoff.
- KH masks achieve higher nilsE than all 3D masks.

- 3D masks consistently outperform Kirchhoff (KH) masks.
- Differences between absorber materials are minimal, especially in achievable depth of focus (DoF).

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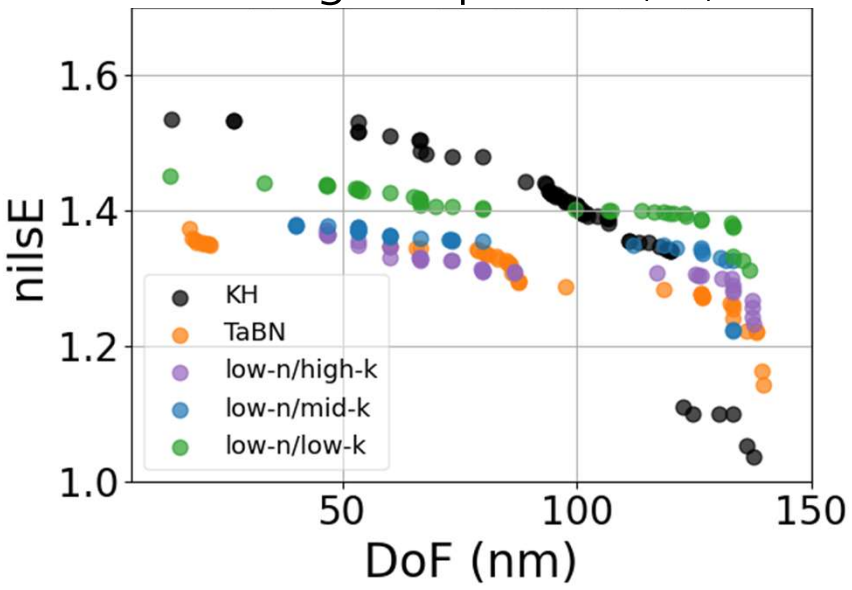
Other use cases

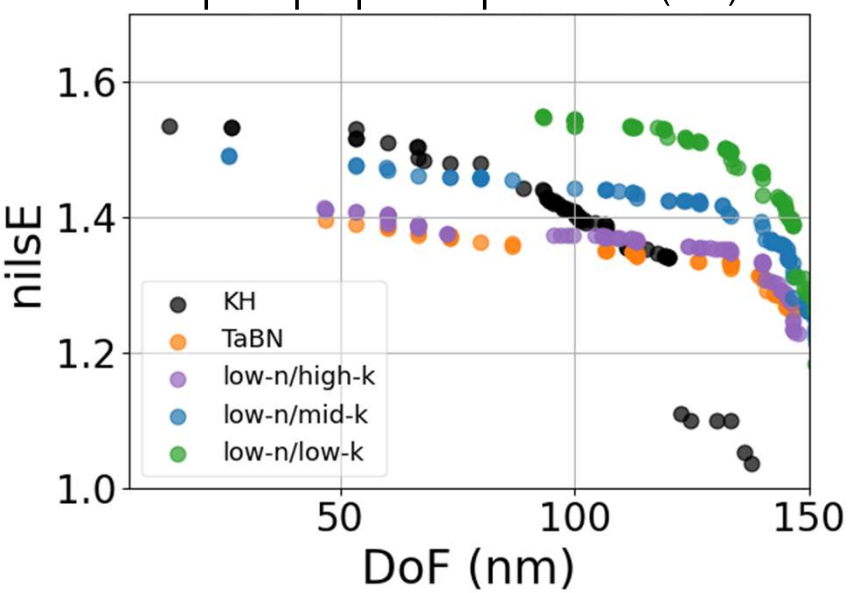
Horizontal L/S

- NA=0.55
- Pitch= 24nm/48nm, target = 12nm/16nm
- Orientation: horizontal
- Tonality: dark field

Single exposure (SE)



Split pupil exposure (SP)



- 3D masks offer a better nilsE/DoF trade-off than KH.
- Low-n/low-k 3D absorbers perform slightly better than other 3D options.
- TaBN performs slightly worse than other 3D absorbers.

- Ultimate performance is comparable to vertical L/S.
- Absorber material has a stronger impact; low-n/low-k absorbers outperform other materials.
- Improvement due to SP less pronounced than for ver L/S.

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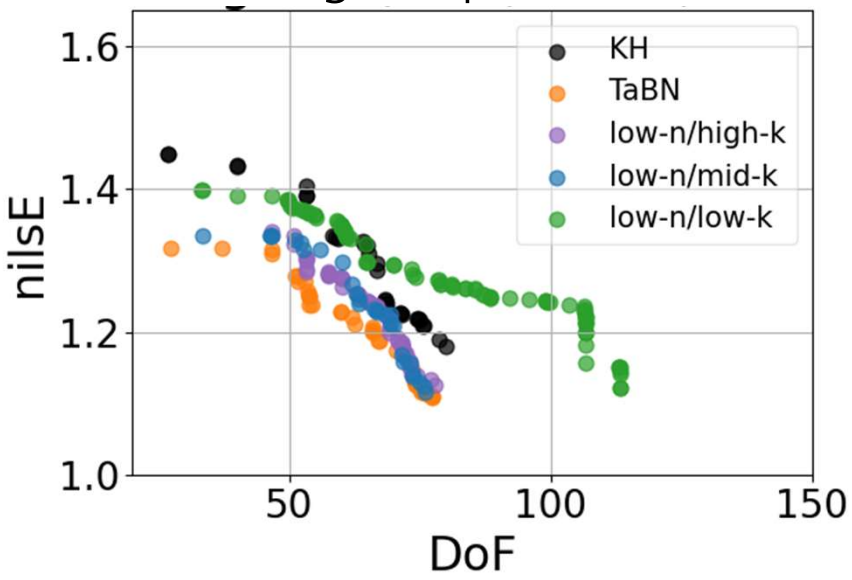
Other use cases

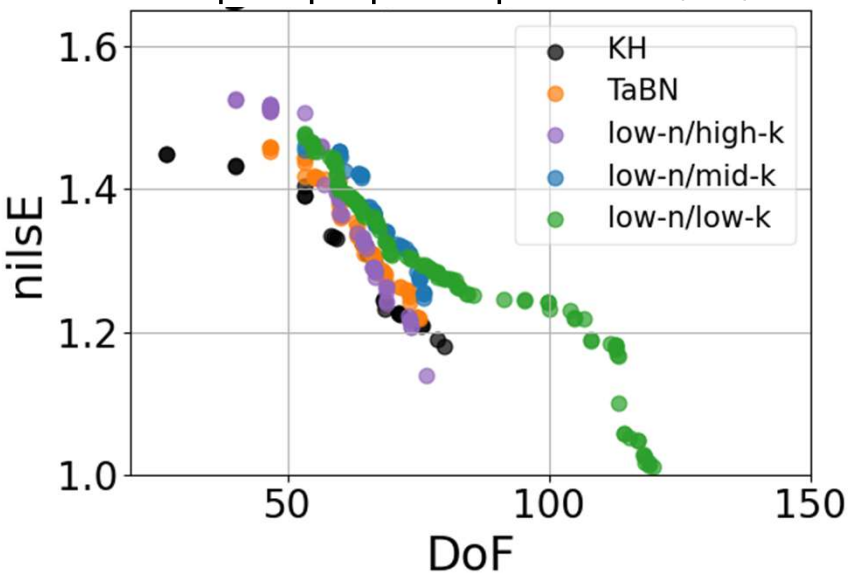
- NA=0.55
- Pitch= 24nm/48nm, target = 12nm/16nm
- Orientation: vertical
- Tonality: bright field

Mask Tonality: bright field mask (lines)

Single exposure (SE)



Split pupil exposure (SP)



- Bright field mask performs significantly worse than dark field, especially in terms of achievable DoF.
- Reason: assist features are consistently removed during optimization, even for Kirchhoff, due to sidelobe printing

- Only minor improvement due to SP.

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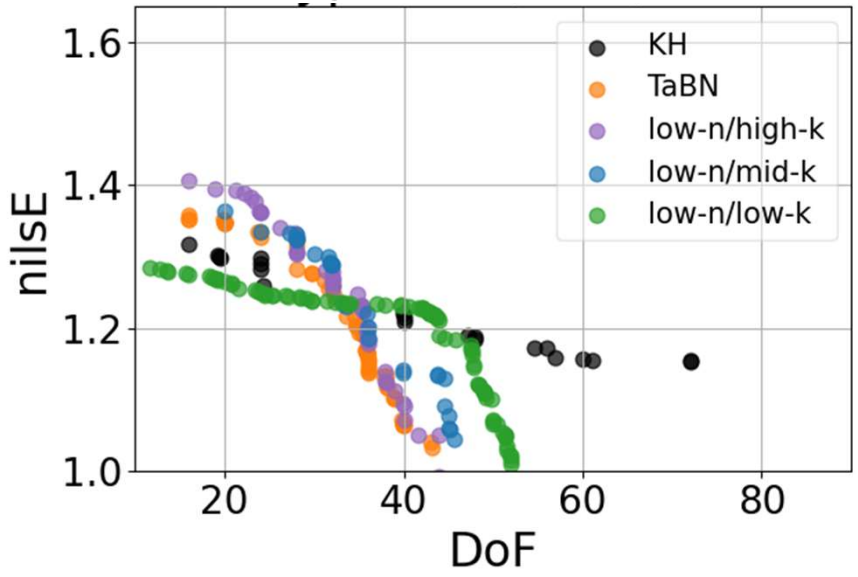
Other use cases

Hyper NA

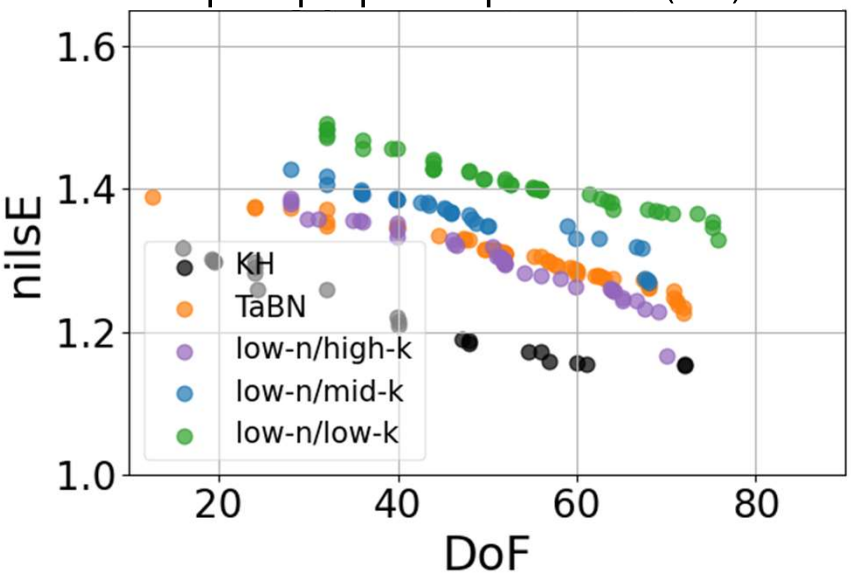
- NA=0.75
- Pitch = 16nm/32nm, target = 8nm/12nm
- Orientation: vertical
- Tonality: dark field

Single exposure (SE)



- 3D mask effects significantly reduce DoF.
- Among 3D masks, low-n/low-k absorbers deliver the highest DoF.

Split pupil exposure (SP)



- 3D masks outperform the KH mask.
- Absorber material has a larger impact than for vertical L/S in a high-NA system.
- Low-n/low-k exhibits the best performance.

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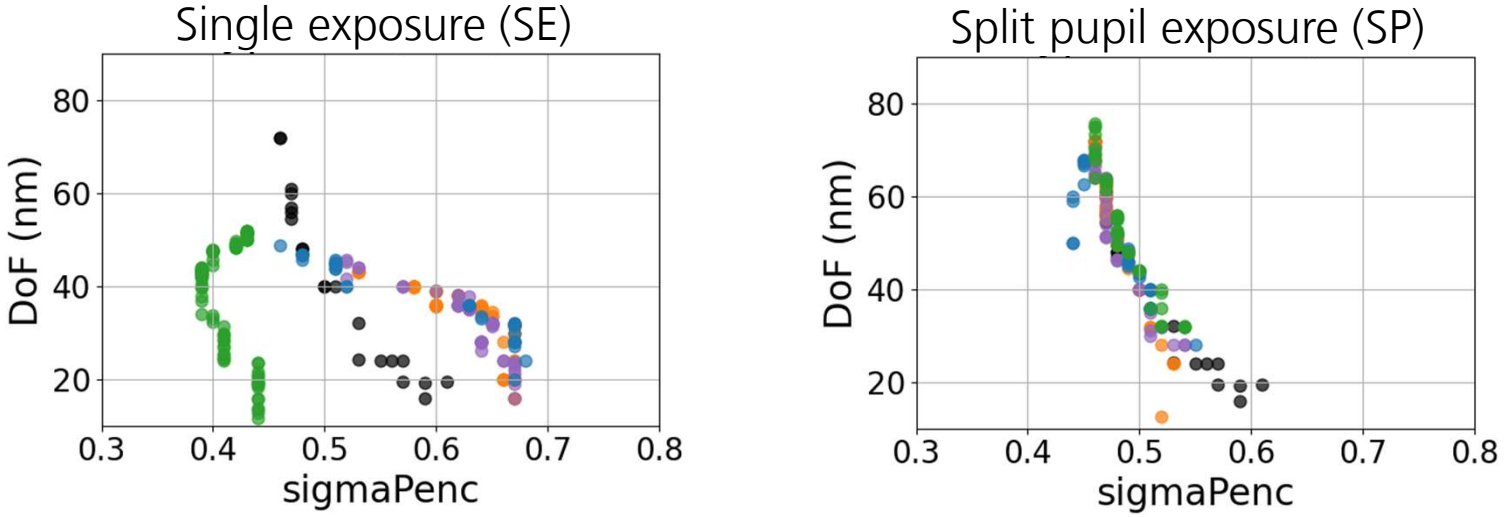
Other use cases

Hyper NA: alternative plot of Paretos

Which illumination provides the best DoF?



- With SP, the optimal illumination is largely independent of mask material and model.
- This suggests that for SP the source can be optimized using a simple Kirchhoff model.
- Similar trends are seen for the high-NA system, though small source variations with mask material remain.
- Further investigation is needed.

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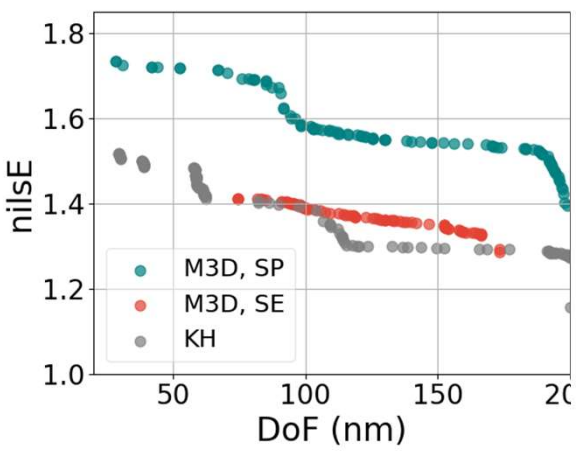
- NA=0.55
- Orientation: vertical
- Tonality: Dark field
- 2D absorber: low-n/mid-k

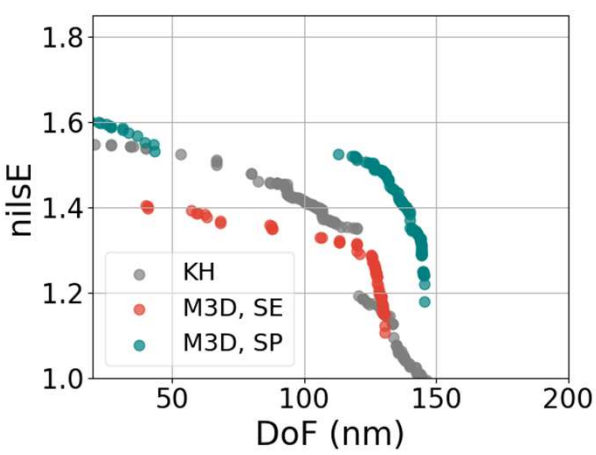
Other use cases

Other pitch combinations

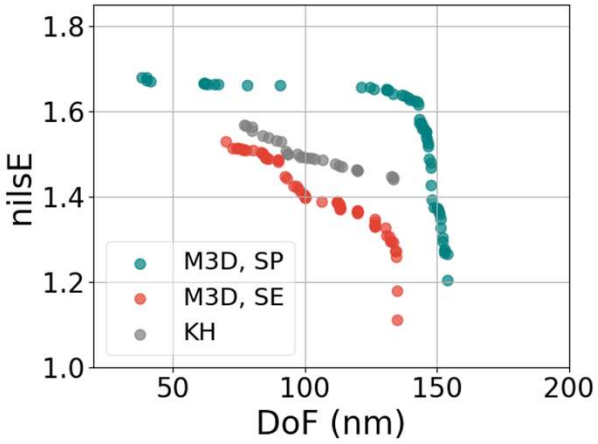
Pitch= 24nm/36nm
Target = 12nm/16nm



Pitch= 24nm/48nm
Target = 12nm/16nm



Pitch= 24nm/60nm
Target = 12nm/16nm



- ➢ The benefits of 3D mask imaged with split pupil exposure appear to be even more pronounced
- ➢ Combination of multiple pitches to be done

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Summary and Outlook

With rigorous SMO, 3D masks can outperform Kirchhoff masks optimized with classical SMO.

Enablers:
- Higher, tighter near-field intensity peaks (light guiding in low-n absorbers).
- More efficient coupling into diffraction orders within the projection NA.

Requirements to realize the gains:
- Split-pupil exposure or pupil engineering to offset contrast fading (e.g., Z6 injection).
- Rigorous, SP-aware SMO and ILT.

Additional insights:
- Benefits are weaker for bright-field masks.
- Potential advantages of M3D effects grow for hyper-NA EUV.

Advances in 3D-mask-aware SMO/ILT and mask technology can further unlock mask-3D benefits.

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Backup

Notation & conventions

KH = Kirchhoff mask model; M3D = rigorous 3D mask model

SE = single exposure; SP = split-pupil exposure; NA = numerical aperture

DoF = Depth of Focus [nm]; NILS = Normalized Image Log Slope [–]

nilsE = NILS × THRS^½ (dimensionless); THRS = threshold-to-size (dimensionless)

σ (sigma) = normalized source radius

CRAO = chief-ray angle at the object; PFR = partial fill ratio (illumination pencil fraction)

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Parameters of selected data from the Pareto frontier

parameter	KH, A	KH, B	M3D, SE, A	M3D, SE, B	M3D, SP, A	M3D, SP, B
bias P24 (nm)	+4.5	0.2	+3.1	-0.3	+4.6	+3.2
bias P48 (nm)	+9.3	1.7	+7.4	+4.4	+6.8	+8.0
assist size (nm)	+8.0	5.9	+1.7	+5.1	+5.4	+9.6
absorber thickness (nm)	-	-	80.0	+30.9	+77.7	+78.8
ref_{BG}	50.0	29.0	0.1	+5.5	0.9	0.3
$\Delta\phi_{BG}$	-180	-180	-74.3	-125.3	+108.1	+154.9
σ_{penc}	0.38	0.64	0.36	0.46	0.70	0.42
ΔPOS_{mask} (nm)	-	-	-	-	+9.1	+5.8
THRS	0.274	0.202	0.293	0.237	0.311	0.306
NILS P24	2.58	2.33	2.51	2.65	2.84	2.68
NILS P48	3.36	2.29	2.58	2.65	2.86	2.68
nilsE	1.35	1.03	1.36	1.29	1.58	1.48
DoF (nm)	120.0	140.1	87.7	+130.0	31.2	140.8

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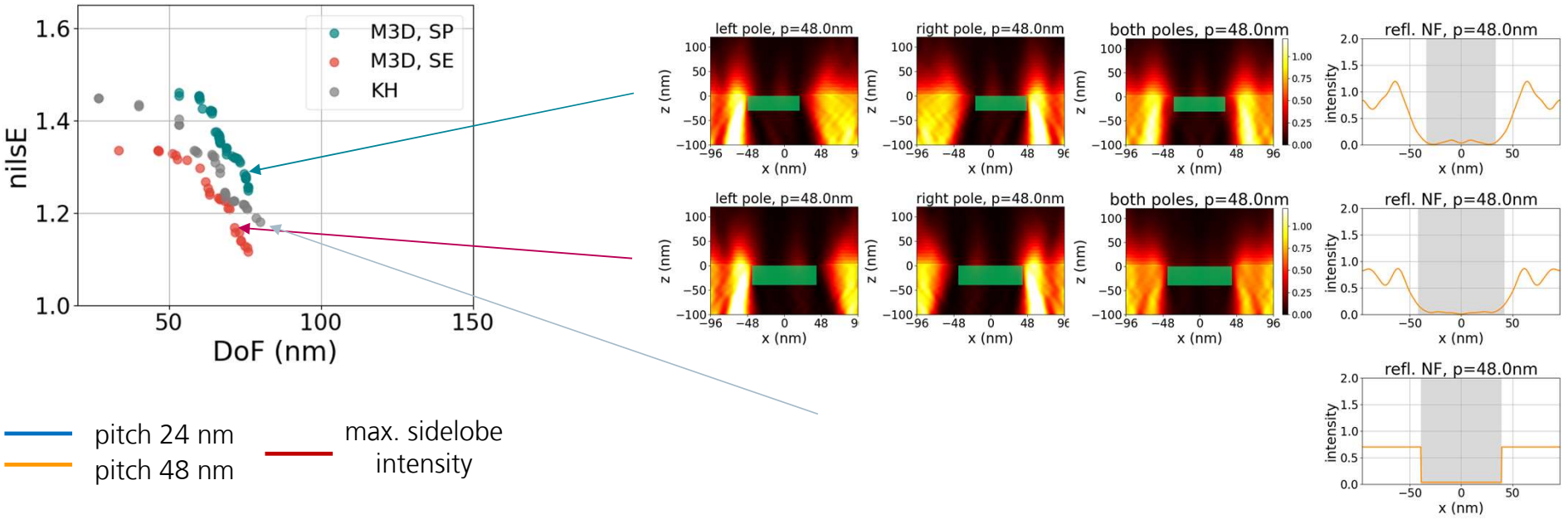
- plot_paretoComparison_lsAssist_86.py
- KH: KH_P24_48_301, ID 17, 11
- M3D, SE. APSM2_Ver_P24_48_SE_201, ID 24/13
- M3D, SP: APSM2_Ver_P24_48_SP_201, ID 1/16

Results for vertical L/S, bright field mask, pitches: 24/48

Near field plots for M3D and pitch 48 nm & Reflected light directly below absorber



- Superposing left and right poles restores symmetry but does not darken or shrink the feature of interest.
- The reflected field directly beneath the absorber is closer to the Kirchhoff case than for the dark-field mask

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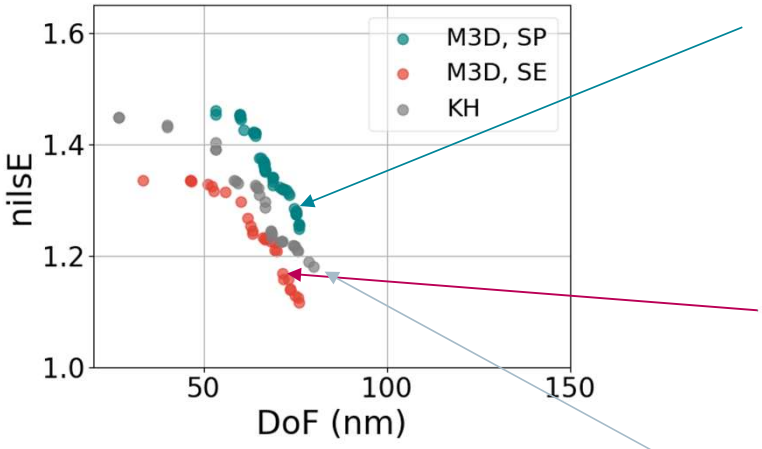
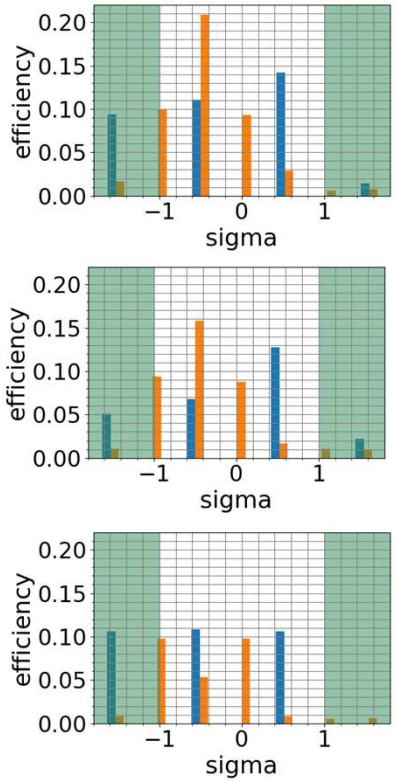
- plot_paretoComparison_lsAssist_86.py
- KH: KH_P24_48_301, ID 17, 11
- M3D, SE. APSM2_Ver_P24_48_SE_201, ID 24/13
- M3D, SP: APSM2_Ver_P24_48_SP_201, ID 1/16

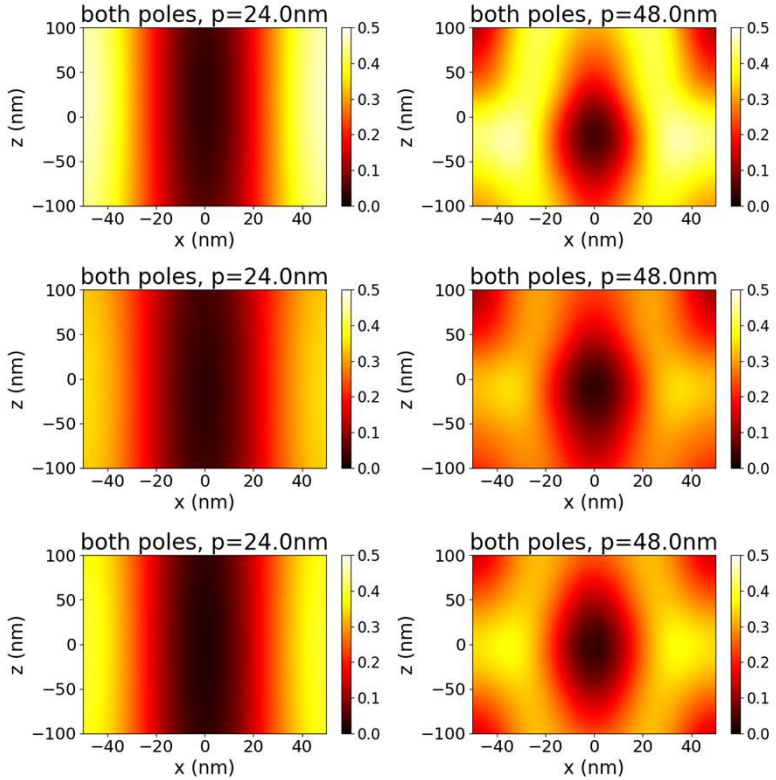
Results for vertical L/S, bright field mask, pitches: 24/48

Diffraction orders & through focus images



pitch 24 nm
pitch 48 nm
max. sidelobe intensity





- Zero-order intensity is substantially higher than in bright-field masks.
- DoF is limited; defocus introduces strong sidelobes.

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