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Exploring the limits of high contrast imaging using split pupil exposures in high NA EUV lithography

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SPIE Advanced Lithography 2024, Feb 26, San Jose, CA

Dr. LiTHO
Lithography
Simulation

CD – critical dimension
NA – numerical aperture
DoF – depth of focus
λ – wavelength
OPC – optical proximity correction
PSM – phase shift mask
NILS – normalized image log slope
LER – line edge roughness
THRS – threshold-to-size

How to push (high NA) EUV to its ultimate limits?

Thoughts from a theoretical imaging perspective

$$\mathrm{CD} = \mathrm{k}_1 \frac{\lambda}{\mathrm{NA}}$$

Reduce k_1 by

- Illumination: off-axis, free form, low pupil fill, …
- Mask: OPC, PSM (low-n), assists, curvilinear, …
- Process, resist: tone reversal, …

What is special about (high NA) EUV?

- DoF approaches physical limit (usable resist thickness)
- High NILS and dose required to minimize LER
- EUV light is more costly → **print at high THRS**
- More significant mask 3D effects can reduce NILS (image blur) and DoF (best focus shifts)

Which imaging solution* provides small k_1 with best tradeoff between NILS, THRS, and DoF?

**practical limitation due to reduced throughput of split pupil (SP) exposure are beyond the scope of this work*

Outline

- **Background and problem statement**
    - **Basic idea of split pupil (dual monopole) exposure**
    - Overview on settings, methods and procedures
- Problem analysis
    - Pupil plots of image metrics
    - Exploration of parameter space by Pareto sampling
    - Understanding of root causes by near field analysis
- Selected further learnings
    - Contributors to improved imaging performance
    - Extendibility towards smaller k_1
- Conclusions and outlook

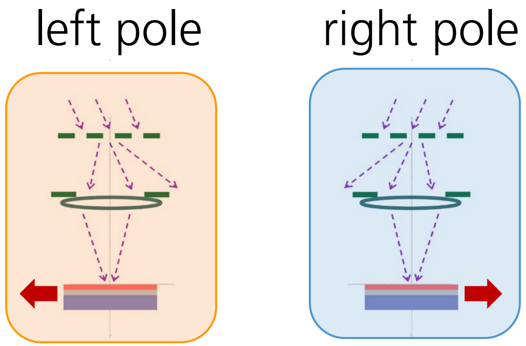
settings:
- absorber: TaBN, 60nm thick
- 8nm vertical lines with 24nm pitch
- NA=0.55, telecentric dipole (2 points)

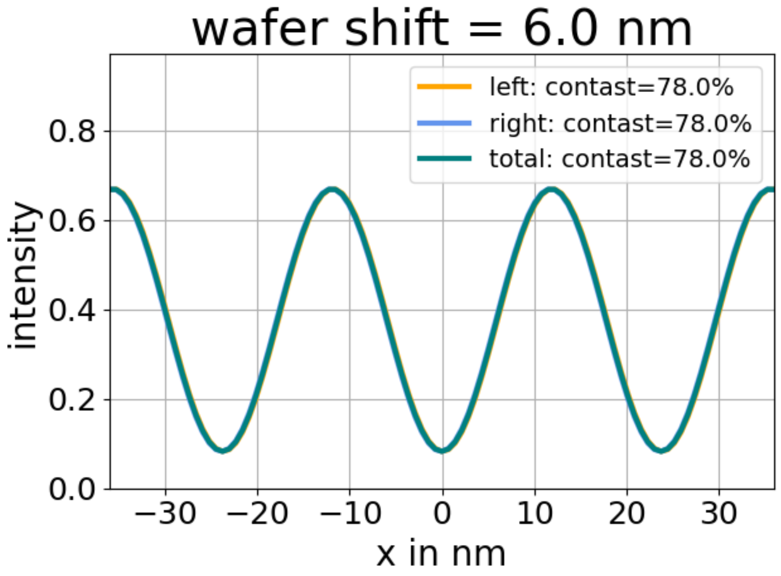
Basic idea of split pupil exposure

Example: dual monopole, single pitch line-space-pattern (L/S)

Basic idea of dual monopole exposure:
J.-H. Franke, T. Brunner, E. Hendrickx, JM3, vol 21 (2022),
https://doi.org/10.1117/1.JMM.21.3.030501

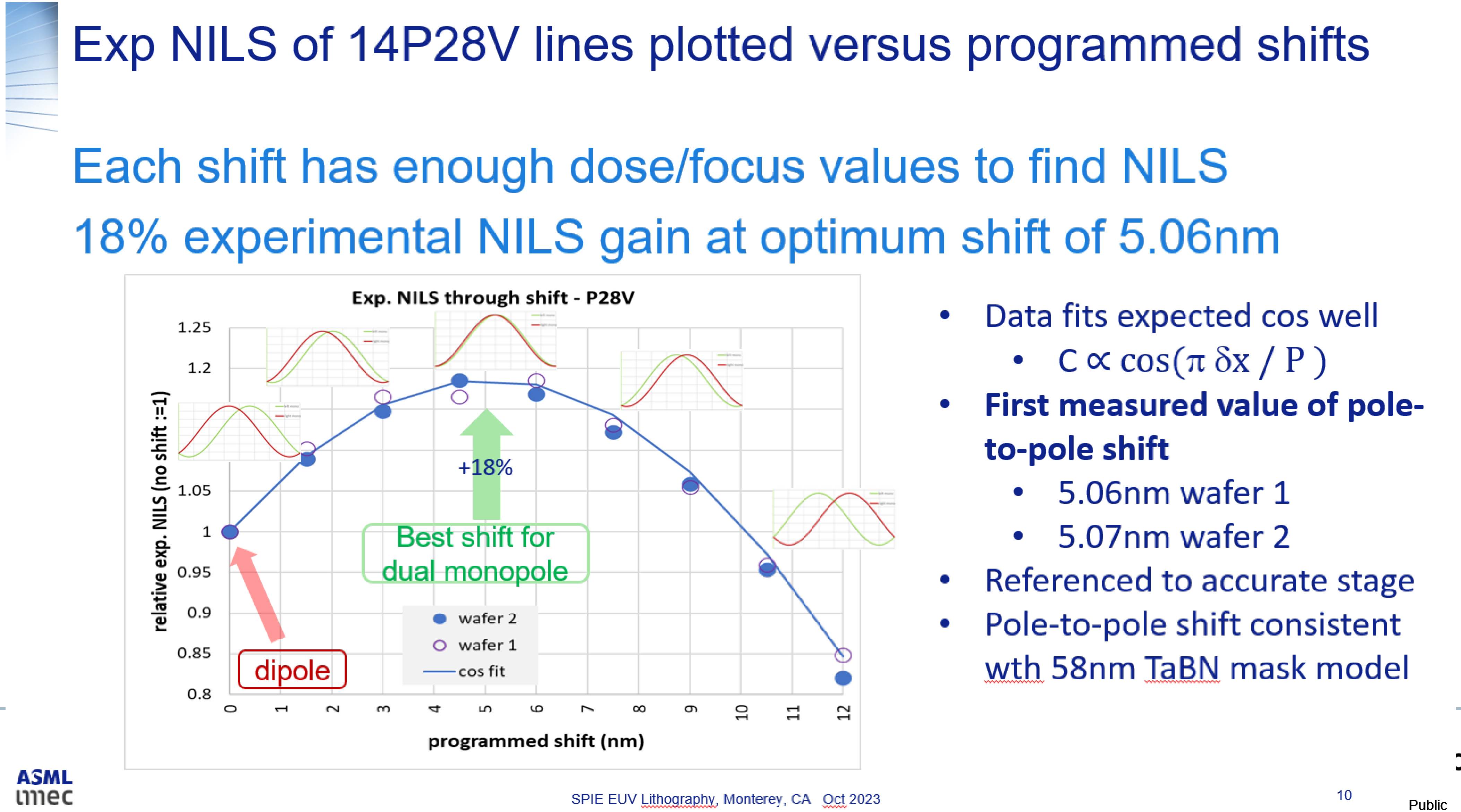
- Image shifts between left/right poles
- Superposition of images causes blurred image (contrast loss)
- Wafer shift between exposure with individual poles can compensate blur





Experimental demonstration of benefits of split pupil exposure

Presentation of Tim Brunner at SPIE EUVL, Monterey, Oct. 2023



Exp NILS of 14P28V lines plotted versus programmed shifts

Each shift has enough dose/focus values to find NILS

18% experimental NILS gain at optimum shift of 5.06nm

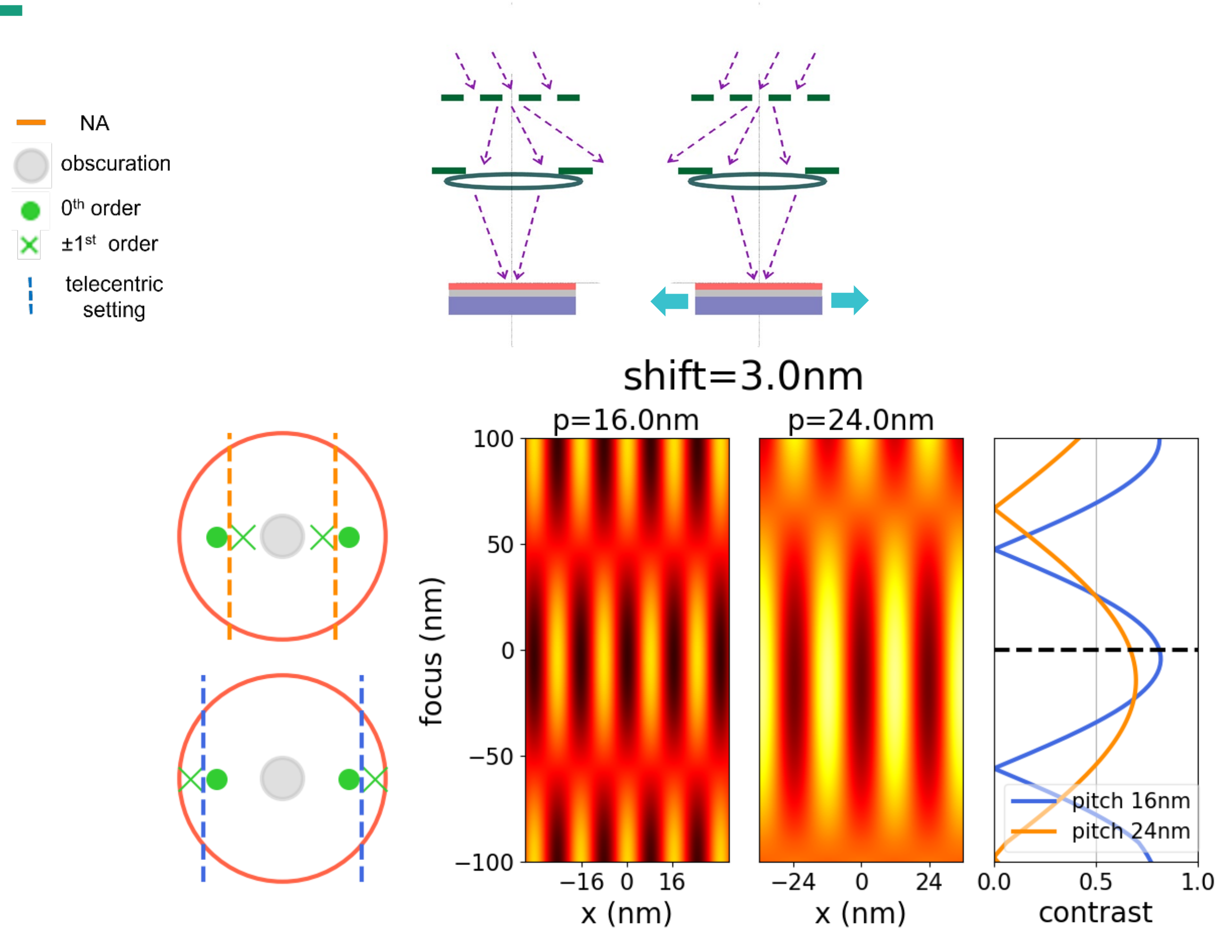
- Data fits expected cos well
  - C ∝ $\cos(\pi\,\delta x / P)$
- **First measured value of pole-to-pole shift**
  - 5.06nm wafer 1
  - 5.07nm wafer 2
- Referenced to accurate stage
- Pole-to-pole shift consistent wth 58nm TaBN mask model

SPIE EUV Lithography, Monterey, CA Oct 2023

settings:
- absorber: low-n, high-k, 40nm
- multilayer: Mo/Si, 2nm Ru-capping
- dipole (2 points)

Basic idea of split pupil exposure

Example: dual monopole, two pitches L/S



Wafer shift in dual monopole exposures aligns both

- Feature position in a given image plane
- Best focus position of the involved pitches

Similar behavior was observed for many other use cases

Problem statement

Split pupil exposure / dual monopole improve imaging of line-space-patterns

Are split pupil exposures for 2D features, e.g., arrays of contacts useful as well?

Selected questions to be addressed*

- Can we gain from two exposures, or do we need more? How to split the pupil? How much can we gain?
- How does split pupil exposure (SP) impact the optimum OPC (biasing), source shape, absorber n, k, thickness?
- How about the impact of tonality and source filling on these statements?

*practical limitation due to reduced throughput and alignment of source (and photoresist) are beyond the scope of this work

CRAO – chief ray angle of incidence
LF – light field
DF – dark field
QP – quadrupole
PW – process window

Use-case settings

Fixed

- NA=0.55, reduction = 4×/8×, CRAO = 5.355°, center obscuration: 20%, unpolarized light
- Target: square/hex contacts/DF or pillars/LF; 11nm 22nm pitch
- Slit position: center

Variables

- Mask variables: absorber (material, thickness), bias, tonality, *multilayer*
- Source variables: combinations of (rotated) ellipses* with a given source fill
- Wafer shift (for split pupil exposure)

Objectives

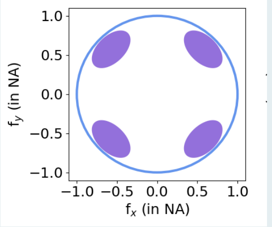
- THRS (threshold-to-size → throughput)
- NILS (contrast): max{min(NILS over all cut directions)}
- DoF (PW-based *and NILS-based*)
- Min. variation of CD vs. cut direction: ΔCD

$$\left.\begin{array}{l}\text{THRS}\\ \text{NILS}\end{array}\right\}\ \text{nilsE: } \mathrm{NILS}\sqrt{\mathrm{THRS}}$$

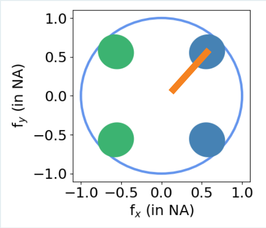
Mask biasing:
sizeX = target + bias
sizeY = sizeX + dbiasXY

- Positive bias means larger holes/pillars on mask
- Positive dbiasXY specifies larger extension in y
- All values are given on wafer scale

single exposure



split pupil exposure



variables:
- QP_sigma
- QP_aspect

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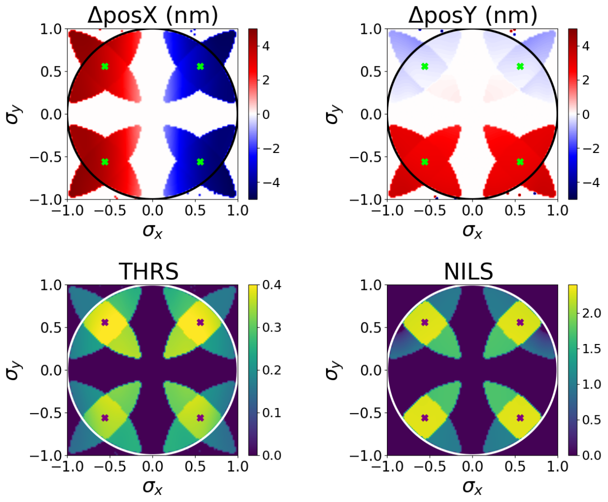
we did not target at the absolute best source, but tried to identify tendencies (source fill, location of "good areas" of the source)

Methods & procedures

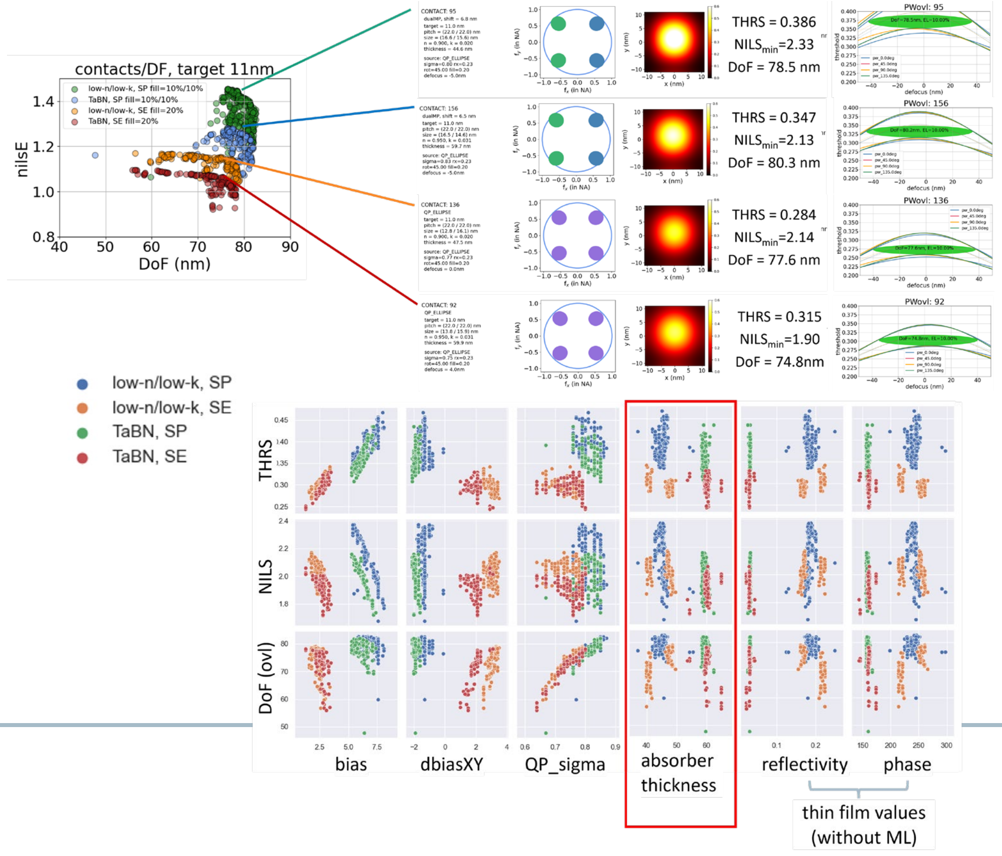
Pupil maps for NILS, THRS, image shifts, …

- identification of most useful source areas
- general tendencies and sensitivities



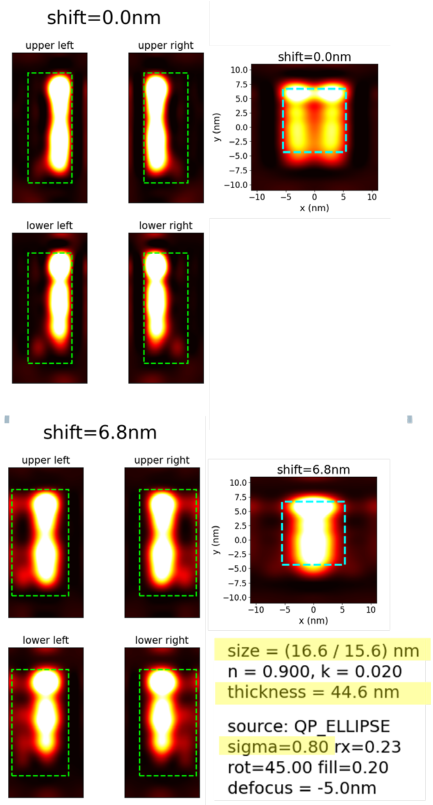
Pareto analysis

- exploration of high-dimensional parameter space
- identification of best settings and tradeoff relationships
- comparison of different options
- consequences for SMO



Near field analysis

- root cause analysis



size = (16.6 / 15.6) nm
n = 0.900, k = 0.020
thickness = 44.6 nm

source: QP_ELLIPSE
sigma=0.80 rx=0.23
rot=45.00 fill=0.20
defocus = -5.0nm

Outline

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    - Overview on settings, methods and procedures

- Problem analysis
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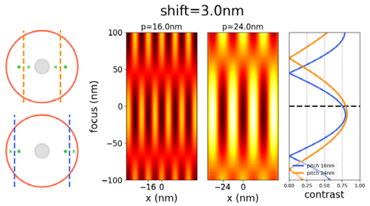
    - Exploration of parameter space by Pareto sampling
    - Understanding of root causes by near field analysis

- Selected further learnings
    - Contributors to improved imaging performance
    - Extendibility towards smaller k_1

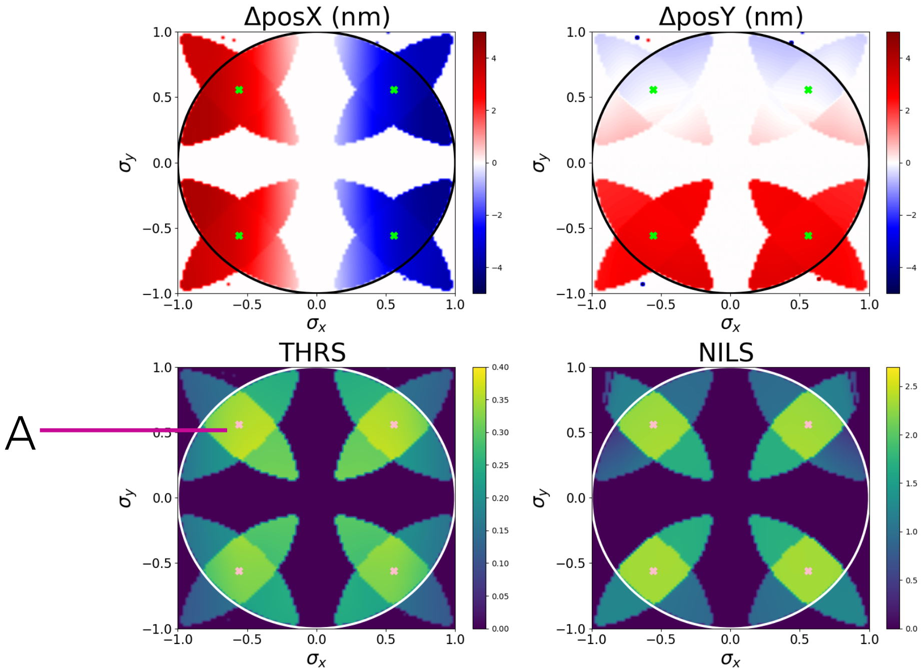
- Conclusions and outlook



Pupil diagrams of image metrics for single source point illumination

11nm contact (DF); low-n/high-k

- bias= 6.4nm / 5.0nm
- thickness=58.2nm



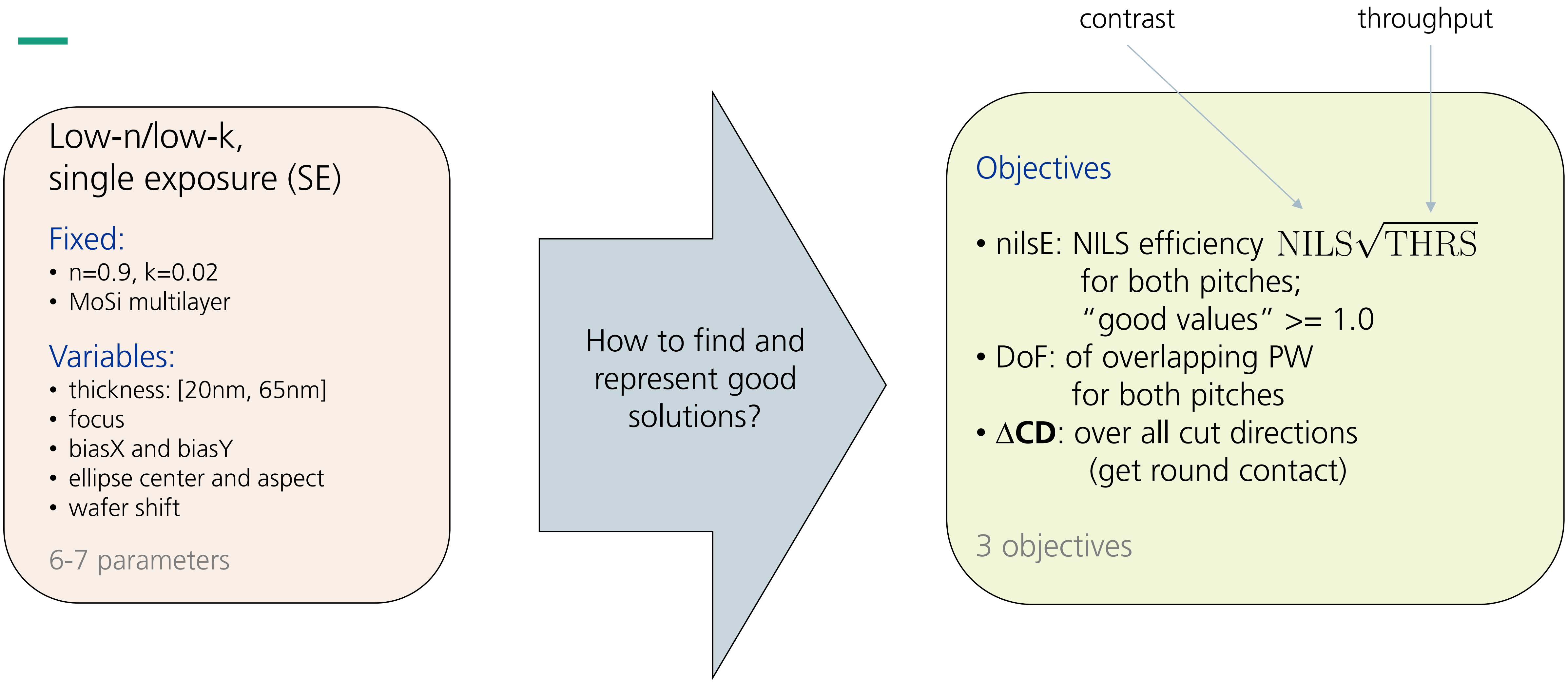
Remarks:

- Bias and thickness values for both cases are taken from Pareto of quadrupole exposure (no split) with largest DoF and nilsE

Observations

- Largest THRS and NILS in Zone A (4-beam interference)
- Noticeable variations of all image metrics between and within zones
- Strong image shift between left/right poles
- Qualitatively similar observations for other absorbers, thickness and biasing

Exploration of parameter space by Pareto sampling



Low-n/low-k,
single exposure (SE)

Fixed:
- n=0.9, k=0.02
- MoSi multilayer

Variables:
- thickness: [20nm, 65nm]
- focus
- biasX and biasY
- ellipse center and aspect
- wafer shift

6-7 parameters

How to find and represent good solutions?

contrast

throughput

Objectives

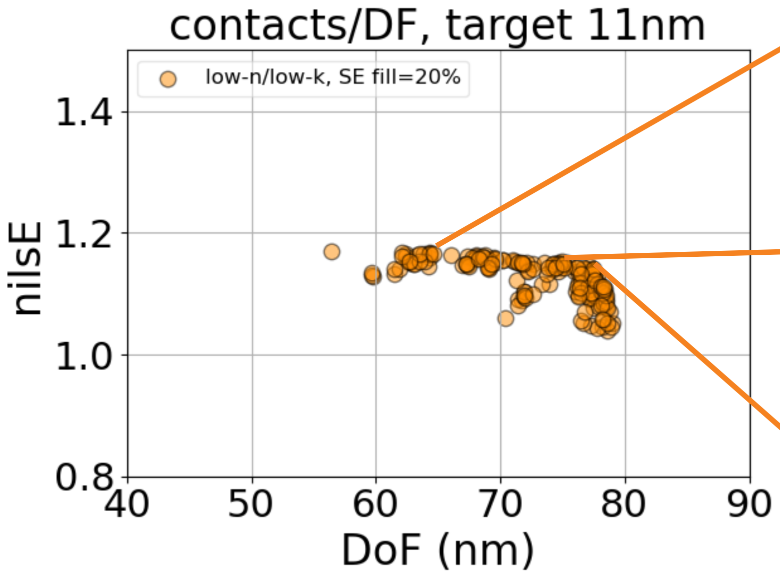
- nilsE: NILS efficiency $\mathrm{NILS}\sqrt{\mathrm{THRS}}$
  for both pitches;
  "good values" >= 1.0
- DoF: of overlapping PW
  for both pitches
- Δ**CD**: over all cut directions
  (get round contact)

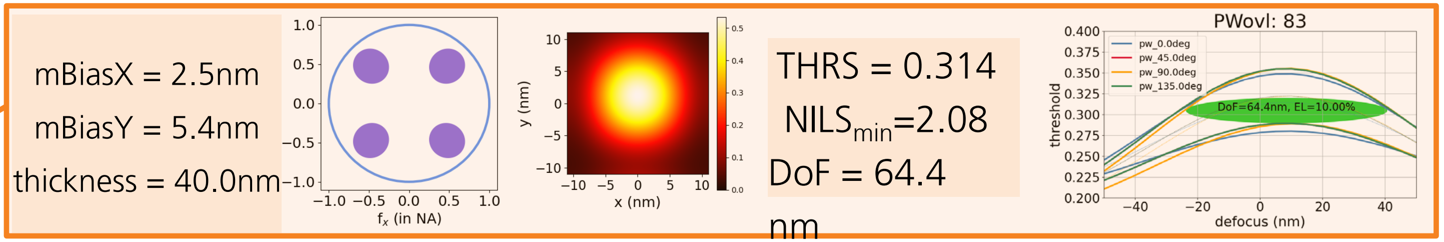
3 objectives

- low-n/low-k, contact hole (DF)
- target: 11nm, pitch: 22nm
- pupil fill: 20%

Exploration of parameter space by Pareto sampling

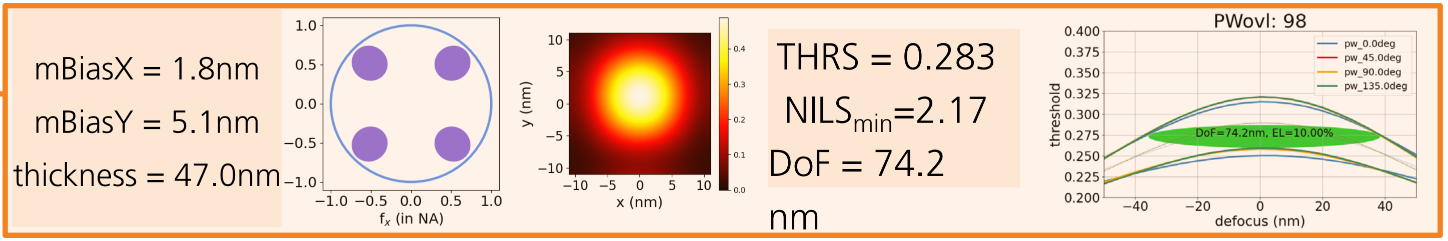
Single Exposure (SE)





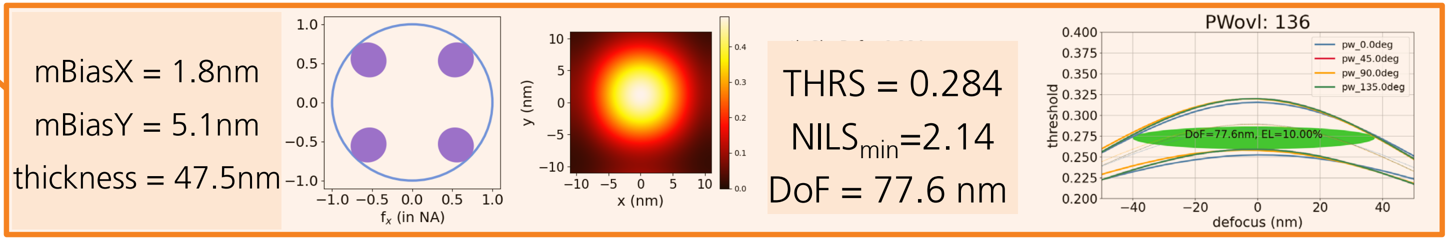
mBiasX = 2.5nm
mBiasY = 5.4nm
thickness = 40.0nm

THRS = 0.314
NILS$_{min}$=2.08
DoF = 64.4 nm



mBiasX = 1.8nm
mBiasY = 5.1nm
thickness = 47.0nm

THRS = 0.283
NILS$_{min}$=2.17
DoF = 74.2 nm



mBiasX = 1.8nm
mBiasY = 5.1nm
thickness = 47.5nm

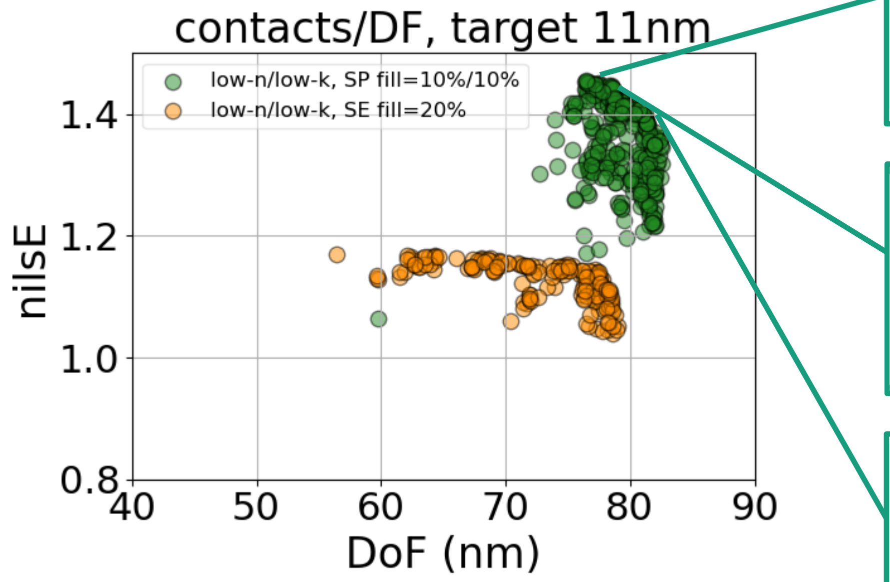
THRS = 0.284
NILS$_{min}$=2.14
DoF = 77.6 nm

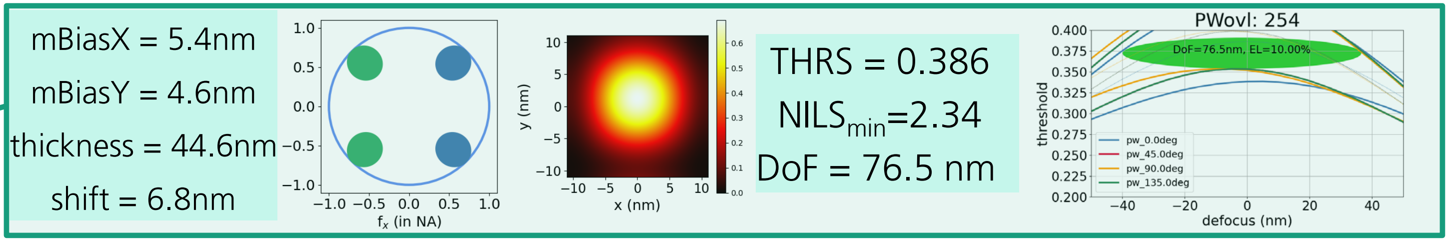
- ➢ Tradeoff between achievable nilsE and DoF
- ➢ Tunable by illumination setting

- low-n/low-k
- target: 11nm, pitch: 22nm
- pupil fill: 10%/10%

Exploration of parameter space by Pareto sampling

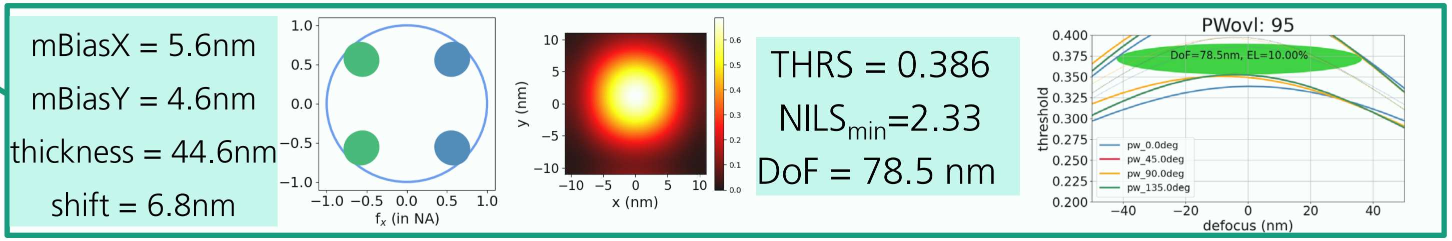
Split Pupil Exposure (SP)





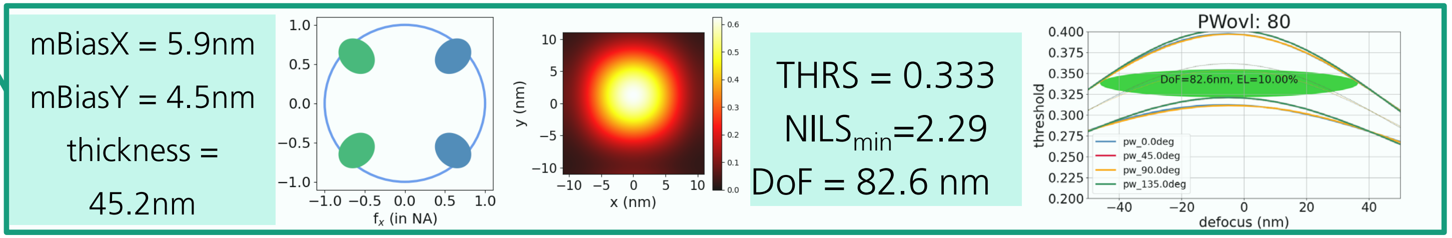
mBiasX = 5.4nm
mBiasY = 4.6nm
thickness = 44.6nm
shift = 6.8nm

THRS = 0.386
$\mathrm{NILS}_{\mathrm{min}}$=2.34
DoF = 76.5 nm



mBiasX = 5.6nm
mBiasY = 4.6nm
thickness = 44.6nm
shift = 6.8nm

THRS = 0.386
$\mathrm{NILS}_{\mathrm{min}}$=2.33
DoF = 78.5 nm



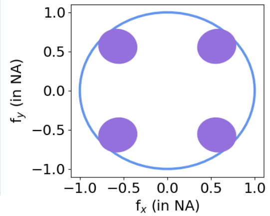
mBiasX = 5.9nm
mBiasY = 4.5nm
thickness = 45.2nm
shift = 7.7nm

THRS = 0.333
$\mathrm{NILS}_{\mathrm{min}}$=2.29
DoF = 82.6 nm

- More than 20% improvement of nilsE (compared to SE)
- Only small improvement of DoF
- Significantly larger bias along shift direction (biasX)

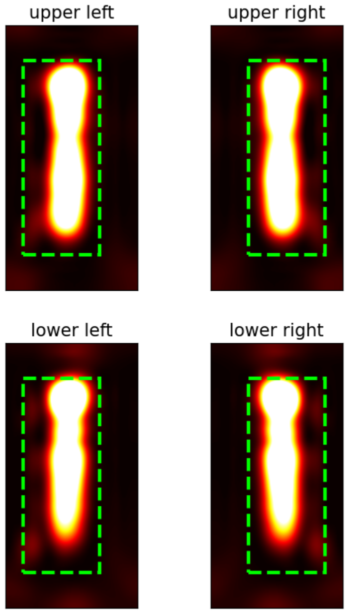
Understanding of root causes by near field analysis

- low-n/low-k
- target: 11nm, pitch: 22nm
- sizeX = 12.8nm, sizeY=16.1nm
- thickness=47.5nm



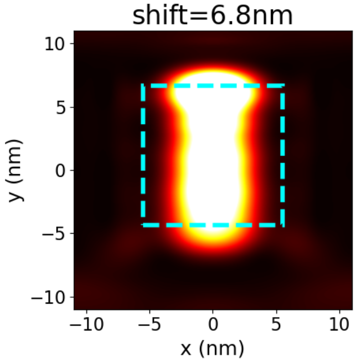
near field (NF) intensity for single (point) poles

shift=6.8nm



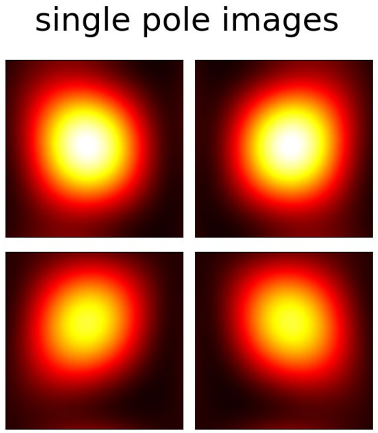
mask feature

sum of NF intensities (wafer scale)

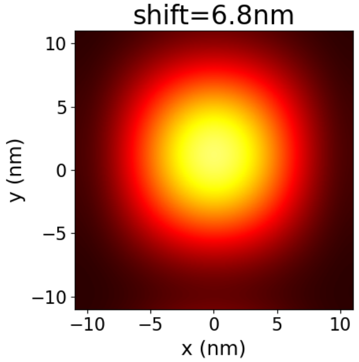


wafer target

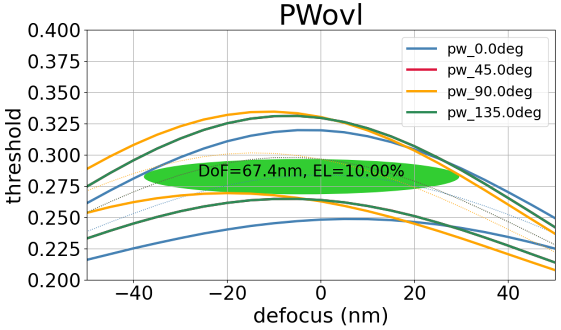
single pole images



total image (at best focus)



process windows (along 4 cuts)



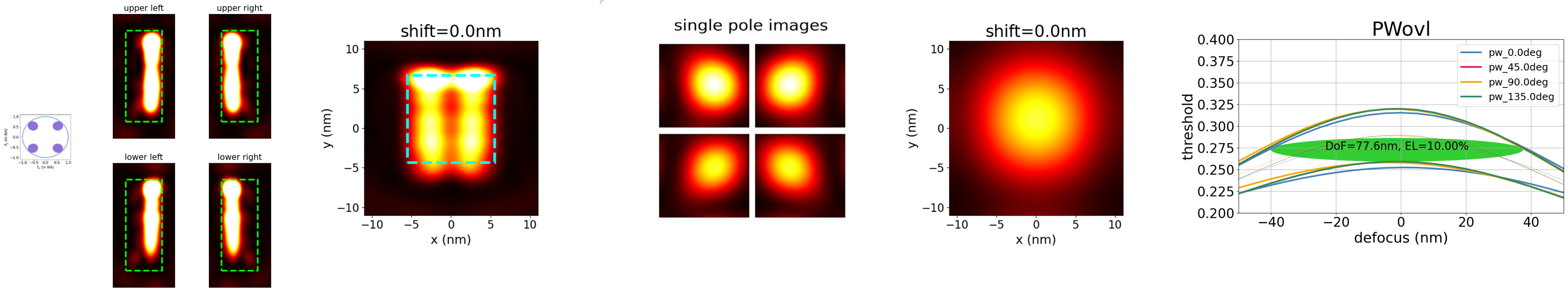
- ➢ Image shift / blur originates from the asymmetries of the NF (excitation of odd waveguide modes in absorber openings) due to off-axis illumination
- ➢ Shift of wafer sharpens superposed near field and image, but degrades overlapping process windows (PW)

- low-n/low-k
- target: 11nm, pitch: 22nm

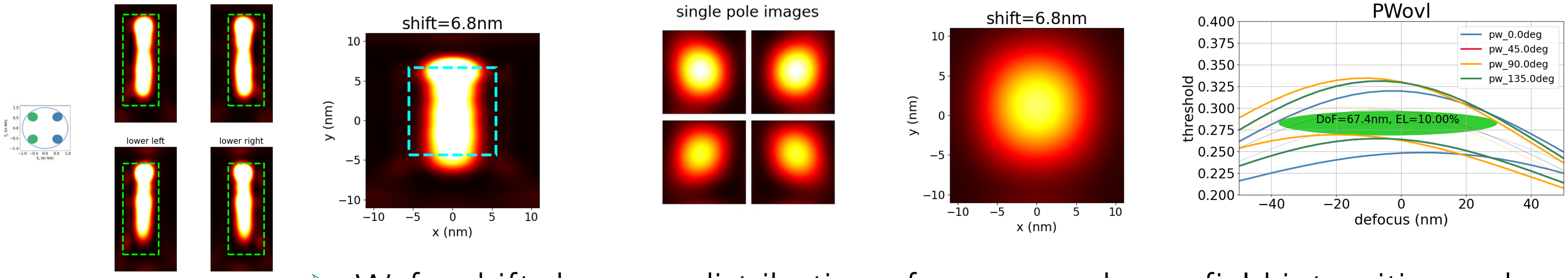
Understanding of root causes by near field analysis

Impact of wafer shift

NF intensity poles | sum NF ➡ pole images | total image ➡ process windows



thrSizeRef = 0.284
pos = (0.00 / 1.16) nm
$CD_{min/max}$ = (11.00 / 11.22) nr
ΔCD = 0.22 nm
$NILS_{min/max}$ = 2.14 / 2.23
nilsE = 1.14
DoF = 77.56nm



thrSizeRef = 0.284
pos = (0.00 / 1.22) nm
$CD_{min/max}$ = (11.00 / 11.48) nm
ΔCD = 0.48 nm
$NILS_{min/max}$ = 2.30 / 2.52
nilsE = 1.22
DoF = 67.35nm

- ➢ Wafer shift sharpens distribution of superposed near field intensities, reduces shift between individual pole images and increases NILS
- ➢ DoF drops, threshold-to-size remains unaffected

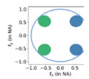
- low-n/low-k
- target: 11nm, pitch: 22nm

Understanding of root causes by near field analysis

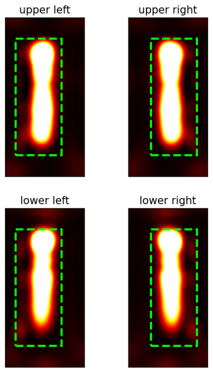
Impact of wafer shift & SMO

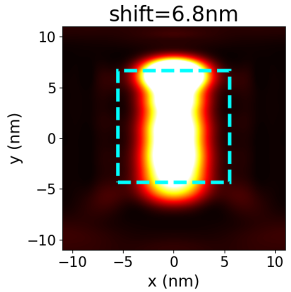
NF intensity poles | sum NF → pole images | total image → process windows

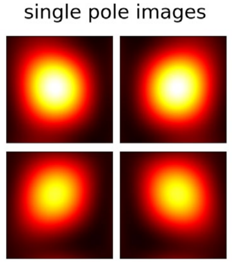
shift=6.8nm

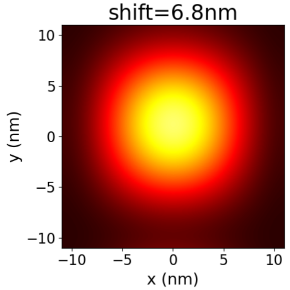


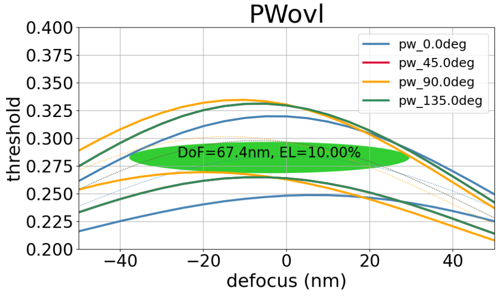
sizeX = 12.8nm
sizeY=16.1nm
thickness=47.5nm





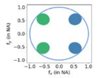




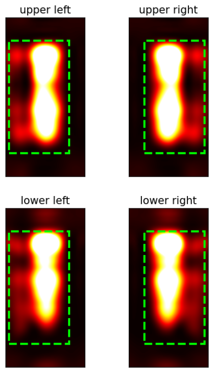


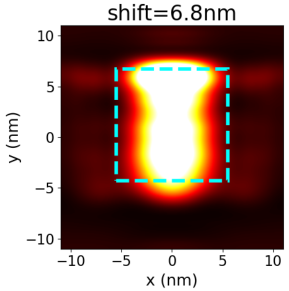
thrSizeRef = 0.284
pos = (0.00 / 1.22) nm
$CD_{min/max}$ = (11.00 / 11.48) nm
ΔCD = 0.48 nm
$NILS_{min/max}$ = 2.30 / 2.52
nilsE = 1.22
DoF = 67.35nm

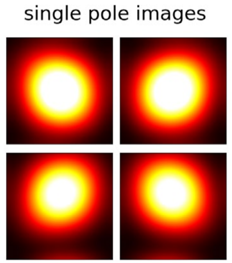
shift=6.8nm

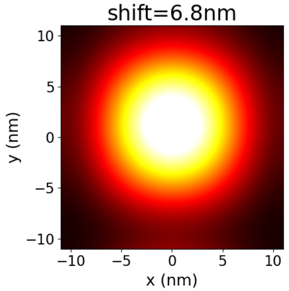


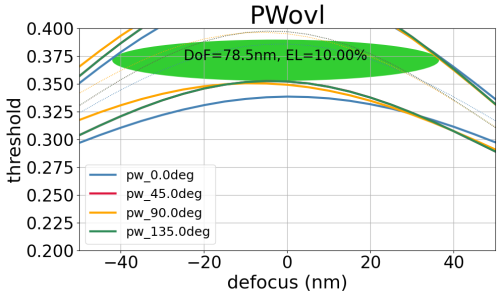
sizeX = 16.6nm
sizeY=15.6nm
thickness=44.6nm









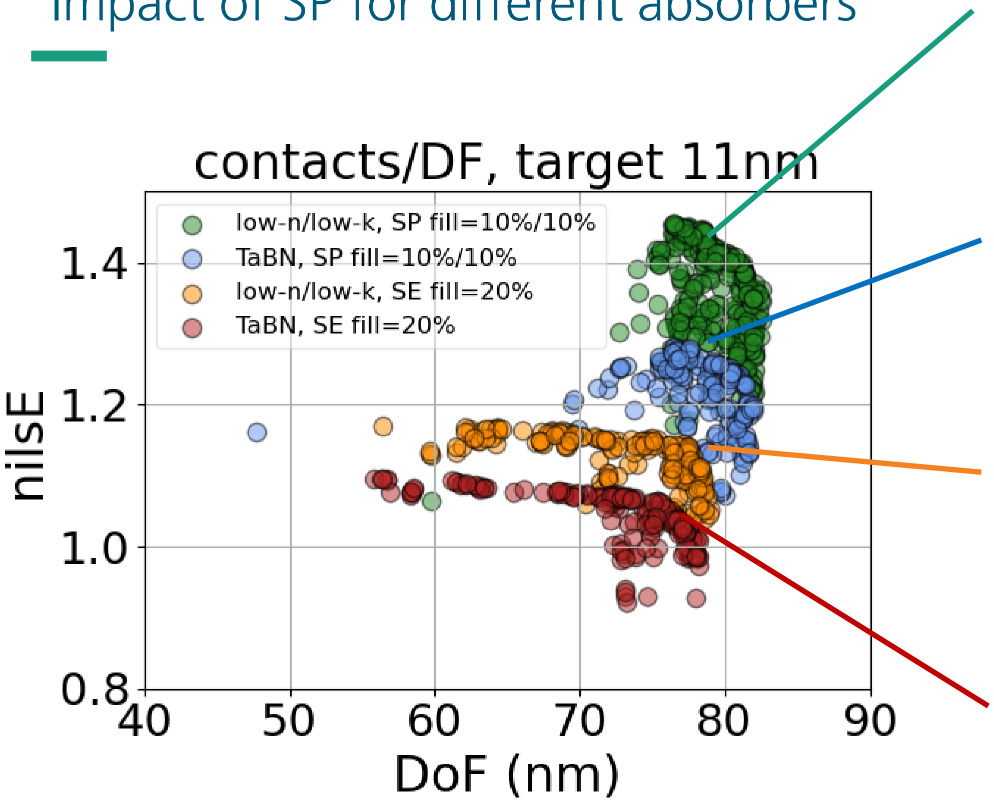


thrSizeRef = 0.386
pos = (0.00 / 1.23) nm
$CD_{min/max}$ = (11.00 / 11.32) nm
ΔCD = 0.32 nm
$NILS_{min/max}$ = 2.33 / 2.47
nilsE = 1.45
DoF = 78.51nm

- ➢ SP with dedicated SMO suggests larger width, larger σ, *smaller height, smaller absorber thickness*
- ➢ SP with dedicated SMO exhibits
  - significantly improved threshold-to-size and nilsE (driven by the larger biasing in x)
  - slightly improved NILS and DoF

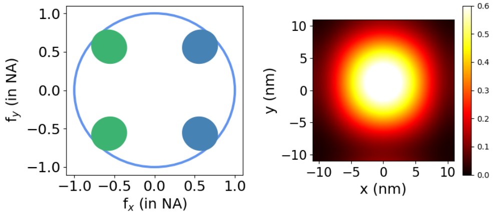
Pareto sampling

Impact of SP for different absorbers

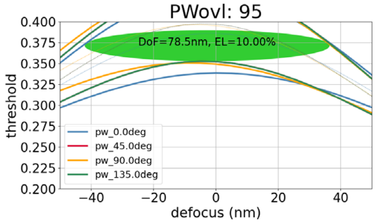


CONTACT: 95
dualMP, shift = 6.8 nm
target = 11.0 nm
pitch = (22.0 / 22.0) nm
size = (16.6 / 15.6) nm
n = 0.900, k = 0.020
thickness = 44.6 nm

source: QP_ELLIPSE
sigma=0.80 rx=0.23
rot=45.00 fill=0.20
defocus = -5.0nm

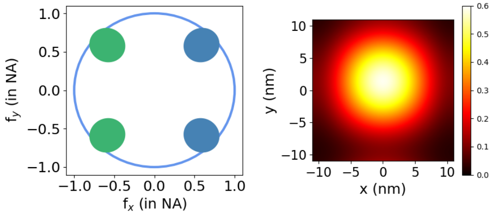


THRS = 0.386
NILS$_{min}$=2.33
DoF = 78.5 nm

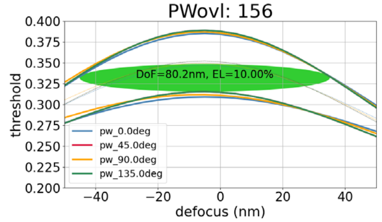


CONTACT: 156
dualMP, shift = 6.5 nm
target = 11.0 nm
pitch = (22.0 / 22.0) nm
size = (16.5 / 14.6) nm
n = 0.950, k = 0.031
thickness = 59.7 nm

source: QP_ELLIPSE
sigma=0.83 rx=0.23
rot=45.00 fill=0.20
defocus = -5.0nm

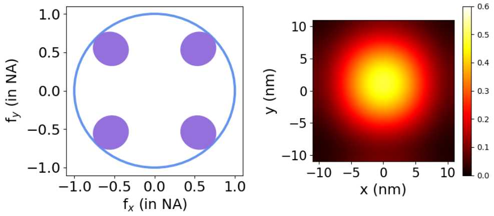


THRS = 0.347
NILS$_{min}$=2.13
DoF = 80.3 nm

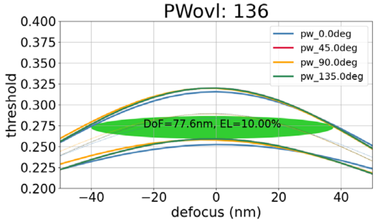


CONTACT: 136
QP_ELLIPSE
target = 11.0 nm
pitch = (22.0 / 22.0) nm
size = (12.8 / 16.1) nm
n = 0.900, k = 0.020
thickness = 47.5 nm

source: QP_ELLIPSE
sigma=0.77 rx=0.23
rot=45.00 fill=0.20
defocus = 0.0nm

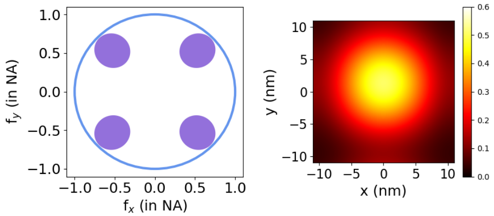


THRS = 0.284
NILS$_{min}$=2.14
DoF = 77.6 nm

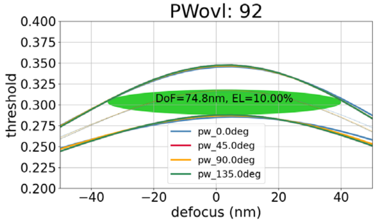


CONTACT: 92
QP_ELLIPSE
target = 11.0 nm
pitch = (22.0 / 22.0) nm
size = (13.8 / 15.9) nm
n = 0.950, k = 0.031
thickness = 59.9 nm

source: QP_ELLIPSE
sigma=0.75 rx=0.23
rot=45.00 fill=0.20
defocus = 4.0nm



THRS = 0.315
NILS$_{min}$=1.90
DoF = 74.8nm

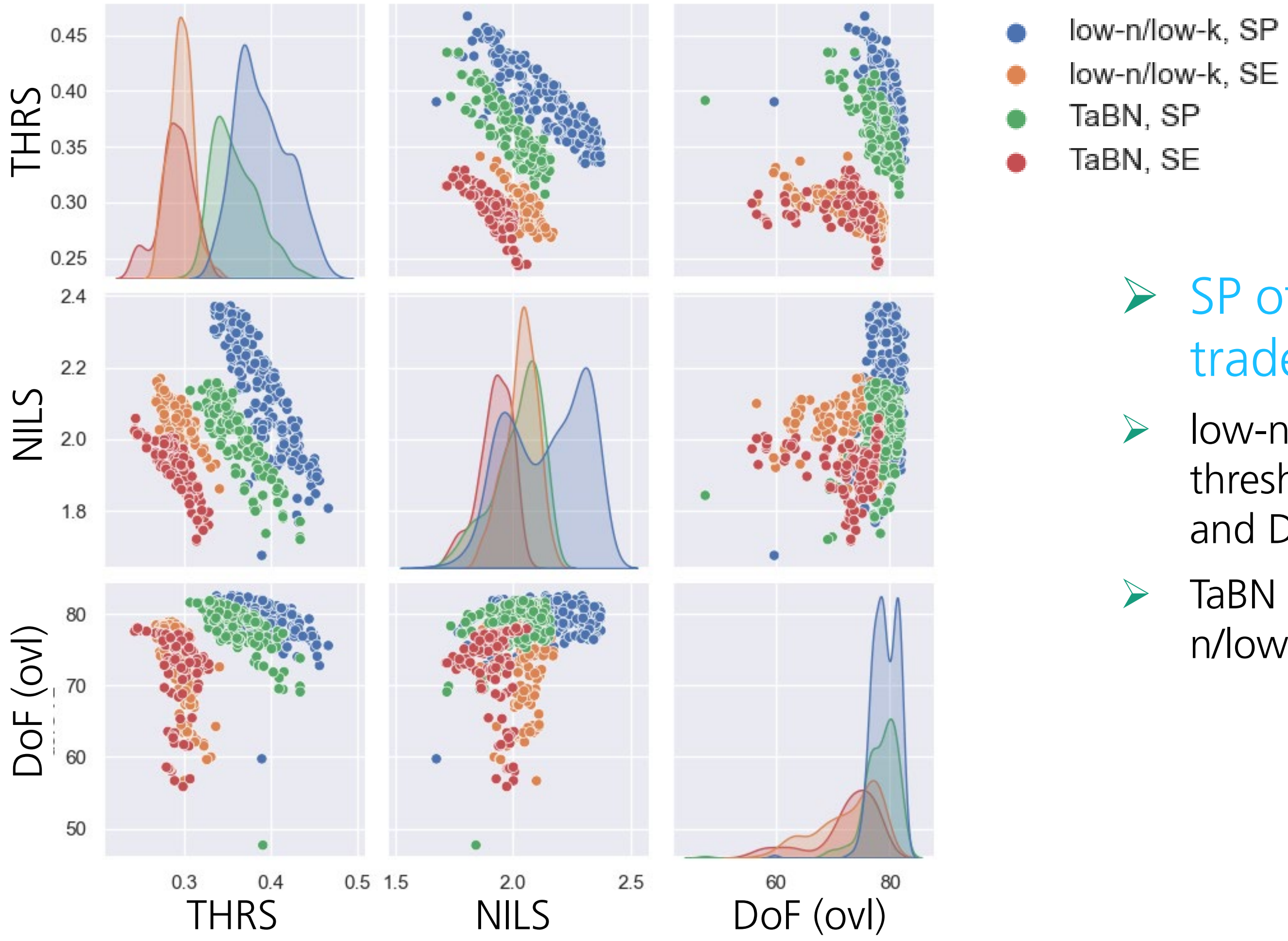


- Split pupil exposure provides significantly larger gain than low-n/low-k absorber
- SP: Low-n/low-k performs better than low-n/high-k (not shown here)
- Free variation of n & k in accessible parameter range does not provide significant improvements

- target: 11nm, pitch: 22nm
- pupil fill: 20% (SE), 10%/10% SPE
- variables: bias, ΔbiasXY, absorberThickness:
- 25nm – 65 nm,
  sigmaQPcenter, QPaspect, focus
- objectives: THRS (max), nilsE (max), ΔCD (min)

Analysis of Pareto Data for square contacts/DF

Comparison of exposure strategies (SE;SP) and absorbers (low-n/low-k; TaBN)

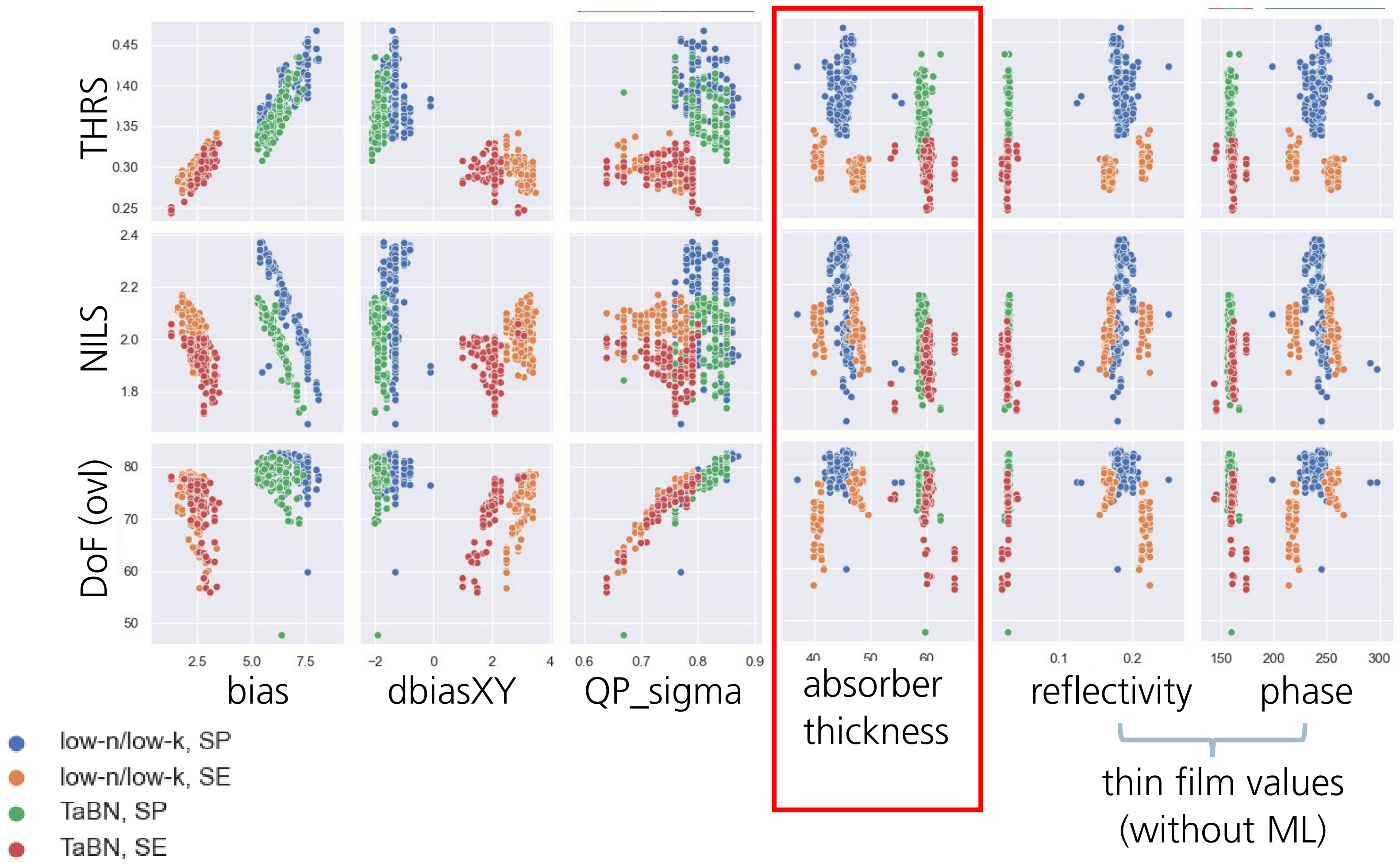


- ➢ SP offer significantly better THRS and better tradeoff between NILS and THRS
- ➢ low-n/low-k with split pupil exposure (SP) enables largest threshold, NILS and DoF, e.g. NILS > 2.3 with THRS >0.4 and DoF>75nm
- ➢ TaBN with SP performs significantly better than low-n/low-k with single exposure

- target: 11nm, pitch: 22nm
- pupil fill: 20% (SE), 10%/10% SPE
- variables: bias, ΔbiasXY, absorberThickness:
- 25nm – 65 nm,
  sigmaQPcenter, QPaspect, focus
- objectives: THRS (max), nilsE (max), ΔCD (min)

Analysis of Pareto Data for square contacts/DF

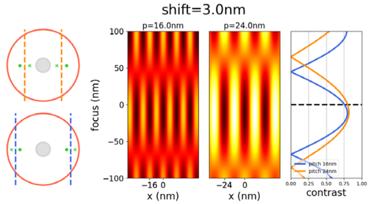
Comparison of exposure strategies (SE;SP) and absorbers (low-n/low-k; TaBN)

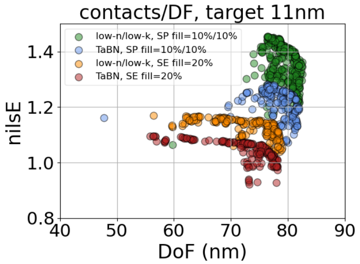


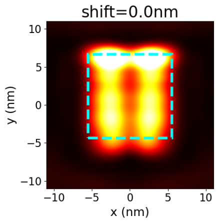
- ➢ Optimum absorber thickness differs between single exposure and split pupil exposure

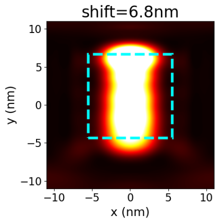
Outline

- **Background and problem statement**
  - **Basic idea of split pupil (dual monopole) exposures**
  - Overview on settings, methods and procedures
- Problem analysis
  - Pupil plots of image metrics
  - Exploration of parameter space by Pareto sampling
  - Understanding of root causes by near field analysis
- Selected further learnings
  - Contributors to improved imaging performance
  - Extendibility towards smaller k_1
- Conclusions and outlook





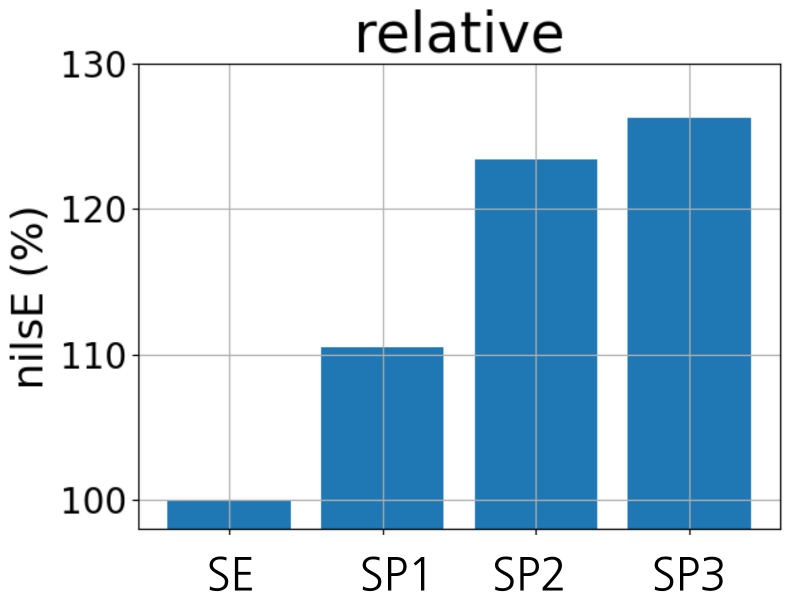




proc.featureType = "CONTACT"
proc.absorberN/K: 0.09/0.02
target = 11 nm, pitch = 22 nm

Overal performance improvements of Split Pupil exposures

Contributions of wafer shift, OPC/SMO and absorber thickness: summary



3 % ↑ SP3: shift + OPC/SMO & abs. thickness

13 % ↑ SP2: shift + OPC/SMO (abs. thickness from Ref.)

10.5 % ↑ SP1: shift only (OPC/SMO & abs. thickness from Ref.)

Ref. SE: OPC/SMO & abs. thickness

- Wafer shift improves NILS
- SP-aware OPC/SMO improves THRS

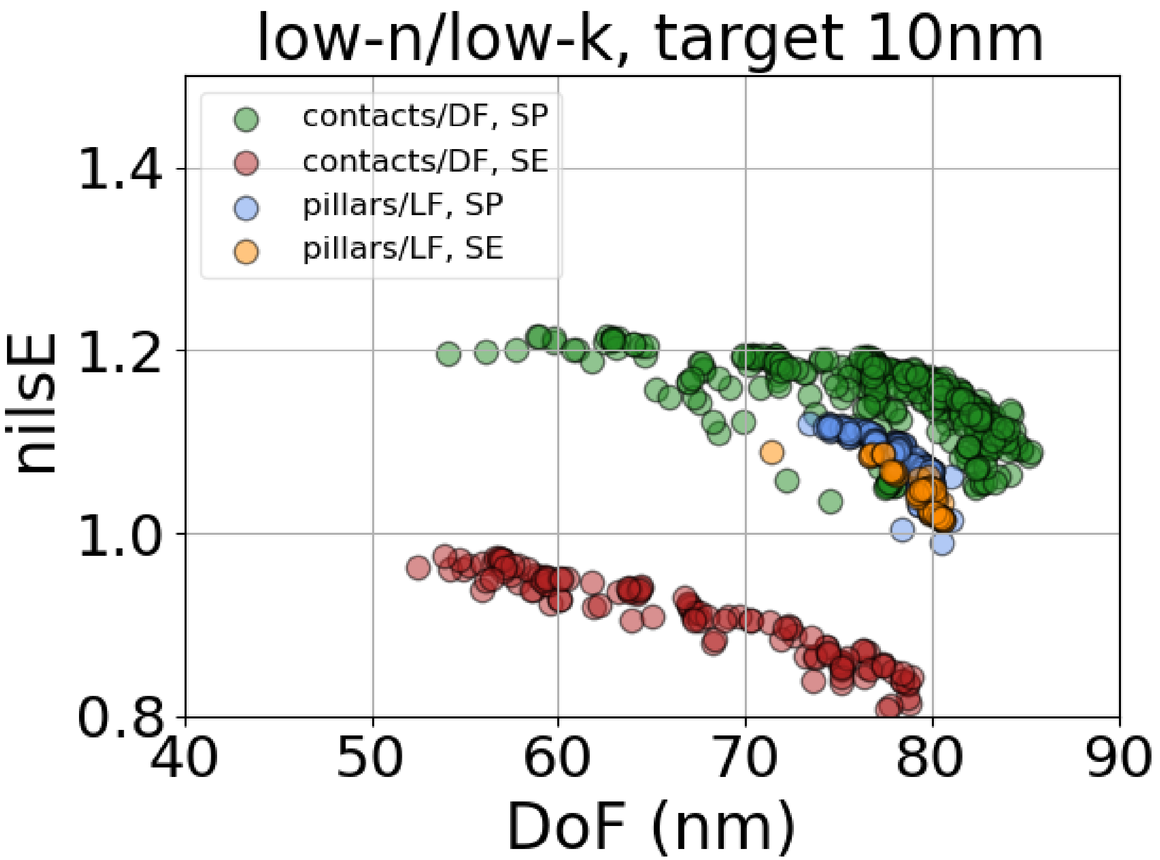
} > 20 % improvement

- Mask absorber thickness can be used for fine tuning: few % improvement

DF – dark field
LF – light field
SE – single exposure
SP – split pupil exposure

Extendibility towards smaller k1

Performance for 10nm target (20nm pitch):

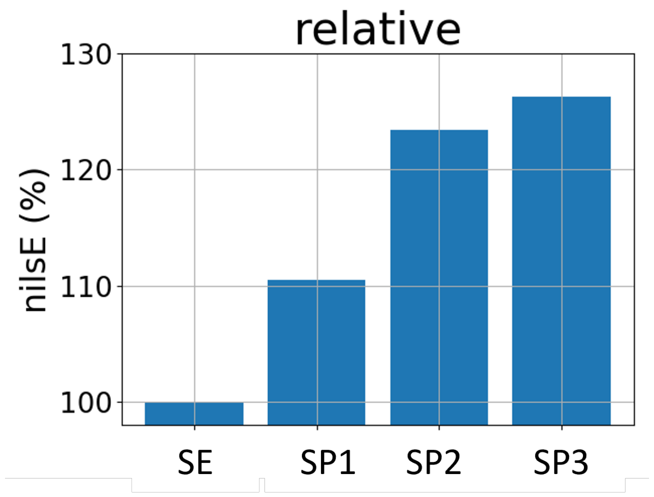


- Insufficient imaging performance for contacts/DF using single exposure
- Comparable imaging performance for pillars/LF using SP and SE
- Comfortable imaging performance for contacts/DF using split exposure

SMO – source mask optimization
ILT – inverse lithography technology

Conclusions and outlook

- Split pupil exposures (SP) are beneficial for 2D features
- Gain depends on tonality, source filling, absorber material and target
- Application of SP has significant impact on SMO: OPC (biasing), optimum source shape and can even impact to optimum absorber thickness
- Flexible (AI enhanced) SMO algorithms/software can take care about the increased complexity
- Combination of low-n absorbers, SP and flexible/multi-objective SMO can push low k_1 high NA imaging to its ultimate limits
- How about split pupil aware ILT?



3 % ↑ SP3: shift + OPC/SMO & abs. thickness

13 % ↑ SP2: shift + OPC/SMO (abs. thickness from Ref.)

10.5 % ↑ SP1: shift only (OPC/SMO & abs. thickness from Ref.)

Ref. SE: OPC/SMO & abs. thickness

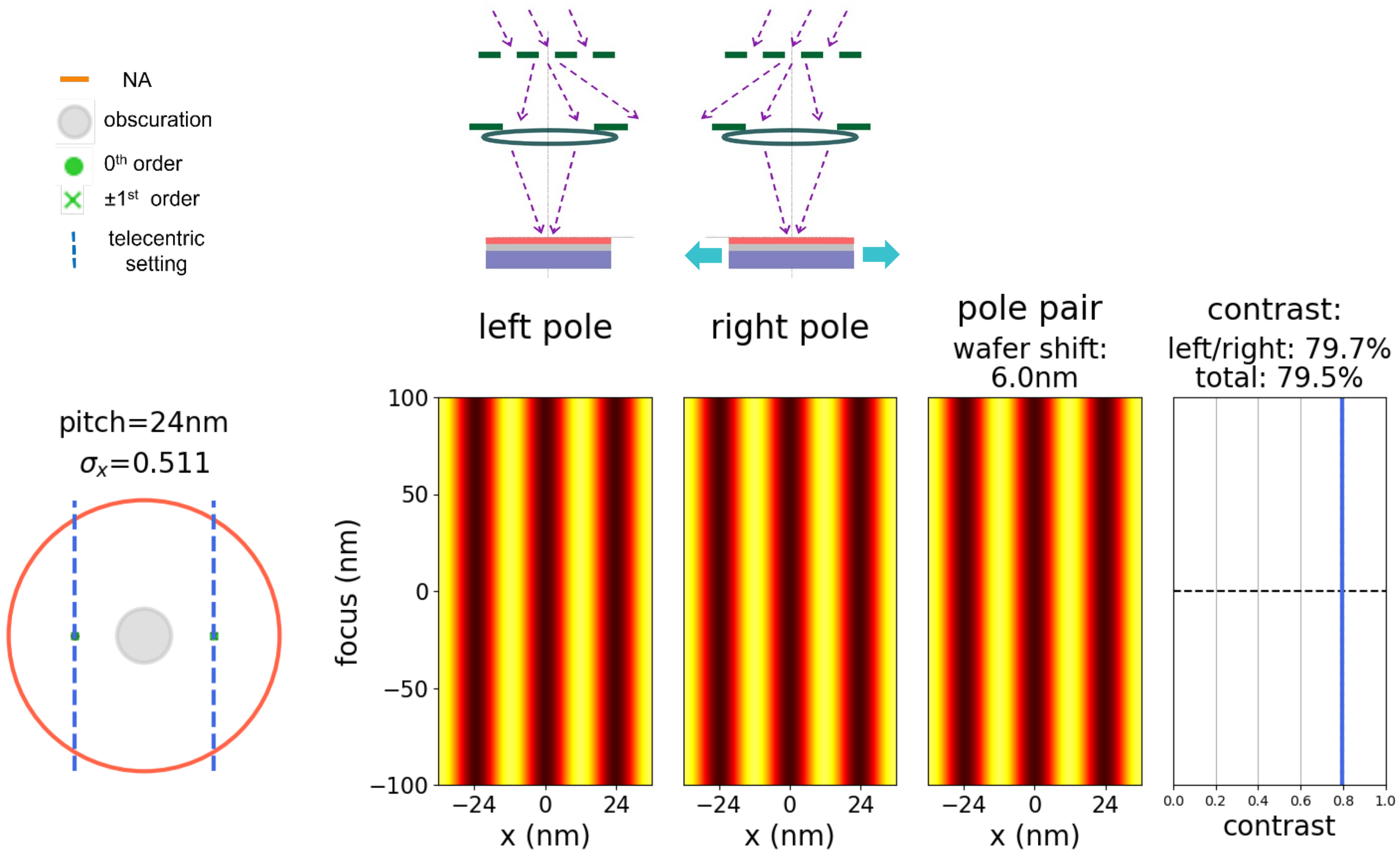
**practical limitation due to reduced throughput and alignment of source (and photoresist) are beyond the scope of this work*

Backup:

settings:
- absorber: low-n, low-k, 40nm
- multilayer: Mo/Si, 2nm Ru-capping
- dipole (2 points)

Basic idea of split pupil exposure

Example: dual monopole, single pitch line-space-pattern (L/S)



- Image shift between left/right poles
- Superposition of images causes blurred image (contrast loss)
- Wafer shift between exposure with individual poles can compensate blur

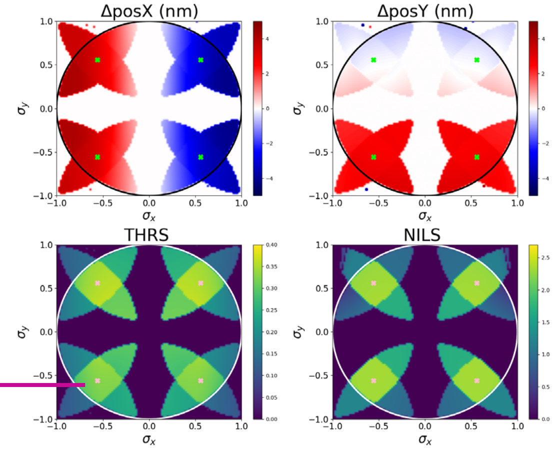
Dual monopole imaging was originally proposed by J.H. Franke et al., Journal of Micro/Nanopatterning, Materials, and Metrology 21 (2022) 030501
https://doi.org/10.1117/1.JMM.21.3.030501

Impact of tonality

Pupil diagrams of image metrics for single SP illumination

11nm contact/DF, low-n/high-k

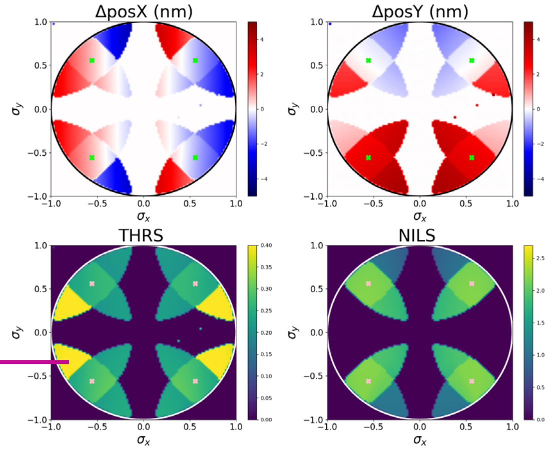
- bias= 6.4nm / 5.0nm
- thickness=58.2nm



A

11nm pillars/LF; low-n/high-k

- bias= -1.6nm / -2.8nm
- thickness=64.9nm



D

Remarks:

- Bias and thickness values for both cases are taken from Pareto of quadrupole exposure (no split) with largest DoF and nilsE

Contacts/DF:

- Largest THRS and NILS in Zone A (4-beam interference)
- Strong image shift between left/right poles

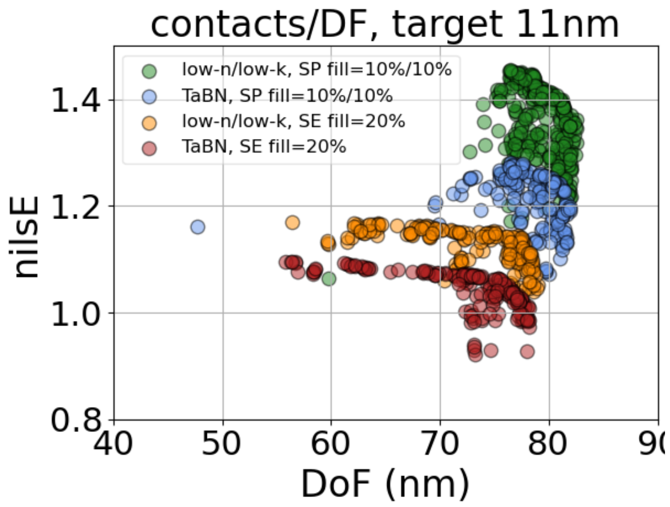
Pillars/LF:

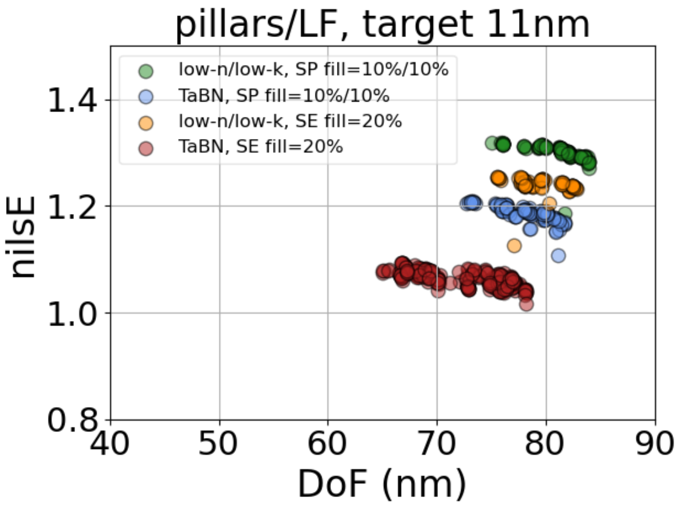
- Zone A
  - Slightly lower THRS and NILS
  - Significantly smaller image shifts
- Zone D
  - Significantly larger THRS in zone D
  - Large image shift and failed feature detection for extraction of NILS along all cut directions

plot_paretoComparison-47.py

Impact of tonality

Pareto: contacts/DF vs. pillars/LF





representative data from Pareto front:

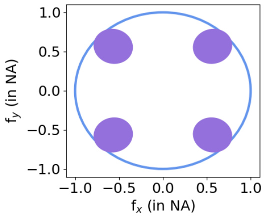
	SE: TaBN	**SE: low-n, low-k**	**SP: TaBN**	**SP: low-n, low-k**
DF: THRS	0.315	0.284	0.347	**0.386**
LF: THRS	0.284	0.288	0.312	0.301
DF: NILS	1.90	2.14	2.13	2.33
LF: NILS	1.96	2.30	2.09	**2.35**

- Contacts/DF with pupil split exposure provides the ultimate best performance for nilsE/LCDU
- Pupil split exposure provides only small performance improvement for pillars/LF
- Contacts/DF using SP and low-n/low-k provides highest THRS;
  best use of EUV light enabled by guiding of light and large biasing
- Pillars/LF using SE or SP can provide comparable (or slightly better) NILS

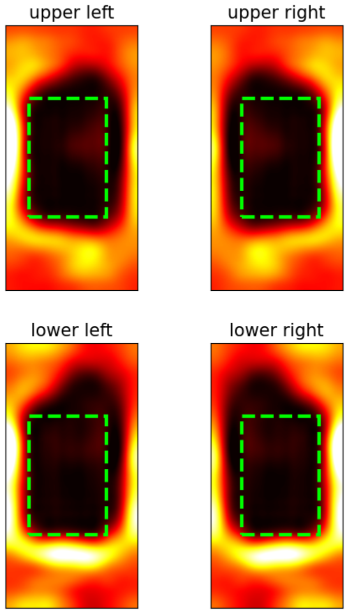
Impact of tonality

Near field analysis for pillars (LF) optimized for single exposure (SE)

- low-n/low-k
- target: 11nm, pitch: 22nm
- sizeX = 12.8nm, sizeY=9.8nm
- thickness=40.1nm

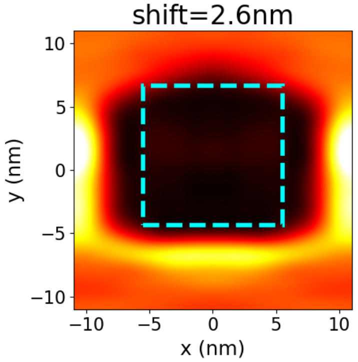


near field (NF) intensity for single (point) poles
shift=2.6nm



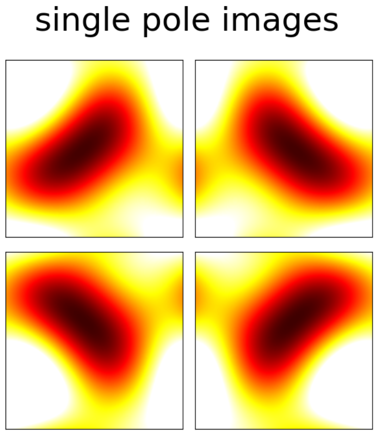
mask feature

sum of NF intensities
(wafer scale)

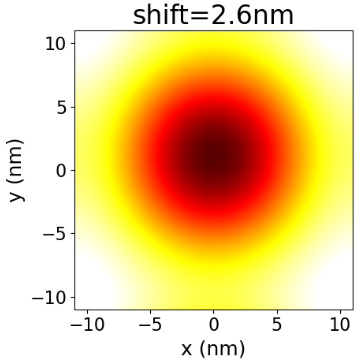


wafer target

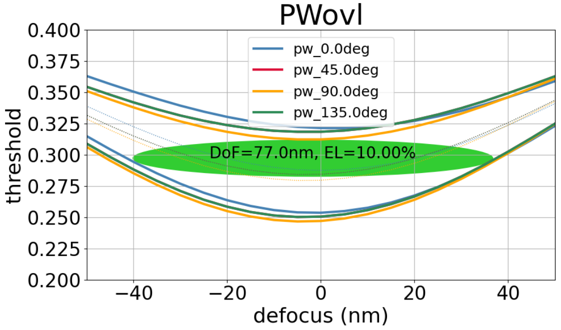
single pole images



total image
(at best focus)



process windows
(along 4 cuts)



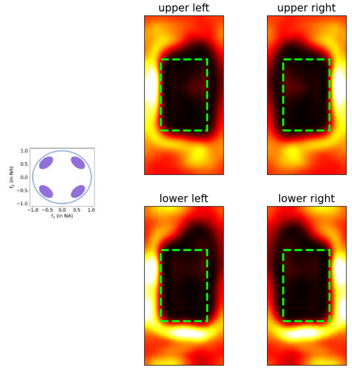
- ➢ Superposition of scattered light from the low-n absorber provides a reasonable bright surrounding of the target
- ➢ Wafer shift decreases performance

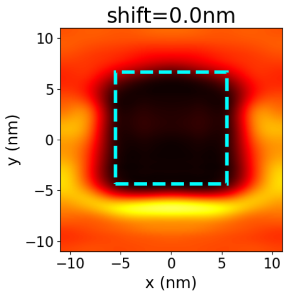
- low-n/low-k
- target: 11nm, pitch: 22nm

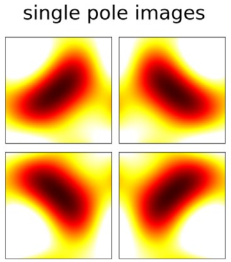
Impact of tonality

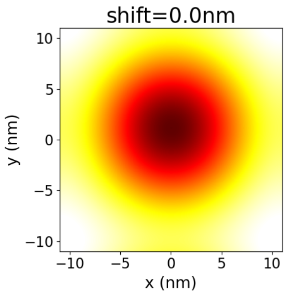
Understanding of root causes by near field analysis: impact of shift on pillars/LF

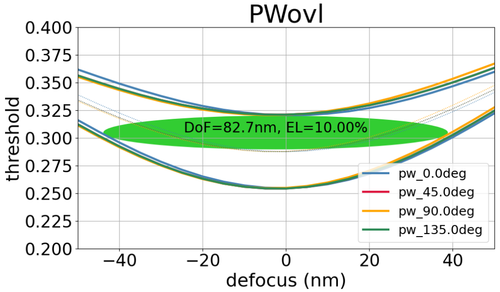
NF intensity poles sum NF pole images total image process windows



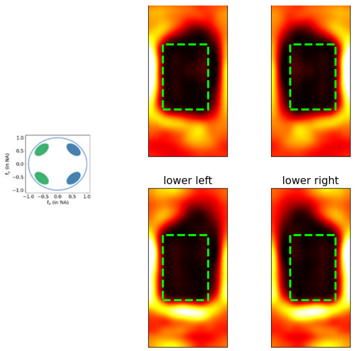


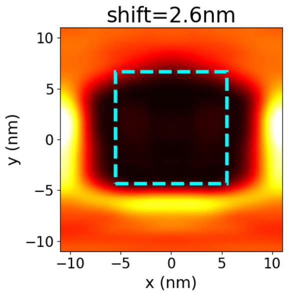


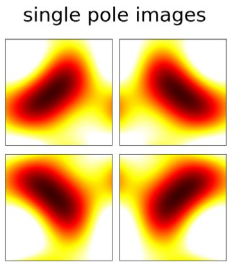


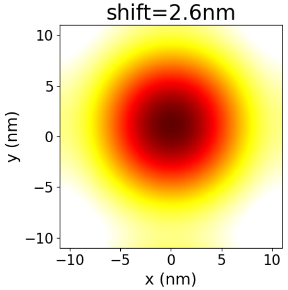


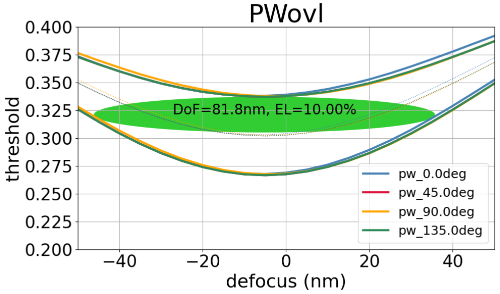
thrSizeRef = 0.288
pos = (0.00 / 1.15) nm
$CD_{min/max}$ = (11.00 / 11.01) nm
ΔCD = 0.01 nm
$NILS_{min/max}$ = 2.30 / 2.32
nilsE = 1.23
DoF = 82.68nm











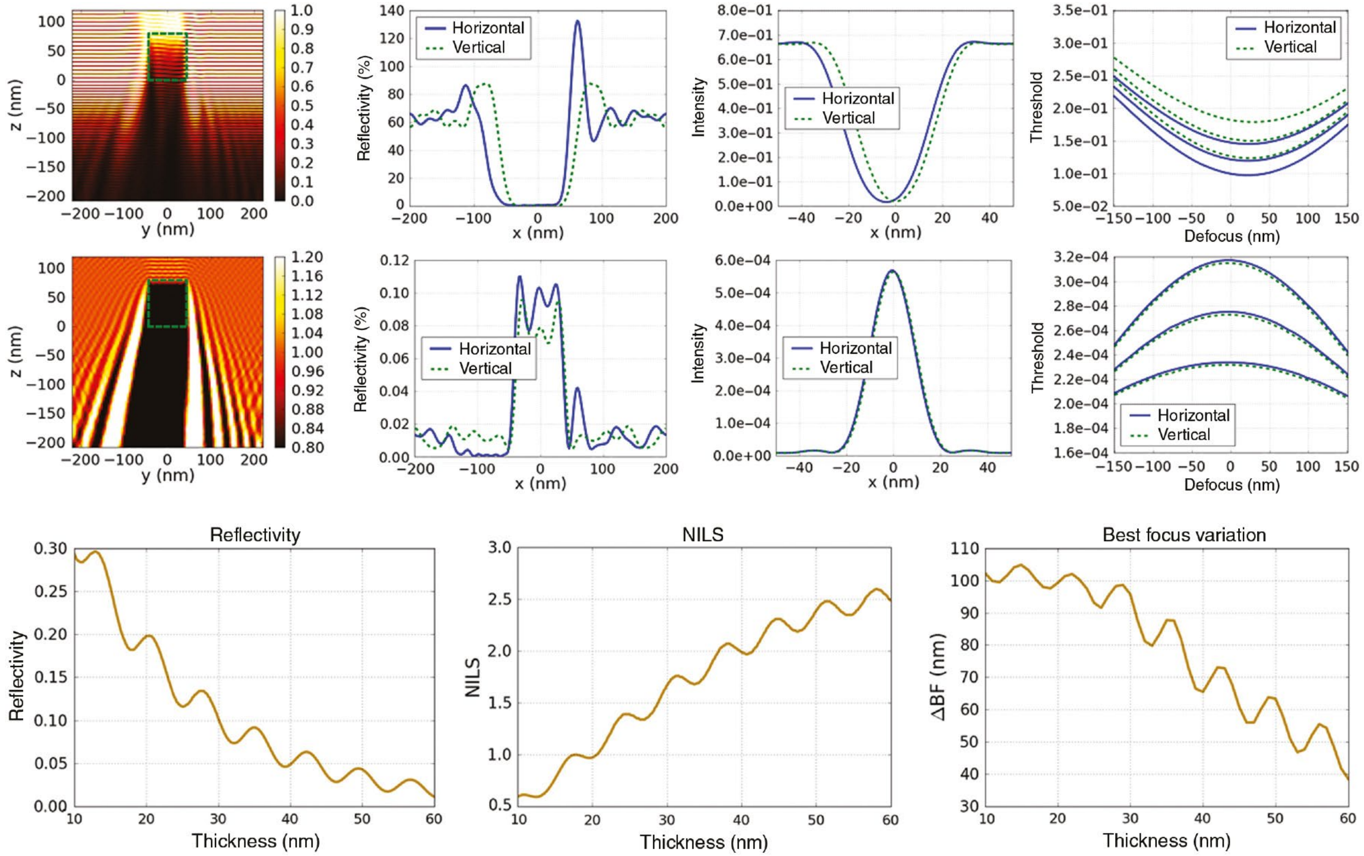
thrSizeRef = 0.303
pos = (0.00 / 1.17) nm
$CD_{min/max}$ = (11.00 / 11.03) nm
ΔCD = 0.03 nm
$NILS_{min/max}$ = 2.32 / 2.33
nilsE = 1.28
DoF = 81.85nm

- ➢ Only minor improvement of nilsE (THRS) by SP, small optimum wafer shift

Root cause of swings: double images

Observations for line-space patterns

- reflections from multilayer and from top of absorber cause two contrast inverted images
- interference and variation of the phase shift between the top absorber-reflected and the multilayer-reflected light cause a swing behavior of the total amount of the total reflected light and many other imaging characteristics like NILS and BF



A. Erdmann et al.: "Characterization and mitigation of 3D mask effects in extreme ultraviolet lithography", Adv. Optical Techn. 6 (2017) 187-201, https://doi.org/10.1515/aot-2017-0019

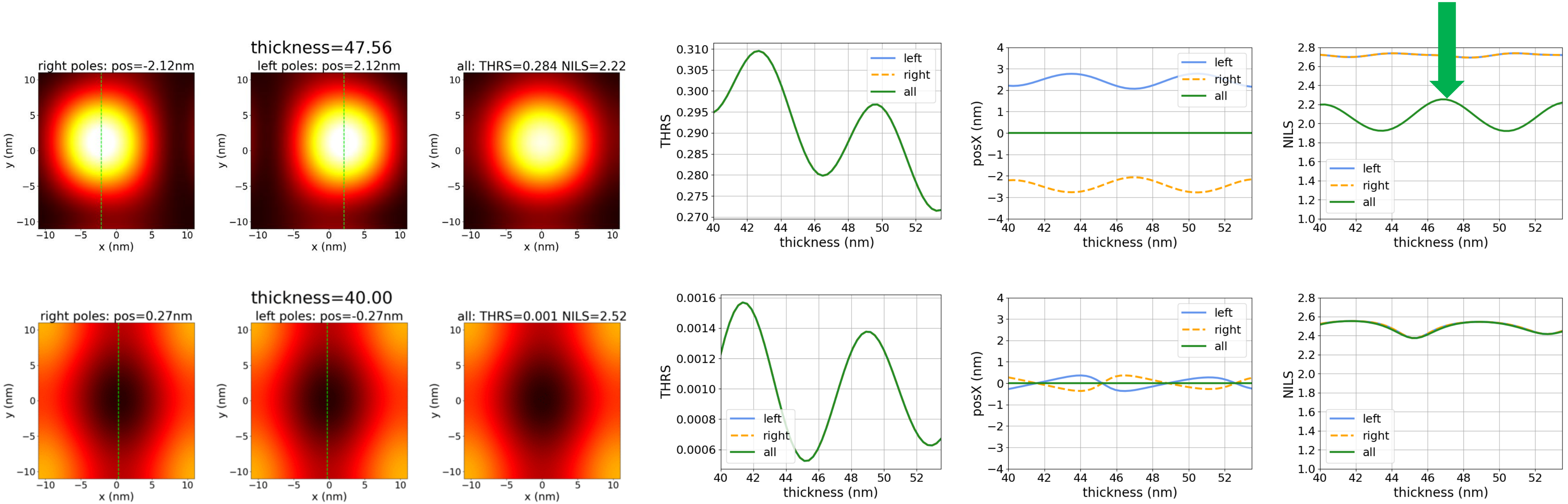
Double images for single exposure

proc.featureType = "CONTACT"
sizeX/Y: 12.8/16.1nm
proc.absorberN/K: 0.09/0.02
proc.qp_sigma/fill: 0.77/0.2

proc.includeML = True
proc.positionShift = 0.0nm
proc.defocus = 0.000nm
vThicknessImages_015/16.zip

image with ML:
(ML reflection
+ top absorber
reflection)

image wo ML:
top (and bottom)
absorber refl.



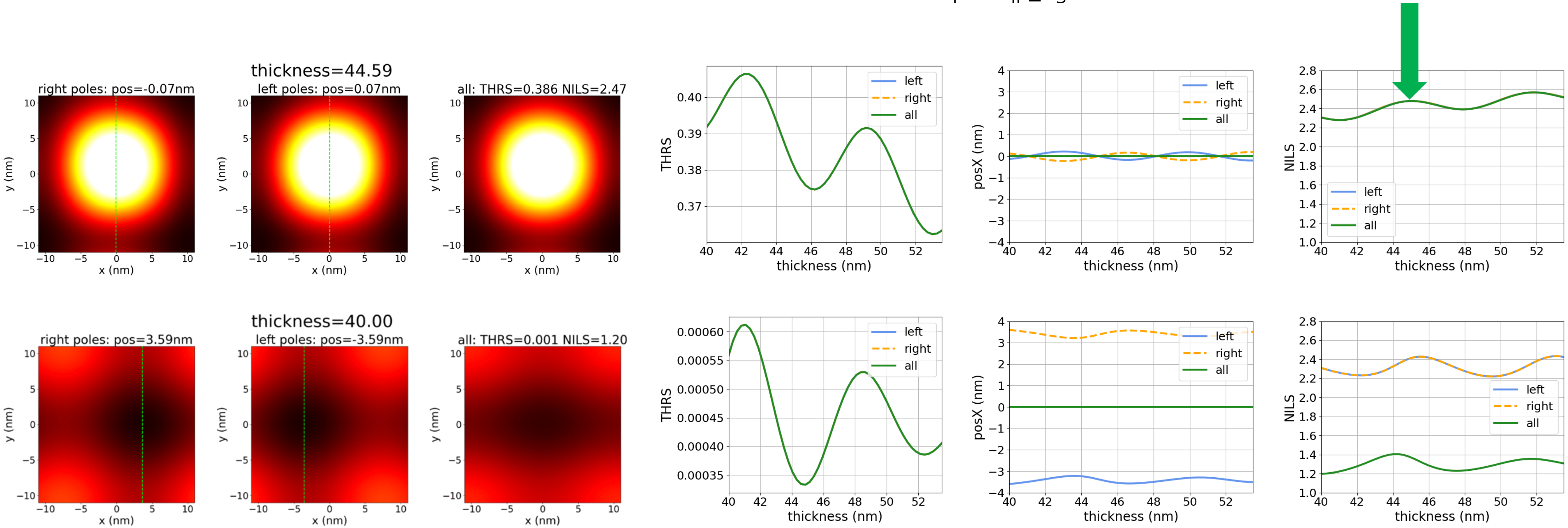
- ➢ Contrast inverted images
- ➢ Image wo ML exhibits
  - almost no shift between poles (less/no contrast blur) → **with proper phase it can act as a weak attPSM**
  - significant variation of intensity vs. thickness
  - difference in contrast between x and y cuts (due different bias)
- ➢ Optimum absorber thickness close to maxima of "threshold-swings" wo ML to "exploit" top absorber image

Double images for Split Pupil Exposure

proc.featureType = "CONTACT"
sizeX/Y: 16.6/15.6nm
proc.absorberN/K: 0.09/0.02
proc.qp_sigma/fill: 0.8/0.2
proc.includeML = True
proc.positionShift = 6.8nm
proc.defocus = -0.005
vThicknessImages_011/12.zip

image with ML:
(ML reflection + top absorber reflection)

image wo ML:
top (and bottom) absorber refl.

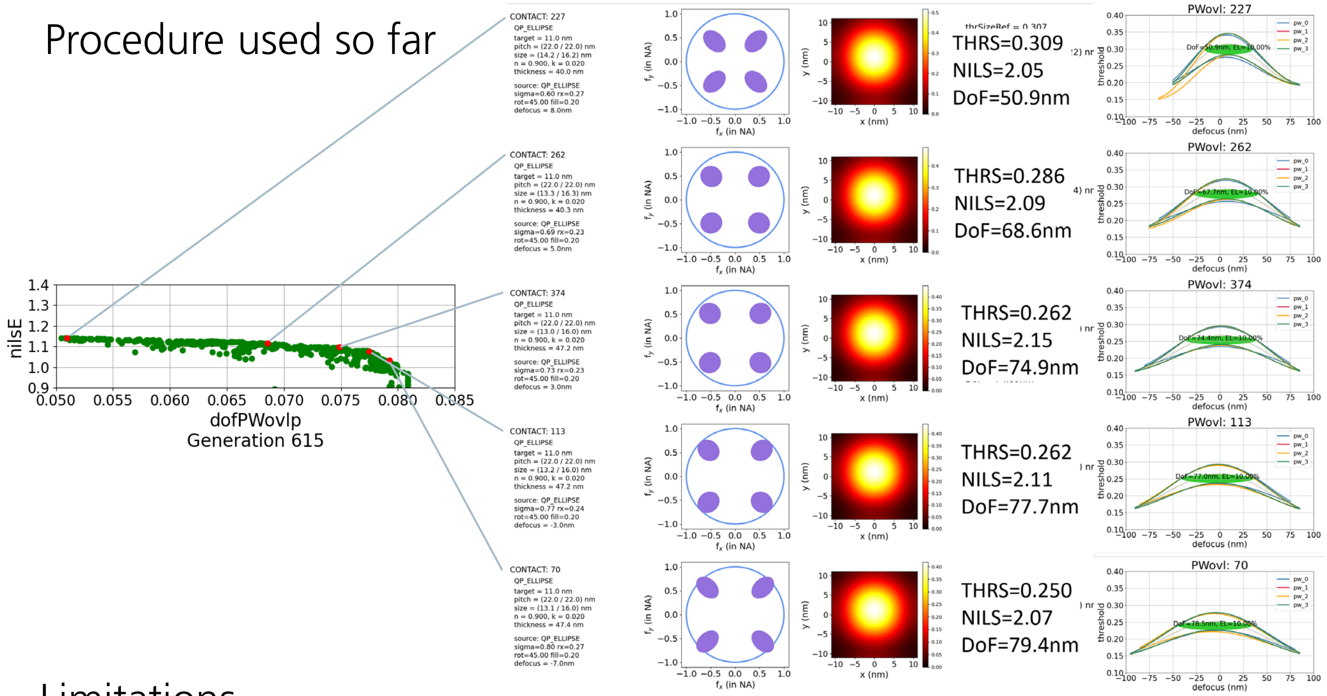


- Contrast inverted images
- Image wo ML exhibits
  - significant shift between poles (pronounced contrast blur)
  - significant variation if intensity vs. thickness
- Optimum absorber thickness at minima of “threshold-swings” wo ML to reduce negative impact of top absorber image

Comprehensive evaluation of Pareto data

General remarks

Procedure used so far



Limitations

- Complete evaluation of few selected data points/settings only
- Missing information on global trends, e.g. NILS or THRS vs. bias
- Limited evaluation of settings: e.g. no data on reflectivity, integrated intensity (ImInt)

Evaluate all points/data on Pareto front

Goal of this investigation is to understand:

- Separate contributions of THRS and NILS to nilsE
- Identification of additional global tendencies
- Comparison between:
  - single exposure (SE) and split pupil exposure (SP)
  - dark field (DF) and light field (LF)
  - materials
    - low-n, low-k: n=0.9, k=0.02
    - TaBN: n=0.95, k=0.031
    - nkVar: n=[0.87, 1.0]. k=[0.01, 0.08]

This was done for:

- target: 11nm, pitch: 22nm
- pupil fill: 20% (SE), 10%/10% SP

Abbreviations used in this document

EUV : Extreme Ultra Violet
CRAO : Chief Ray Angle of incidence at Object
CRAA : Chief Range Azimuthal Angle of incidence
CD : critical dimension
NA : numerical aperture
DoF : depth of focus
l – wavelength
OPC : Optical proximity Correction
SMO : Source Mask Optimization
ILT : Inverse Lithography Technology
PSM : Phase Shift Mask
NILS : Normalized Image Log Slope
LER : Line Edge Roughness
THRS : Threshold-to-size
nilsE : NILS Efficiency = NILS x THRS^{½}
DF : Dark field
ILF : Light field
SE : Single Exposure
SP : Split Pupil exposure
QP : Quadrupole
PW : Process Window