GenISys
Advancing the Standard

GenISys Team
November 4th, 2020

Proximity Effect in E-Beam Lithography

Overview and Agenda

Please note that this session will be recorded (may be discoverable in legal matters). By joining these webinar sessions, you automatically consent to such recordings. If you do not consent to being recorded, do not join the session.

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Webinar Outline

Part	Subject	Date
1	Electron Scattering and Proximity Effect	07-Oct-2020, 6:00pm CEST, 12:00pm EDT, 9:00am PDT
2	Dose PEC Algorithm and Parameter	14-Oct-2020, 6:00pm CEST, 12:00pm EDT, 9:00am PDT
3	Optimization of Dose PEC Parameter	21-Oct-2020, 6:00pm CEST, 12:00pm EDT, 9:00am PDT
4	Process Effect, Calibration and Correction	28-Oct-2020, 5:00pm CET, 12:00pm EDT, 9:00am PDT
5	Shape PEC – "ODUS" Contrast Enhancement	04-Nov-2020, 6:00pm CET, 12:00pm EST, 9:00am PST
	Break	11-Nov-2020 -- No Session
6	3D Surface PEC for greyscale lithography	18-Nov-2020, 6:00pm CET, 12:00pm EST, 9:00am PST
	Thanksgiving Week	25-Nov-2020 -- No Session
7	T-Gate PEC	02-Dec-2020, 6:00pm CET, 12:00pm EST, 9:00am PST

- The webinar series will explain one of the most important techniques in advanced e-beam lithography. Modern E-beam systems are able to form small spot sizes in nm range. In principle this enables to achieve feature sizes in nm-range. In practice this is limited by physics, chemistry and tool limitations…

Doc Daugherty, Nezih Unal

November 4th, 2020

Proximity Effect in E-Beam Lithography

Part 5: Shape PEC – "ODUS" Contrast Enhancement

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Outline

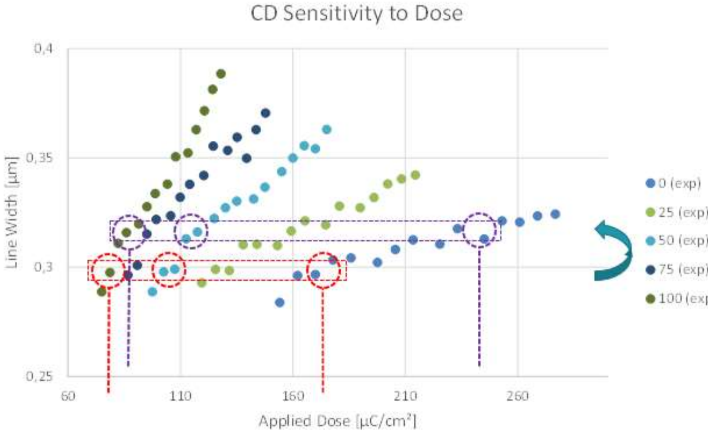
- Part 4 Summary: Process Effects, Calibration and Correction
- Shape vs. Dose
- OverDose-UnderSize (ODUS)
- Resist Profile with ODUS
- Application Example
- Summary
- Q&A

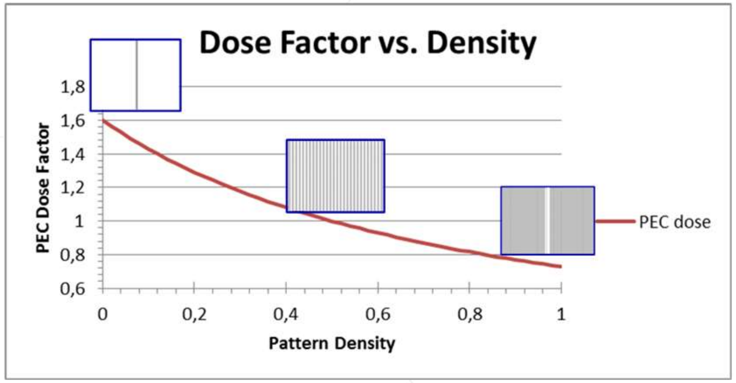
Calibration Summary

- “Real” processes have many effects beyond electron scattering
  - Lateral development from finite resist contrast (density dependent)
  - Process (e.g. etching) / metrology bias
  - Additional midrange process effects
- The “Base Dose” is most important process parameter
  - Simple method –> Dose matrix for dose to size
- Issue
  - Processes Bias is not known (e.g. lateral development, etch bias)
  - Process Bias is typically density dependent
- Solution
  - Proper **PEC Dose-Range** for PSF is the correct working point
  - The dose ratio D_{iso} / D_{dense} only depends on back-scattering (NOT on process point)

$$D_f = \frac{1}{1 + BE(2\rho - 1)}$$

BE = 0.4
ρ = 1 for dens / 0 isolated





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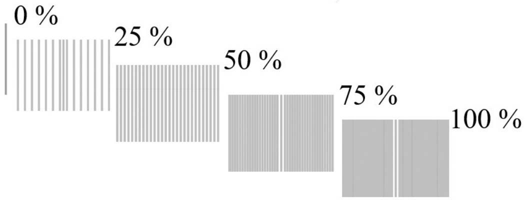
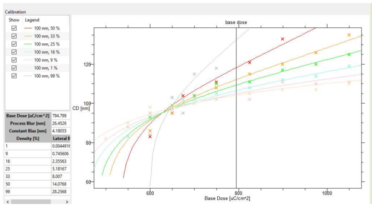
Process Calibration Procedure

Expose Dose Matrix, Process, & Measure Calibration Pattern

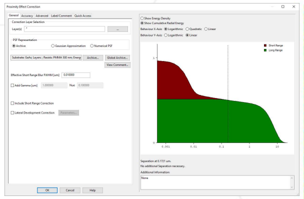


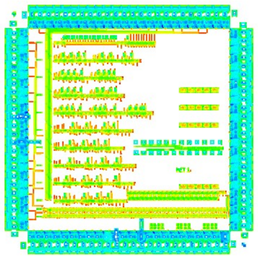
Use TRACER to fit the data and determine correction parameters



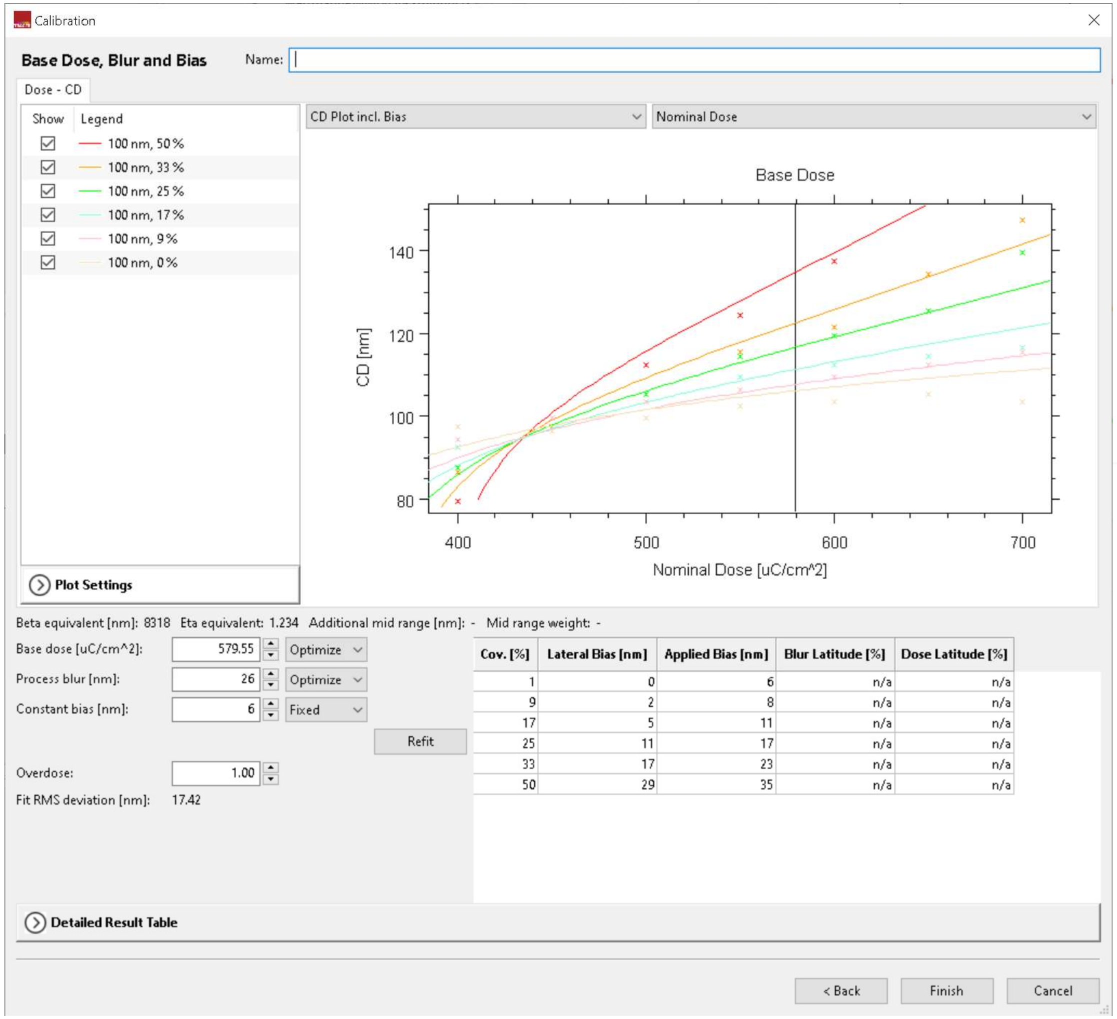
- Base Dose
- Effective Process Blur
- Constant and density-dependent bias
- UC/OC Mix Factor

Apply correction parameters using BEAMER's PEC module





Calibration Results



Beta equivalent [nm]: 8318 Eta equivalent: 1.234 Additional mid range [nm]: - Mid range weight: -

Base dose [uC/cm^2]: 579.55 Optimize

Process blur [nm]: 26 Optimize

Constant bias [nm]: 6 Fixed

Overdose: 1.00

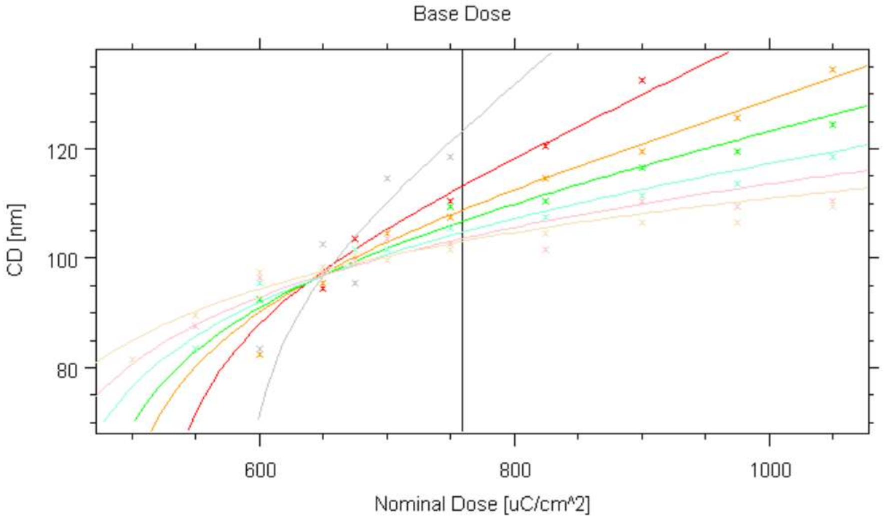
Fit RMS deviation [nm]: 17.42

Cov. [%]	Lateral Bias [nm]	Applied Bias [nm]	Blur Latitude [%]	Dose Latitude [%]
1	0	6	n/a	n/a
9	2	8	n/a	n/a
17	5	11	n/a	n/a
25	11	17	n/a	n/a
33	17	23	n/a	n/a
50	29	35	n/a	n/a

- The fitting procedure results in an “Extended Point Spread Function”, adding terms to the scattering PSF
  - Optimal Base Exposure Dose
  - Effective Process Blur
  - Constant Process Bias
  - Density-dependent Bias terms to compensate
  - Additional Midrange Gaussian
  - “Mix-Factor”

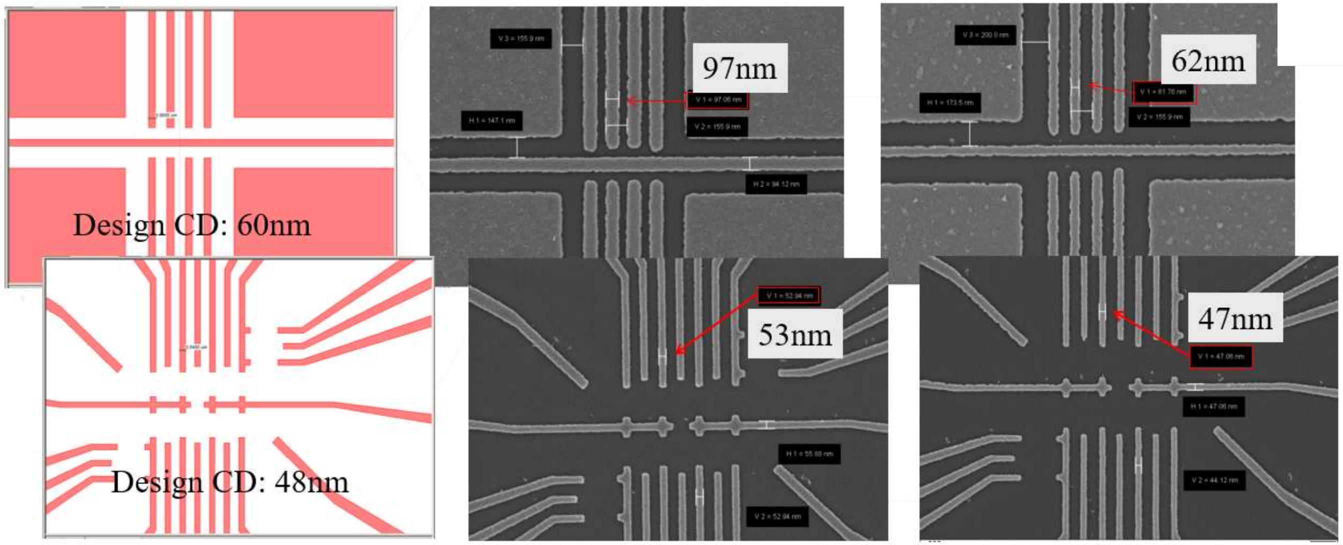
Calibration Summary

- PEC Process parameter (working point) depends on Resist contrast:
- Density dependent (lateral development) bias
  - Low contrast / high density subrate -> larger bias
- iso-focal shift (image iso-focal -> process iso-focal)
    - High-contrast requires $D_{iso}/D_{dense} = 1 + 2*BS/FS$,
    - PMMA required $D_{iso}/D_{dense} = 1 + 1.2*BS/FS$
  - Optimum Contrast / Uniform Clearing Mic-Factor



Process:
200nm PMMA on GaAs @ 100 kV
Development: 2 minutes at 12^{0}C
Calibration resulted:

- Base Dose = 795 µC/cm²
- Process Blur = 26nm
- $Bias_{0\%}$ = 4nm; $Bias_{25\%}$ = 9nm; $Bias_{50\%}$ = 18nm; $Bias_{99\%}$ = 32nm

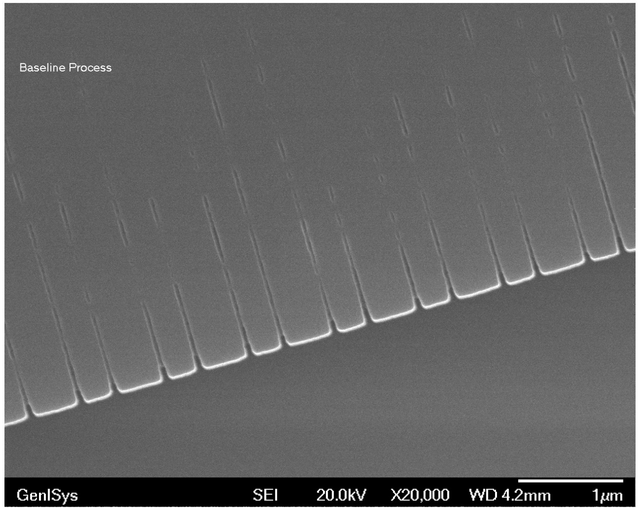


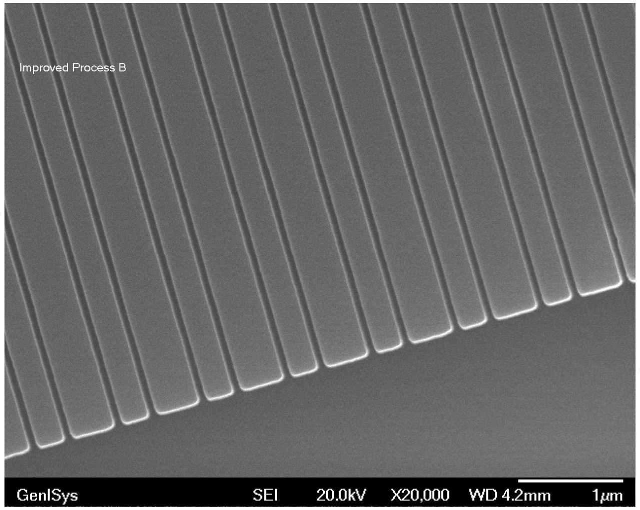
Conventional PEC Only

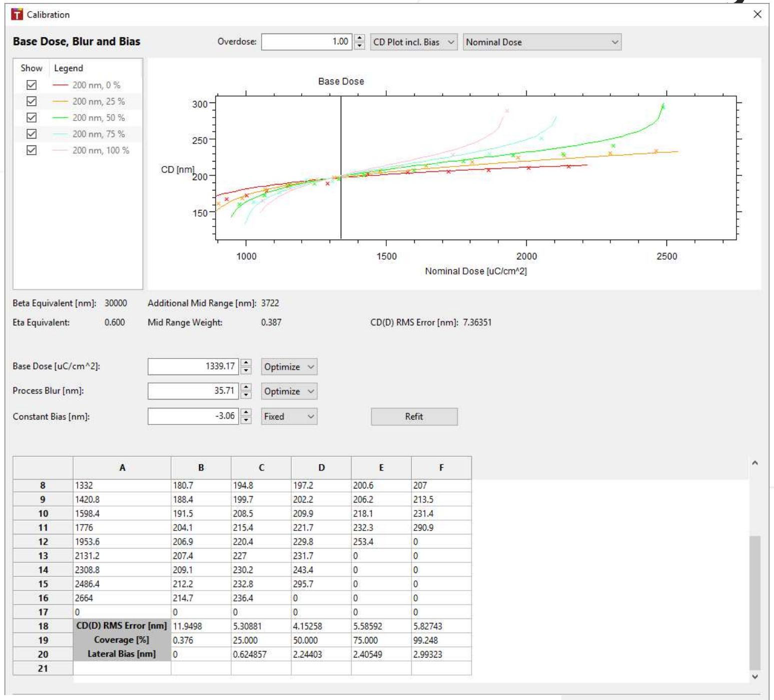
PEC with Process Calibration

Calibration Summary

- PEC Process parameter (working point) depends on
  - Resist contrast: consequence of the iso-focal shift (image iso-focal -> process iso-focal)
    - High-contrast requires $D_{iso}/D_{dense} = 1 + 2*BS/FS$,
    - PMMA required $D_{iso}/D_{dense} = 1 + 1.2*BS/FS$
  - Additional mid-range terms such as resist sensitivity changes (e.g. from catalytic reactions)
    - HSQ process correction





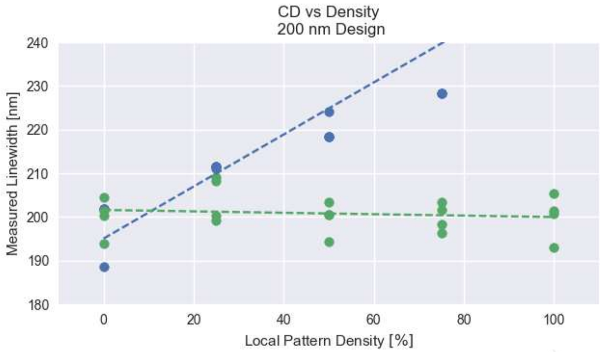


Overdose: 1.00

Beta Equivalent [nm]: 30000
Eta Equivalent: 0.600
Additional Mid Range [nm]: 3722
Mid Range Weight: 0.387
CD(D) RMS Error [nm]: 7.36351

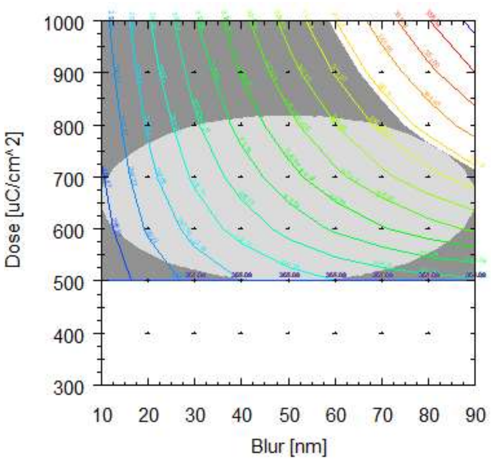
Base Dose [uC/cm^2]: 1339.17 Optimize
Process Blur [nm]: 35.71 Optimize
Constant Bias [nm]: -3.06 Fixed

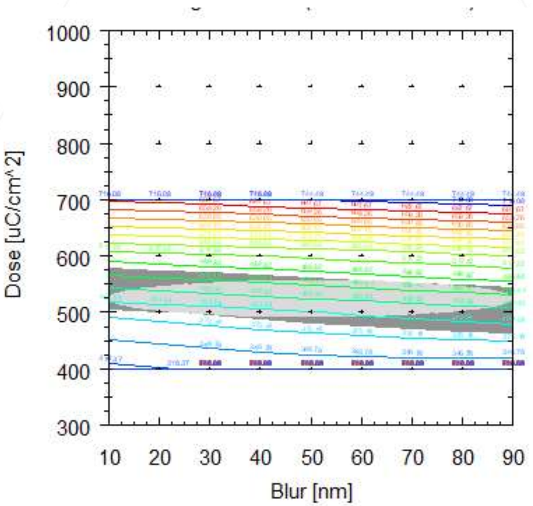
	A	B	C	D	E	F
8	1332	180.7	194.8	197.2	200.6	207
9	1420.8	188.4	199.7	202.2	206.2	213.5
10	1598.4	191.5	208.5	209.9	218.1	231.4
11	1776	204.1	215.4	221.7	232.3	290.9
12	1953.6	206.9	220.4	229.8	253.4	0
13	2131.2	207.4	227	231.7	0	0
14	2308.8	209.1	230.2	243.4	0	0
15	2486.4	212.2	232.8	295.7	0	0
16	2664	214.7	236.4	0	0	0
17	0	0	0	0	0	0
18	**CD(D) RMS Error [nm]**	11.9498	5.30881	4.15258	5.58592	5.82743
19	**Coverage [%]**	0.376	25.000	50.000	75.000	99.248
20	**Lateral Bias [nm]**	0	0.624857	2.24403	2.40549	2.99323
21						

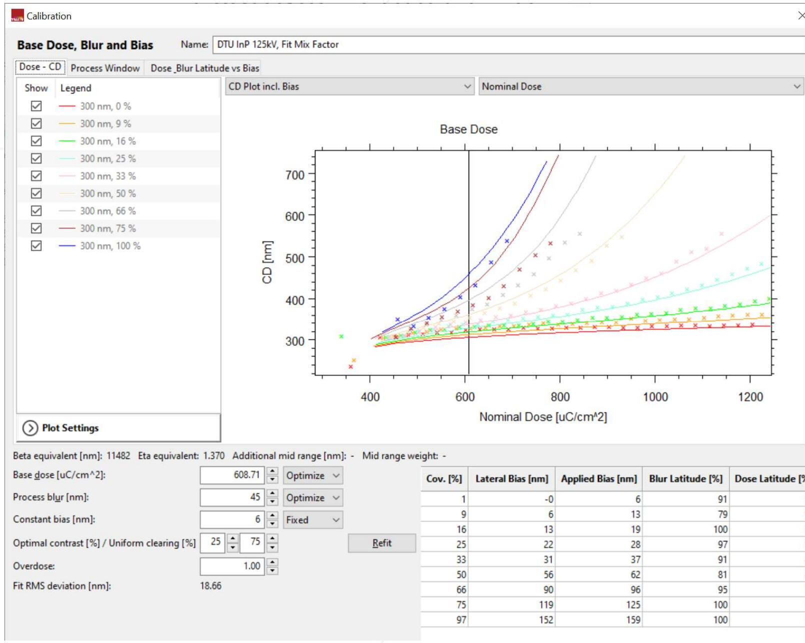


Calibration Summary

- TRACER can plot and fit the experimental data, providing the necessary process correction parameters
  - Maximizing the blur latitude important because
    - Shot size dependent focus shifts
    - Shot size dependent blur variability
  - This results in Uniform Clearing or mix factor strategies (substrate and contrast dependent)
  - Ability to play with parameters & see effects on process window







Name: DTU InP 125kV, Fit Mix Factor

CD Plot incl. Bias

Nominal Dose

Beta equivalent [nm]: 11482 Eta equivalent: 1.370 Additional mid range [nm]: - Mid range weight: -

Base dose [uC/cm^2]: 608.71 Optimize

Process blur [nm]: 45 Optimize

Constant bias [nm]: 6 Fixed

Optimal contrast [%] / Uniform clearing [%]: 25 75

Overdose: 1.00

Fit RMS deviation [nm]: 18.66

Cov. [%]	Lateral Bias [nm]	Applied Bias [nm]	Blur Latitude [%]	Dose Latitude [
1	-0	6	91	
9	6	13	79	
16	13	19	100	
25	22	28	97	
33	31	37	91	
50	56	62	81	
66	90	96	95	
75	119	125	100	
97	152	159	100	

- InP, PMMA (γ=3) @ 125kV,
- D2C known as 480µC/cm^2
- Process Iso-focal at 609µC/cm^2
  - Mix-Factor at 25/75
  - Above D2C (609*0.88 = 538µC/cm^2)

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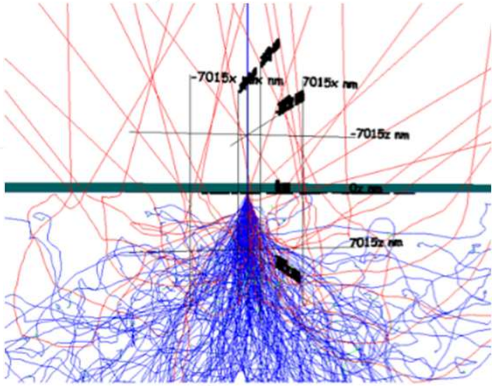
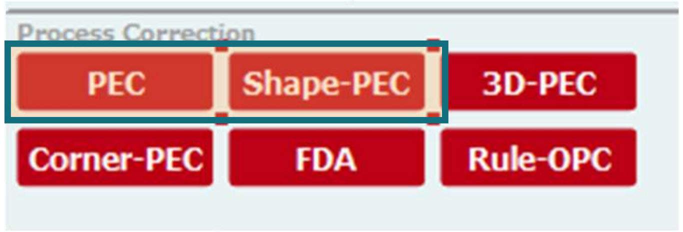
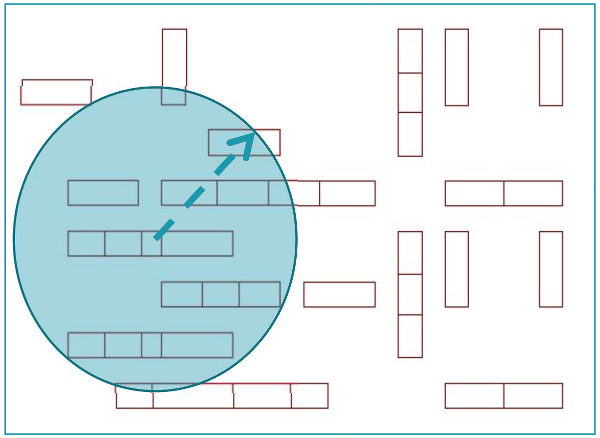
Dose or Shape

- PEC modulates the exposure dose by taking into account the PSF, effective process blur
  - LR correction pixel based
  - SR using self consistent method (feature edge based algorithm) with adjusting the dose
- Shape PEC modulates dose & layout
  - LR correction pixel based (same as Dose PEC)
  - SR using self consistent method (feature edge based algorithm) with moving the layout edge



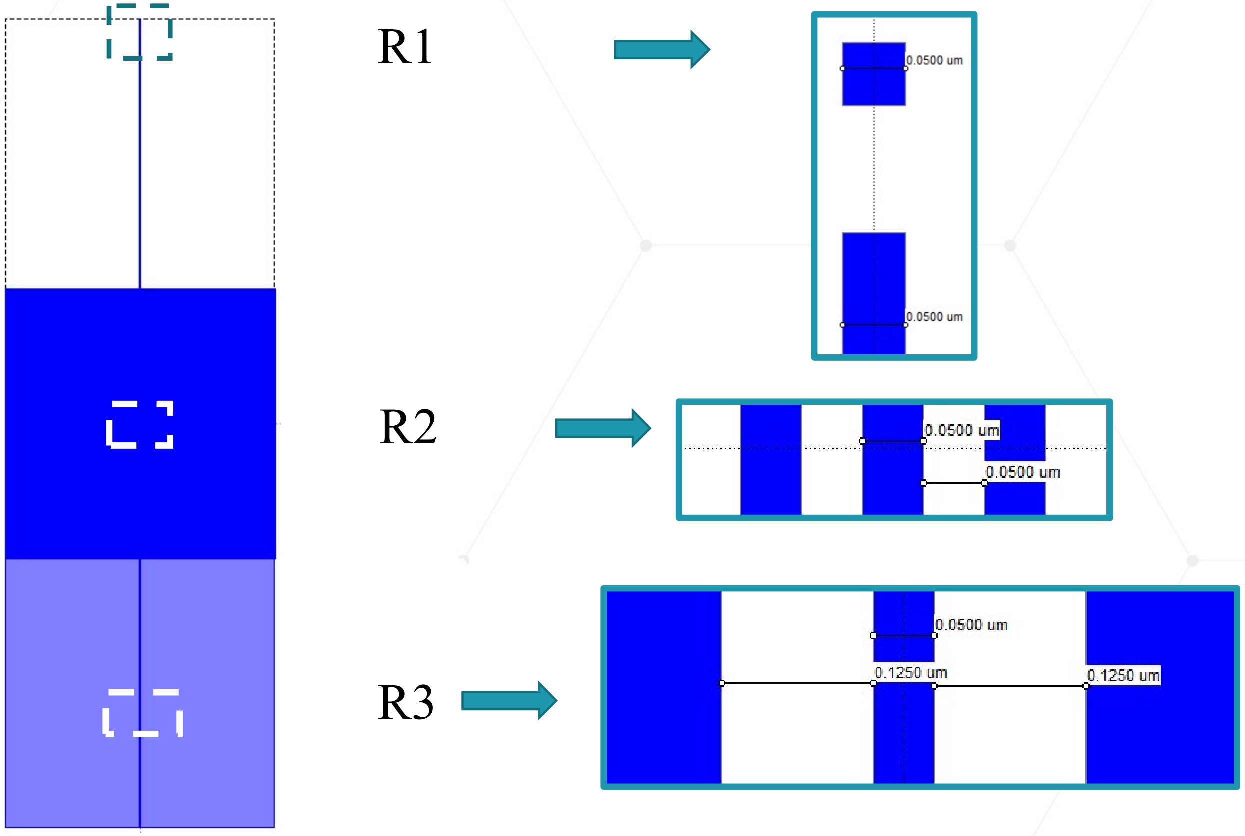
E-beam scattering





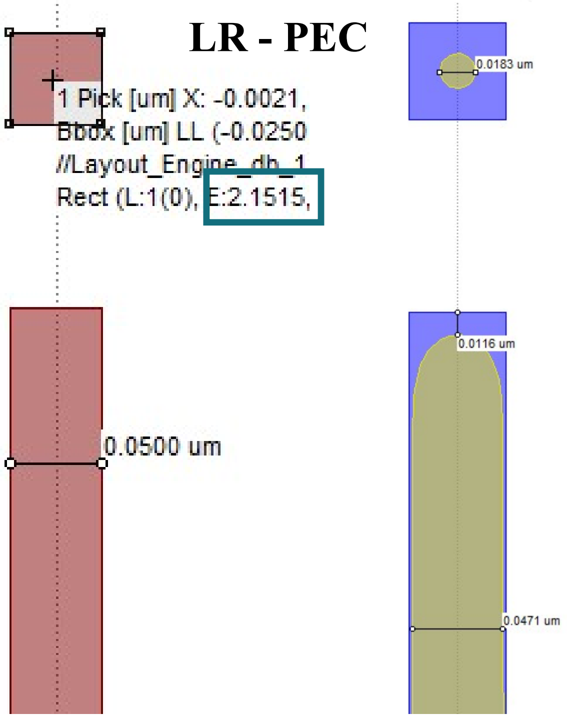
Example Pattern

- The pattern for analysis is shown below.
- Material stack: 500nm PMMA 950K is deposited on GaAs substrate
- PEC, Shape PEC, ODUS shape PEC (overdose = 2) are taken for pattern correction.



Long Range Dose Correction

- Corrections for iso by dose modulation with and without SR (blur 50nm):
  - LR PEC is compensating the energy loss due to the back scattering.
  - Short Range loss is not compensated, resulting to small size for small feature



LR - PEC

```
1 Pick [um] X: -0.0021,
Bbox [um] LL (-0.0250
//Layout_Engine_db_1
Rect (L:1(0), E:2.1515,
```

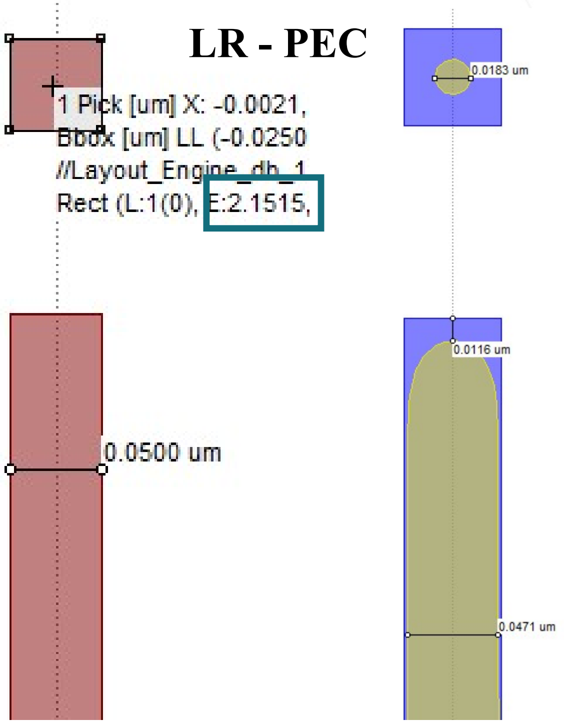
Dose = 2.15
CD = 50 nm

Shortrange effects start showing up for feature sizes:
< 3* SR Sigma
< 2* Effective Blur (FWHM)

Smaller feature need SR correction.

Short Range Dose Correction

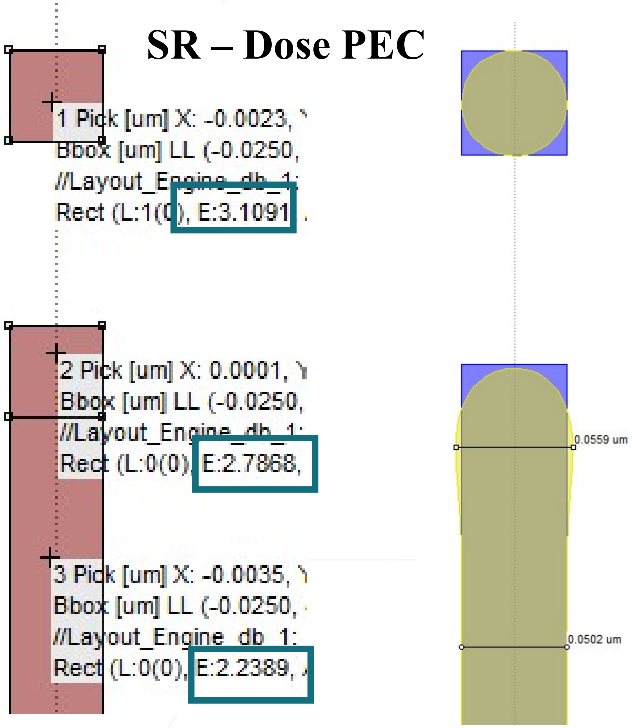
- Corrections for iso by dose modulation with and without SR (blur 50nm):
  - LR PEC is compensating the energy loss due to the back scattering.
  - SR Dose PEC is compensating short range energy loss by increasing the dose



LR - PEC

```
1 Pick [um] X: -0.0021,
Bbox [um] LL (-0.0250
//Layout_Engine_db_1
Rect (L:1(0), E:2.1515,
```

Dose = 2.15
CD = 50 nm



SR – Dose PEC

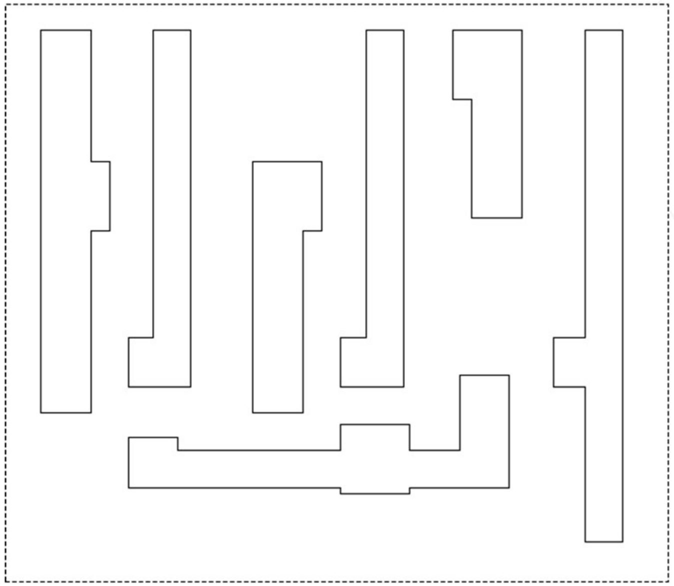
```
1 Pick [um] X: -0.0023,
Bbox [um] LL (-0.0250,
//Layout_Engine_db_1:
Rect (L:1(0), E:3.1091
```

```
2 Pick [um] X: 0.0001,
Bbox [um] LL (-0.0250,
//Layout_Engine_db_1:
Rect (L:0(0), E:2.7868,
```

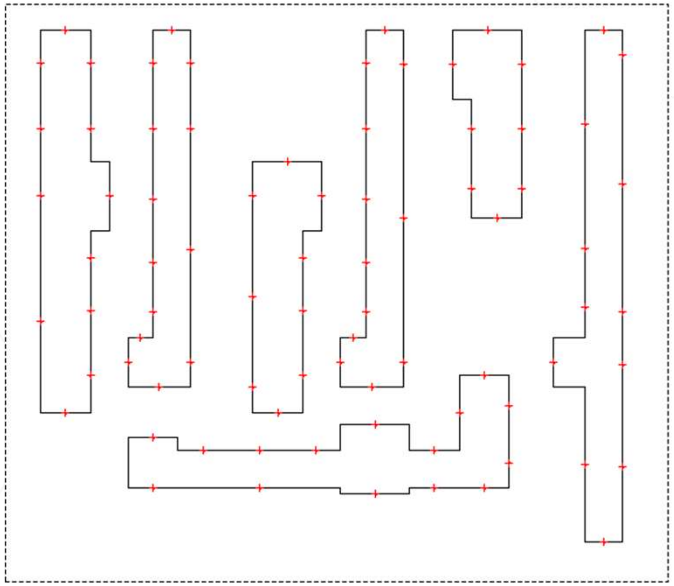
```
3 Pick [um] X: -0.0035,
Bbox [um] LL (-0.0250,
//Layout_Engine_db_1:
Rect (L:0(0), E:2.2389,
```

Dose = 2.23 – 3.1
CD = 50 nm

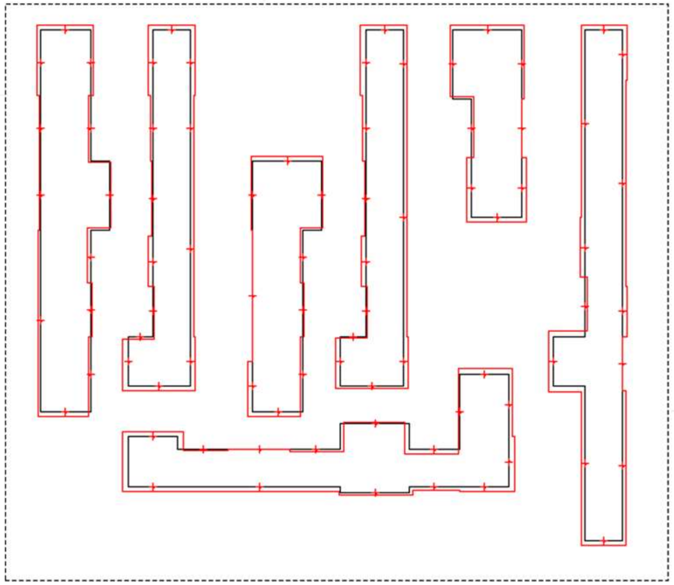
Shape PEC Principle



Shape PEC goal:
Move edges locally to compensate for short- and mid-range energy loss and obtain a uniform dose at all layout edges.

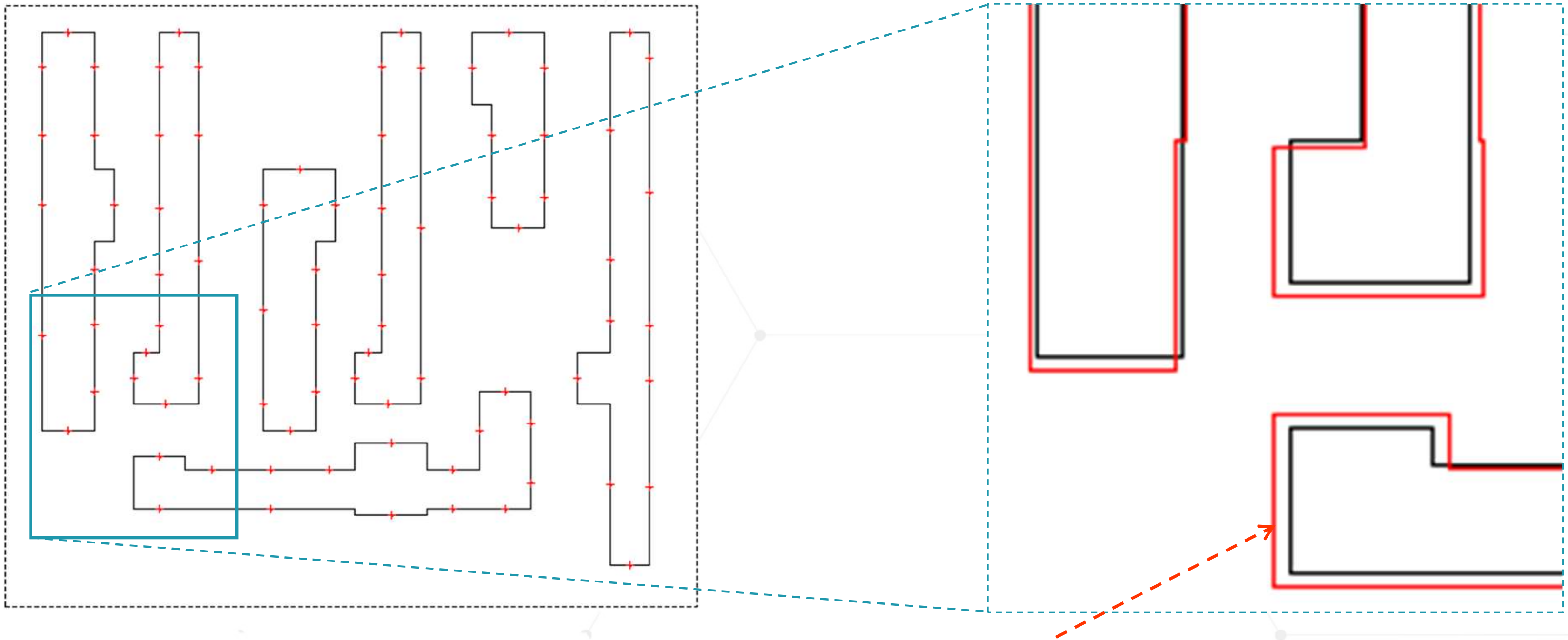


In a DRC step all edge segments are analyzed for the CD and distance to adjacent shapes.
A set of representative evaluation points (+) is defined.



Move for all PEC segments (eval. points) are **iteratively** adjusted.

Self consistent edge equalization method

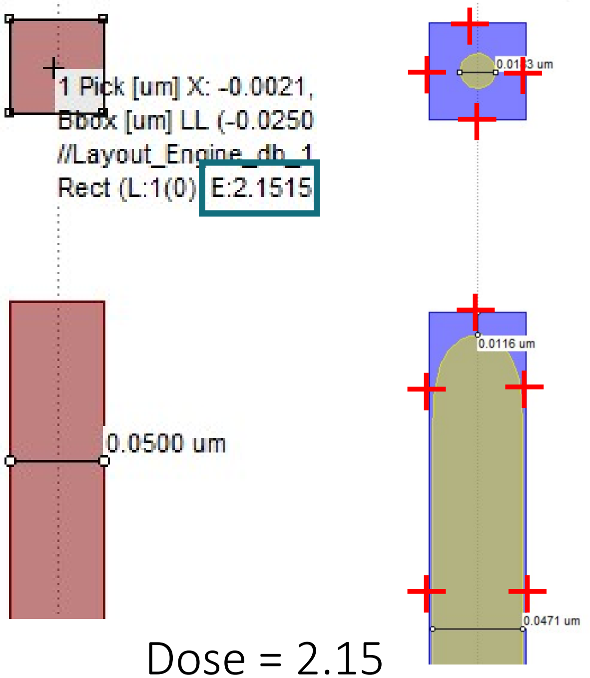


Each bias adds or subtracts exposed area : energy at the evaluation point is changed iteratively until a self consistent solution has been found, as the change of one edge influences all other neighboring changes.

Shape Correction

- SR Dose PEC vs. Shape PEC:
  - Dose PEC is compensating SR by dose increase
  - Shape PEC is compensating SR by moving feature edges
    - Better feature fidelity by „directional“ correction

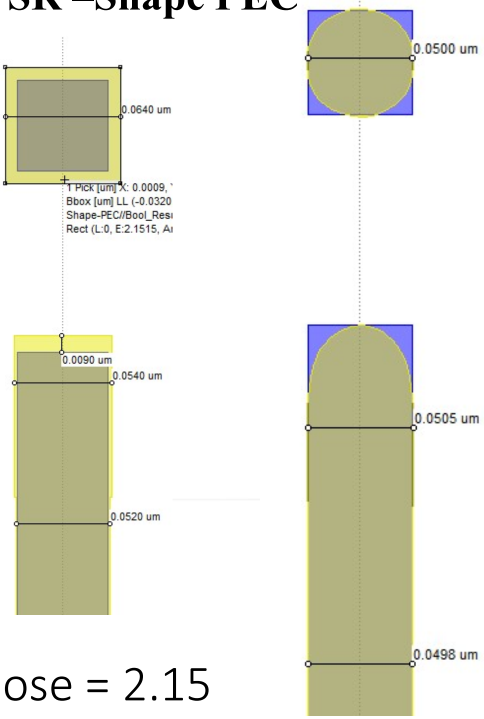
LR - PEC



1 Pick [um] X: -0.0021,
Bbox [um] LL (-0.0250
//Layout_Engine_db_1
Rect (L:1(0) E:2.1515

Dose = 2.15
CD = 50 nm

SR –Shape PEC



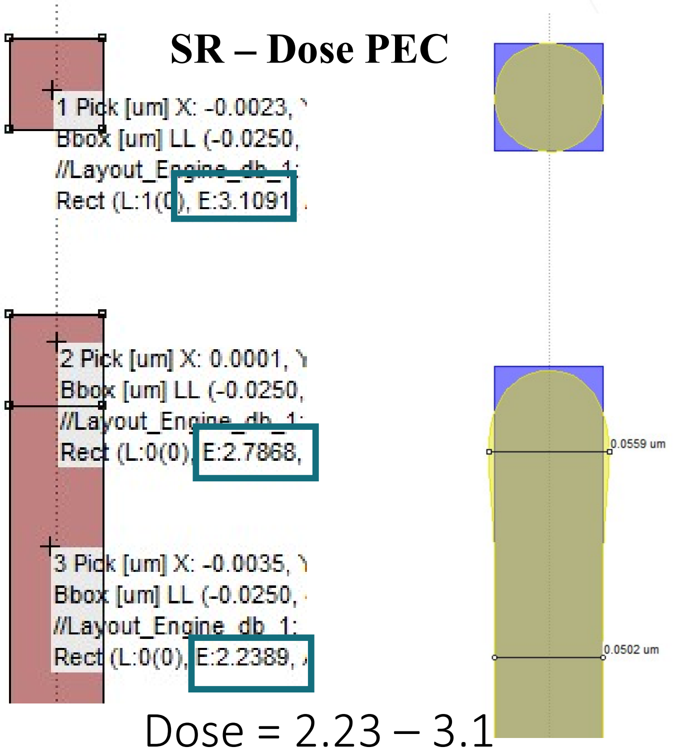
1 Pick [um] X: 0.0009,
Bbox [um] LL (-0.0320
Shape-PEC//Bool_Res
Rect (L:0, E:2.1515, A

Dose = 2.15
CD = 52-64 nm

Iso Dose vs. Shape

- SR Dose PEC vs. Shape PEC:
  - Dose PEC is compensating SR by dose increase
  - Shape PEC is compensating SR by moving feature edges
    - Better feature fidelity by „directional“ correction

SR – Dose PEC



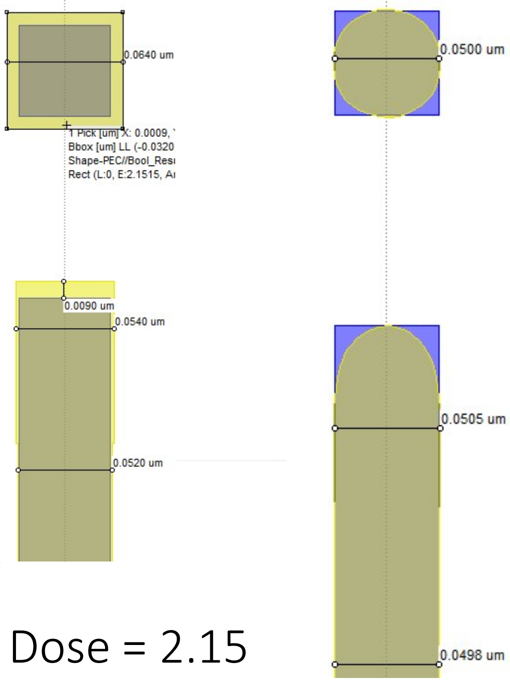
1 Pick [um] X: -0.0023,
Bbox [um] LL (-0.0250,
//Layout_Engine_db_1:
Rect (L:1(0), E:3.1091

2 Pick [um] X: 0.0001,
Bbox [um] LL (-0.0250,
//Layout_Engine_db_1:
Rect (L:0(0), E:2.7868,

3 Pick [um] X: -0.0035,
Bbox [um] LL (-0.0250,
//Layout_Engine_db_1:
Rect (L:0(0), E:2.2389,

Dose = 2.23 – 3.1
CD = 50 nm

SR –Shape PEC



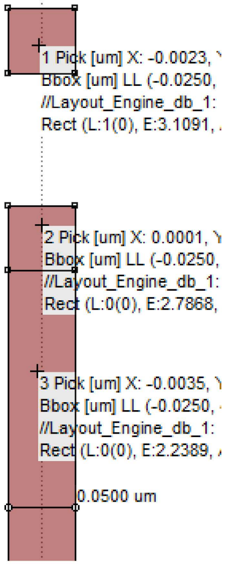
1 Pick [um] X: 0.0009,
Bbox [um] LL (-0.0320
Shape-PEC//Bool_Res
Rect (L:0, E:2.1515, A

Dose = 2.15
CD = 52-64 nm

Iso Shape Correction

- SR Dose PEC vs. Shape PEC:
  - Dose PEC is compensating SR by dose increase
  - Shape PEC is compensating SR by moving feature edges
    - Image contrast (quality) is reduced by shape adjustment

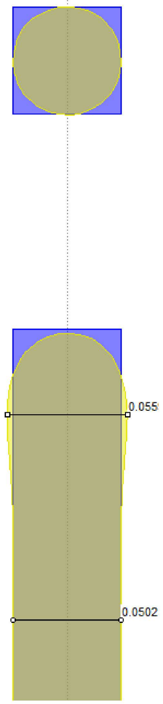
SR – Dose PEC

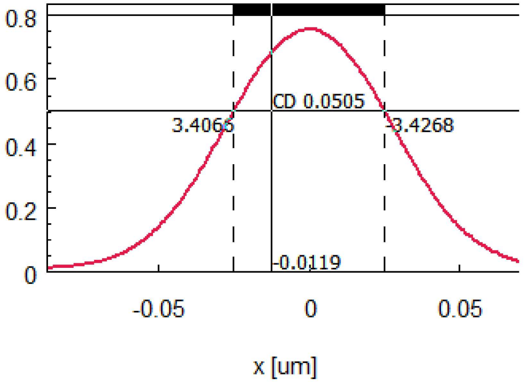


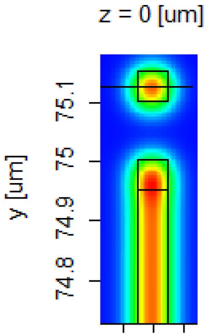
1 Pick [um] X: -0.0023, Y
Bbox [um] LL (-0.0250,
//Layout_Engine_db_1:
Rect (L:1(0), E:3.1091, .

2 Pick [um] X: 0.0001, Y
Bbox [um] LL (-0.0250,
//Layout_Engine_db_1:
Rect (L:0(0), E:2.7868,

3 Pick [um] X: -0.0035, Y
Bbox [um] LL (-0.0250, .
//Layout_Engine_db_1:
Rect (L:0(0), E:2.2389, ,

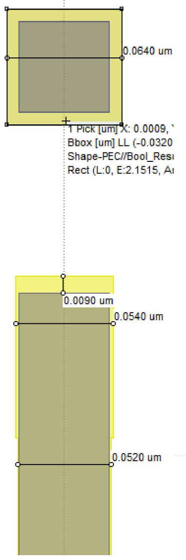




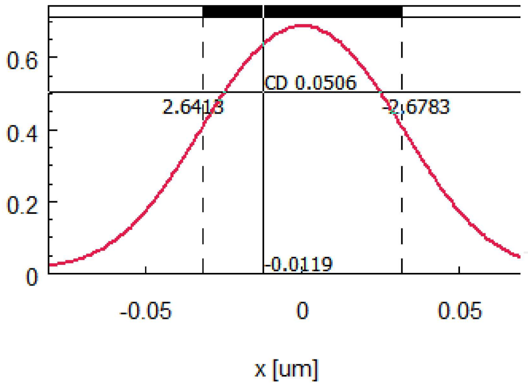


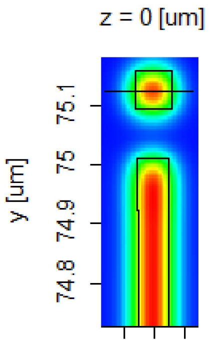
Dose = 2.23 – 3.1
CD = 50 nm

SR –Shape PEC



1 Pick [um] X: 0.0009, Y
Bbox [um] LL (-0.0320
Shape-PEC//Bool_Resu
Rect (L:0, E:2.1515, Ai





Dose = 2.15
CD = 52-64 nm

Outline

- Part 4 Summary: Process Effects, Calibration and Correction
- Shape vs. Dose
- OverDose-UnderSize (ODUS)
- Resist Profile with ODUS
- Application Example
- Summary
- Q&A

What is ODUS

- Experience lithographer know the trick „ODUS“
  - „Undersize“ your feature (apply a specific Bias)
  - Expose a dose matrix and determine the (over) dose to get to size
  - Extreme example: Expose „single line“ with adjusted dose to get to size

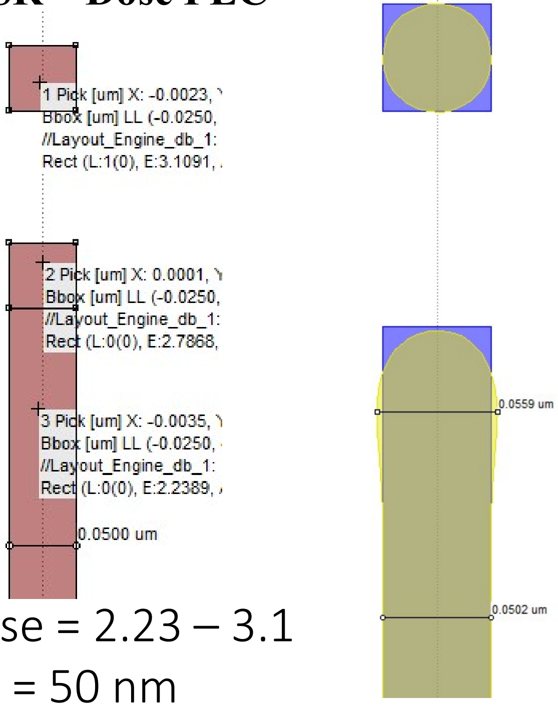
- Limitation:
  - Needs a lot of „trial & error“
  - Limited to simple and uniform pattern (e.g. isolated lines)

- Solution: Model based OverDose-UnderSize correction
  - Overdose factor in combination with blur determine how „aggressive“ the correction will be
  - Typical overdose values are in range 2x – 4x

Contrast Enhancement by ODUS

- SR Dose PEC vs. Shape PEC vs. ODUS:
  - Shape PEC with overdose (e.g. 2x dose!) is shrinking the feature (instead of growing)
    - Better feature fidelity by „directional“ correction

SR – Dose PEC



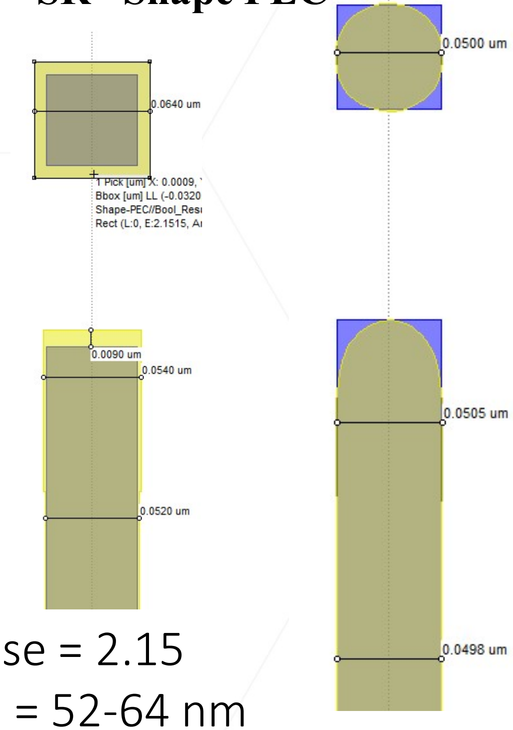
```
1 Pick [um] X: -0.0023, Y
Bbox [um] LL (-0.0250,
//Layout_Engine_db_1:
Rect (L:1(0), E:3.1091, .

2 Pick [um] X: 0.0001, Y
Bbox [um] LL (-0.0250,
//Layout_Engine_db_1:
Rect (L:0(0), E:2.7868,

3 Pick [um] X: -0.0035, Y
Bbox [um] LL (-0.0250, -
//Layout_Engine_db_1:
Rect (L:0(0), E:2.2389, ,
```

Dose = 2.23 – 3.1
CD = 50 nm

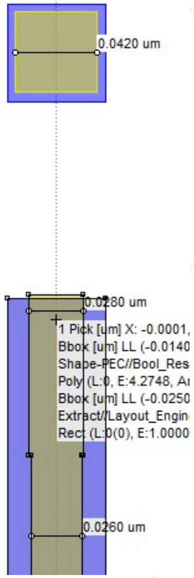
SR –Shape PEC



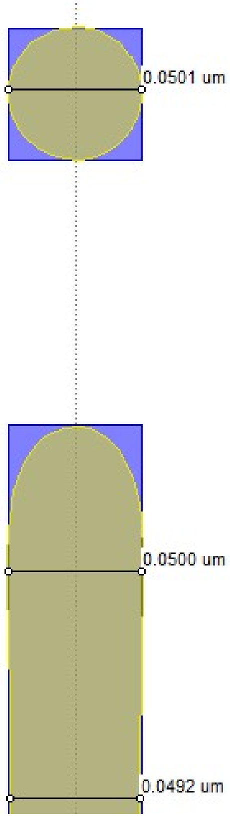
```
1 Pick [um] X: 0.0009, Y
Bbox [um] LL (-0.0320
Shape-PEC//Bool_Resu
Rect (L:0, E:2.1515, Ar
```

Dose = 2.15
CD = 52-64 nm

SR –Shape PEC
OverDose 2x



```
1 Pick [um] X: -0.0001,
Bbox [um] LL (-0.0140
Shape-PEC//Bool_Res
Poly (L:0, E:4.2748, Ar
Bbox [um] LL (-0.0250
Extract//Layout_Engin
Rect (L:0(0), E:1.0000
```

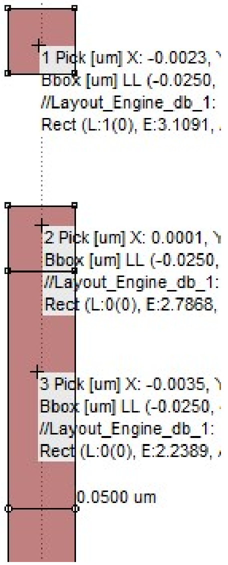


Dose = 4.3
CD = 50 nm

Iso Shape Correction

- SR Dose PEC vs. Shape PEC vs. ODUS:
  - Shape PEC with overdose (e.g. 2x dose!) is shrinking the feature (instead of growing)
    - Better feature fidelity by „directional“ correction
    - Better image contrast by smaller feature and higher dose

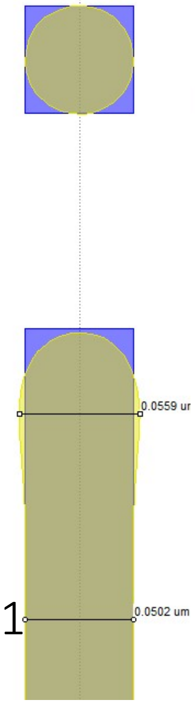
SR – Dose PEC

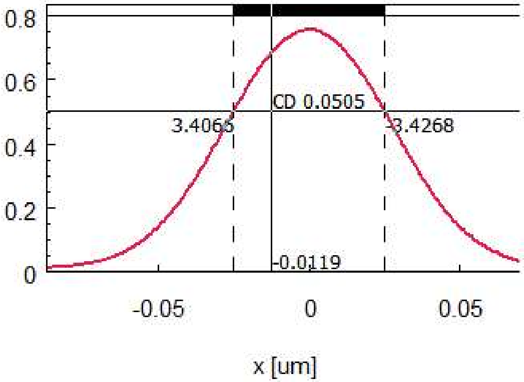


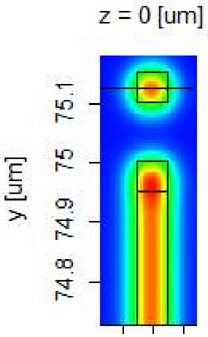
```
1 Pick [um] X: -0.0023, Y
Bbox [um] LL (-0.0250,
//Layout_Engine_db_1:
Rect (L:1(0), E:3.1091, .
```

```
2 Pick [um] X: 0.0001, Y
Bbox [um] LL (-0.0250,
//Layout_Engine_db_1:
Rect (L:0(0), E:2.7868,
```

```
3 Pick [um] X: -0.0035, Y
Bbox [um] LL (-0.0250, .
//Layout_Engine_db_1:
Rect (L:0(0), E:2.2389, .
```

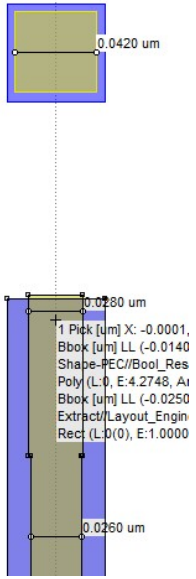




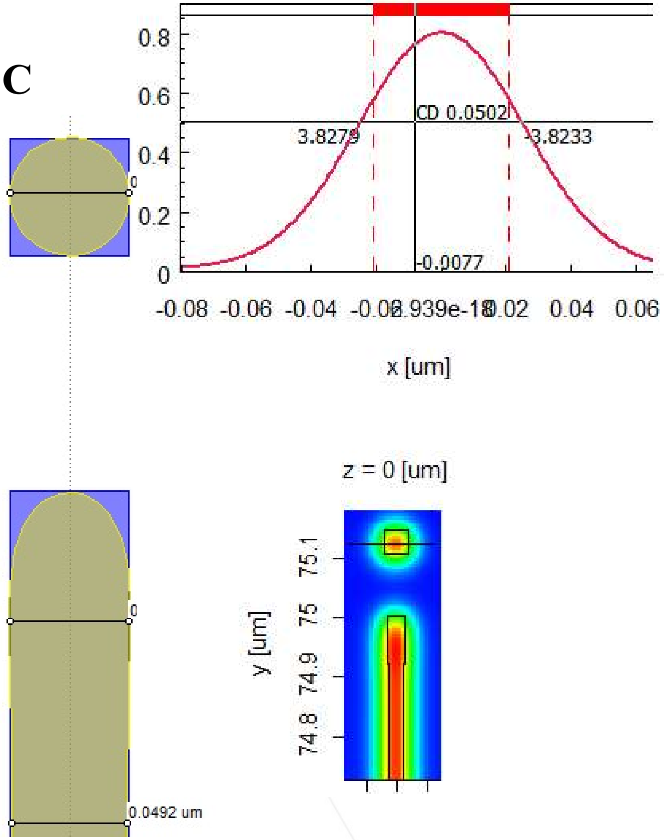


Dose = 2.23 – 3.1
CD = 50 nm

SR –Shape PEC OverDose 2x



```
1 Pick [um] X: -0.0001,
Bbox [um] LL (-0.0140
Shape-PEC//Bool_Res
Poly (L:0, E:4.2748, Ar
Bbox [um] LL (-0.0250
Extract//Layout_Engin
Rect (L:0(0), E:1.0000
```

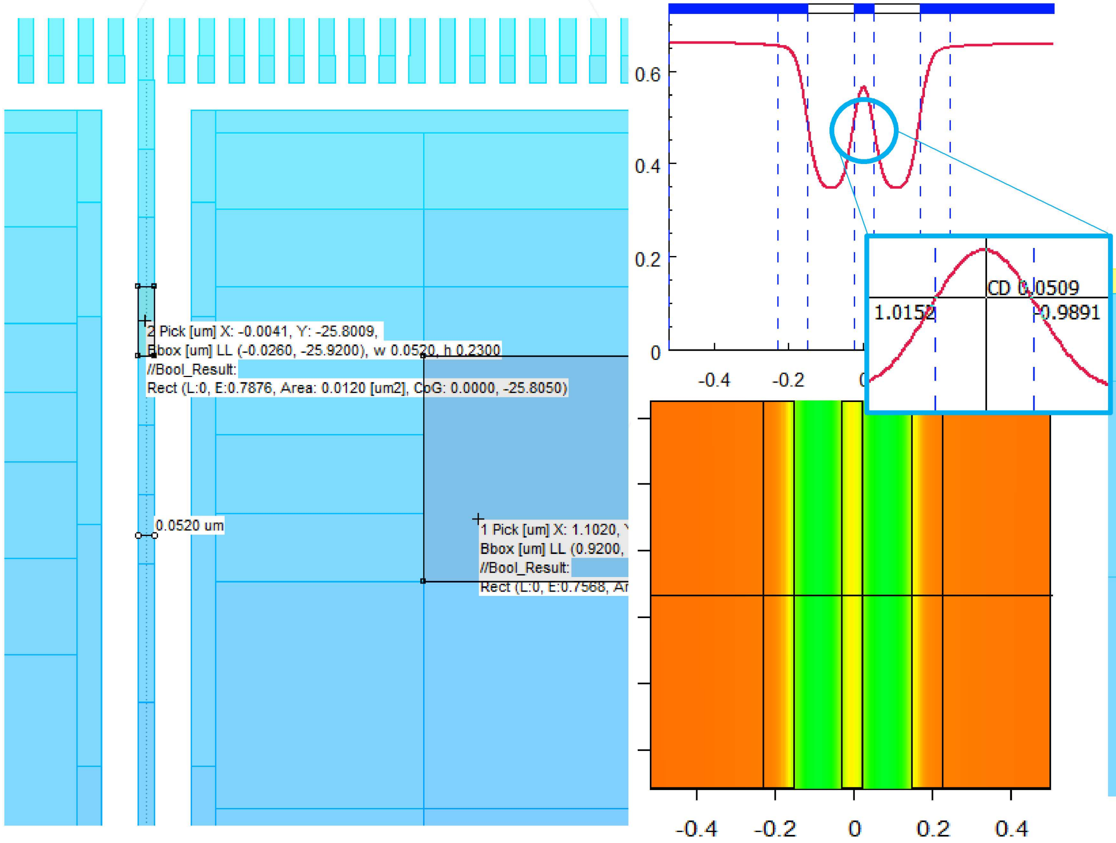


Dose = 4.3
CD = 50 nm

Large Pattern Correction

- ODUS shape PEC for large feature:
    - The over-dose is limited around the edges of the pattern -> better contrast

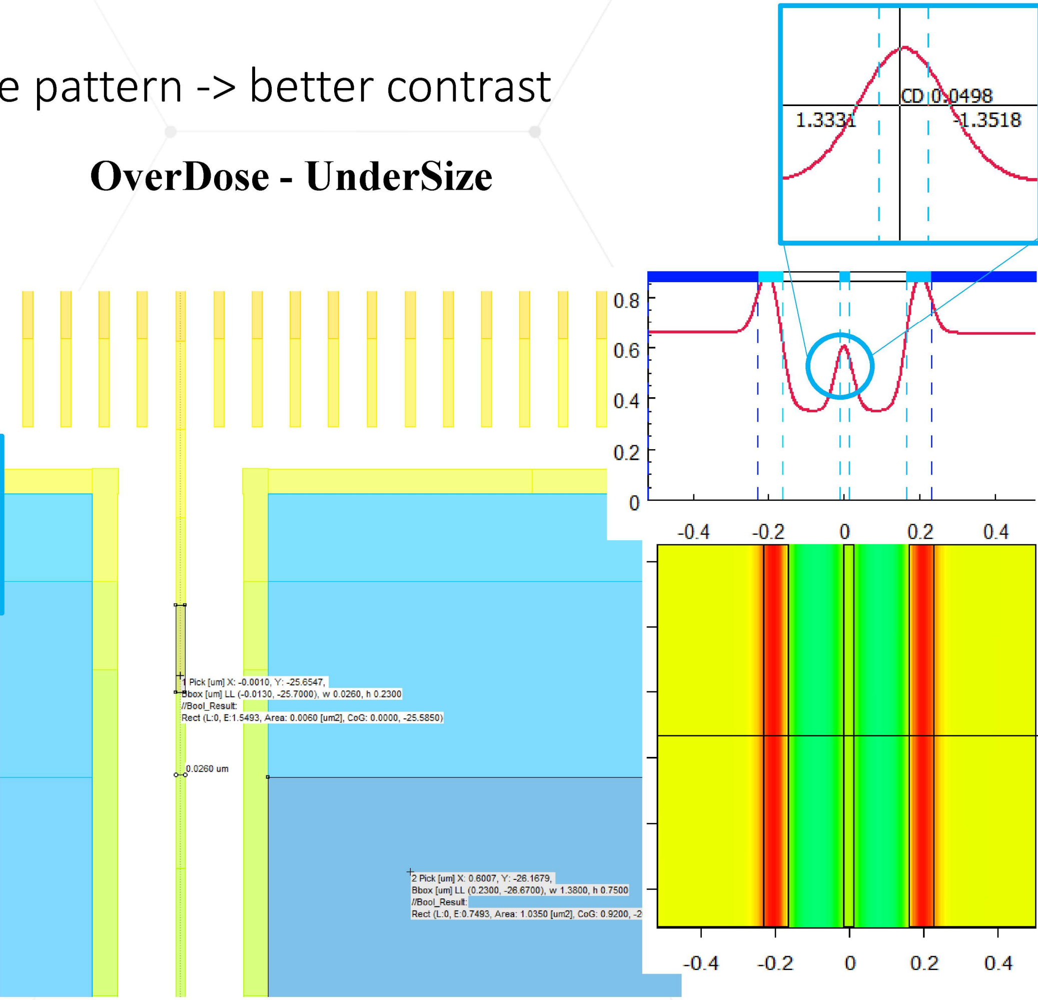
Shape PEC - Dose 1x



```
2 Pick [um] X: -0.0041, Y: -25.8009,
Bbox [um] LL (-0.0260, -25.9200), w 0.0520, h 0.2300
//Bool_Result:
Rect (L:0, E:0.7876, Area: 0.0120 [um2], CoG: 0.0000, -25.8050)
```

```
1 Pick [um] X: 1.1020, Y
Bbox [um] LL (0.9200,
//Bool_Result:
Rect (L:0, E:0.7568, Ar
```

OverDose - UnderSize



```
1 Pick [um] X: -0.0010, Y: -25.6547,
Bbox [um] LL (-0.0130, -25.7000), w 0.0260, h 0.2300
//Bool_Result:
Rect (L:0, E:1.5493, Area: 0.0060 [um2], CoG: 0.0000, -25.5850)
```

```
2 Pick [um] X: 0.6007, Y: -26.1679,
Bbox [um] LL (0.2300, -26.6700), w 1.3800, h 0.7500
//Bool_Result:
Rect (L:0, E:0.7493, Area: 1.0350 [um2], CoG: 0.9200, -2
```

Outline

- Part 4 Summary: Process Effects, Calibration and Correction
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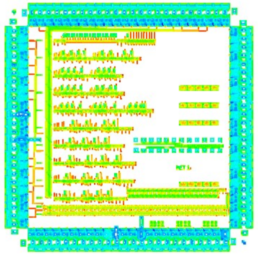
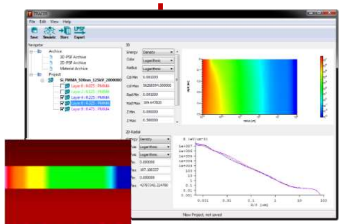
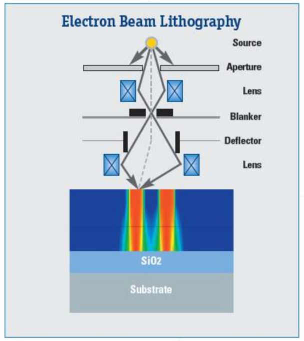
LAB 3D Simulation

Layout

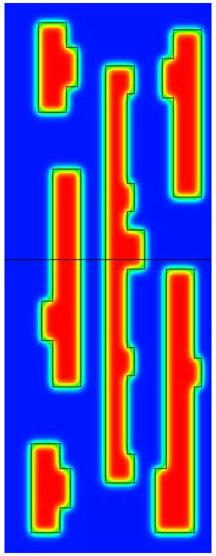




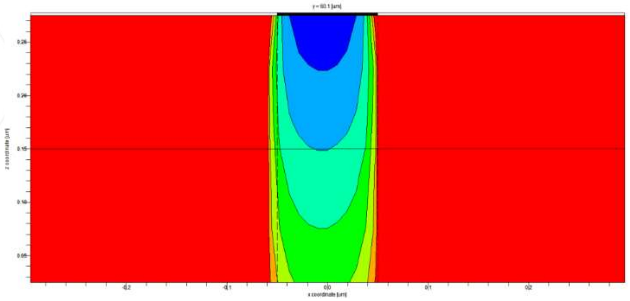
3D PSF

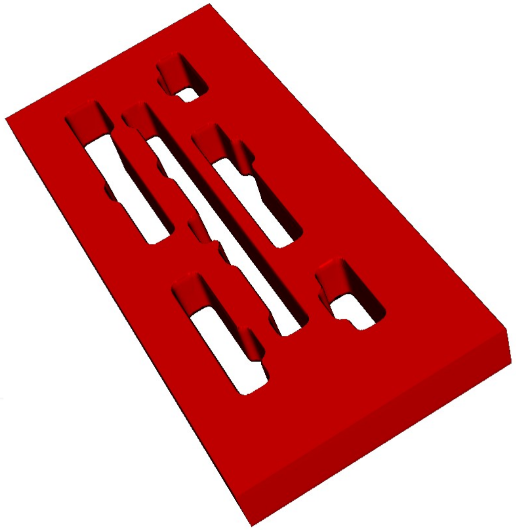


E-Beam Exposure



3D
Bulk Energy



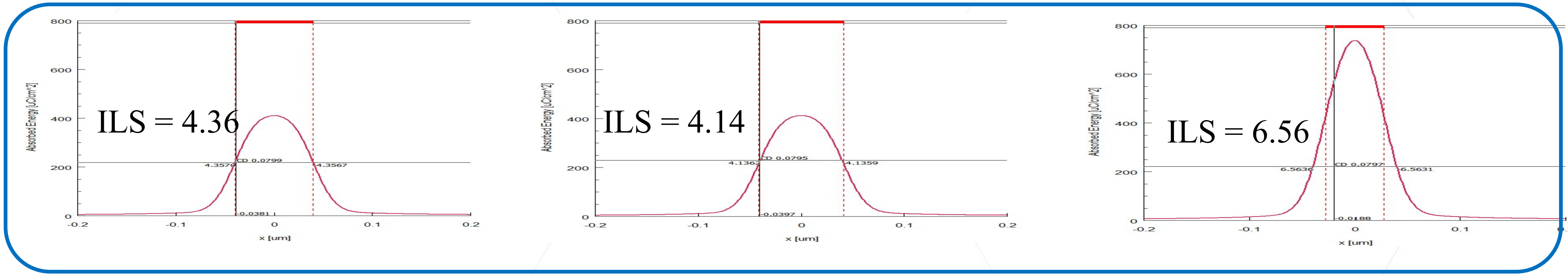


3D Resist
Development

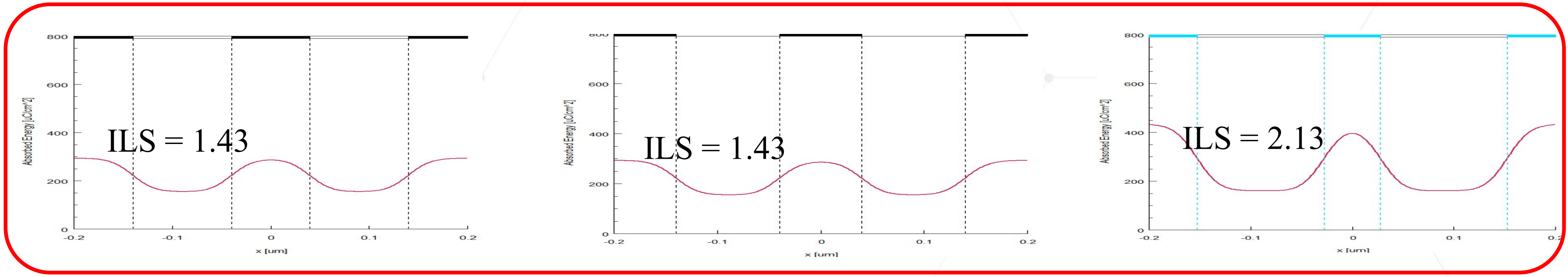
Contrast Comparison

- Simulation is carried out for 100keV electron exposure on 200nm PMMA 950K on GaAs substrate.
- The intensity image shows
  - the enhancement of image contrast by ODUS
  - the dependence of image contrast on pattern density

Dose PEC **Shape PEC** **ODUS**



isoline



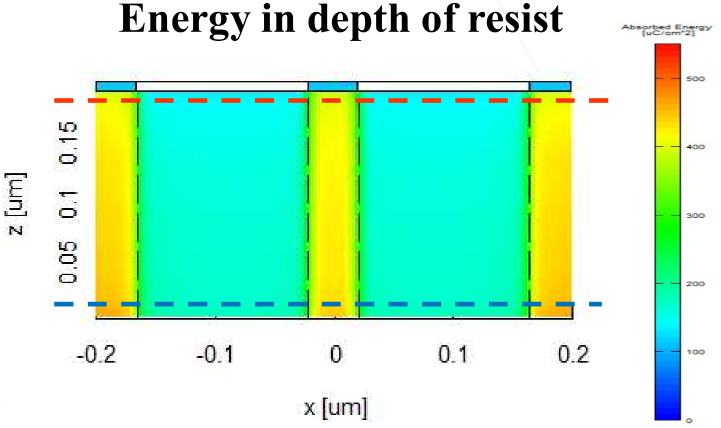
dense line

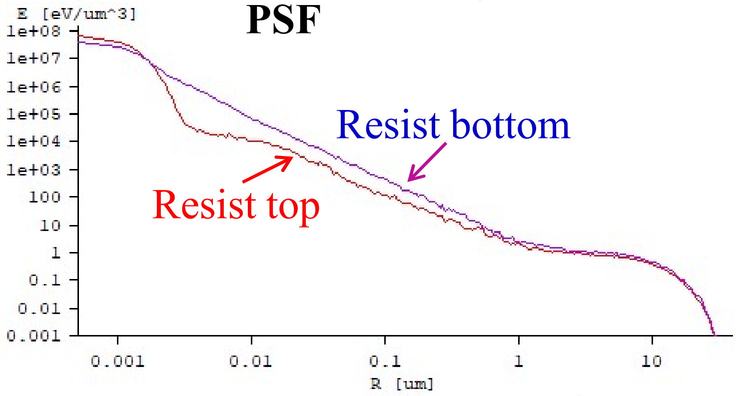
Bulk Energy

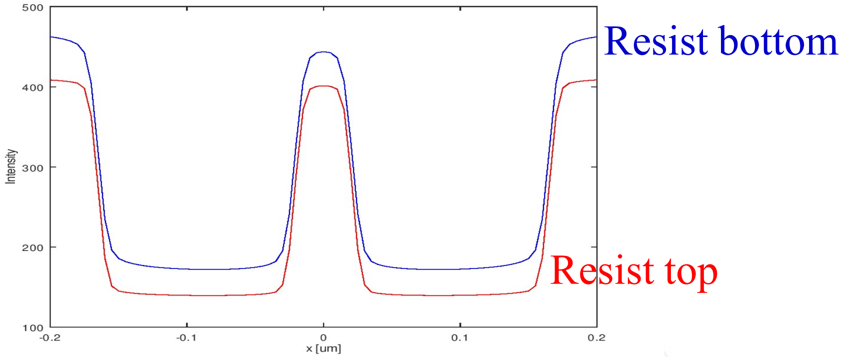
- Simulation is carried out for 100keV electron exposure on 200nm PMMA on GaAs substrate
- The PSF varies with beam scattering into the resist.
- 20% more energy at the bottom for unexposed area.

Energy in depth of resist

ODUS (overdose = 2)

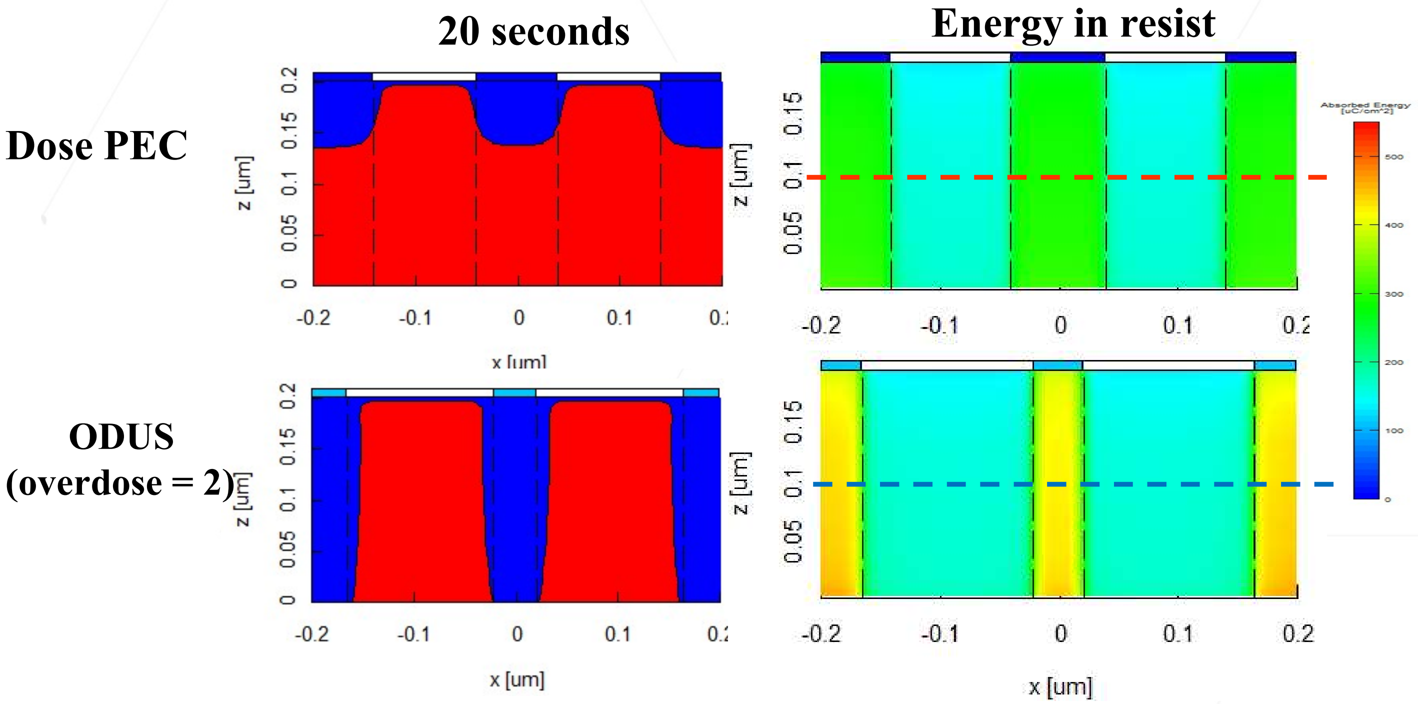


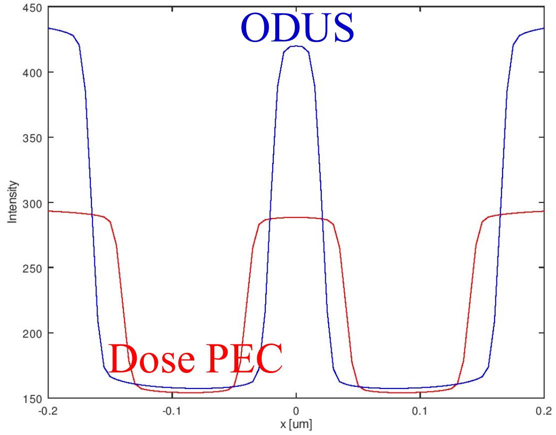




Resist Development

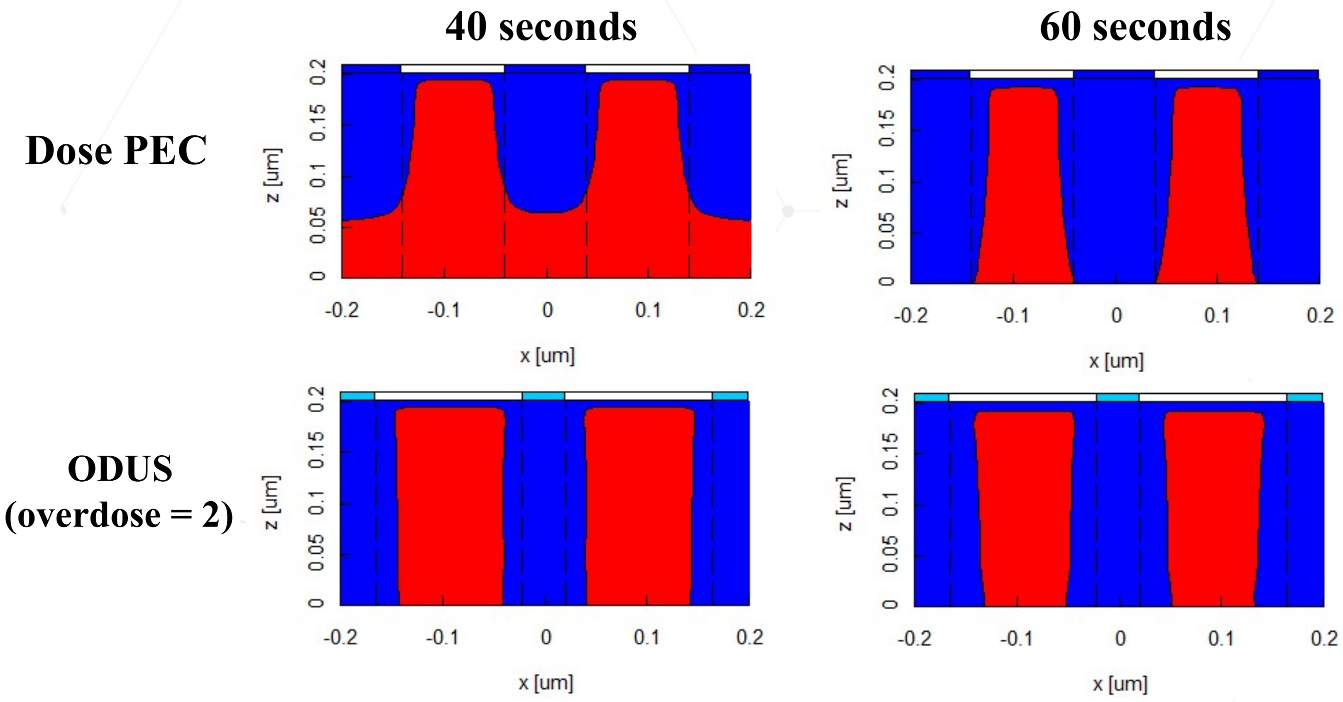
- Resist (red area) development front is modeled over time.
  - Developer is moving both in depth and side direction.
  - The ODUS has the developer moves faster down into the resist

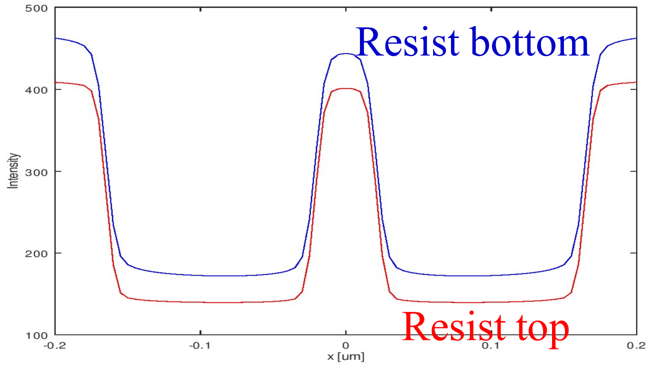




Resist Development

- Resist (red area) development front is modeled over time.
  - Developer is moving both in depth and side direction.
  - After reaching the bottom, the developer is moving to the side at the bottom faster than at the top.



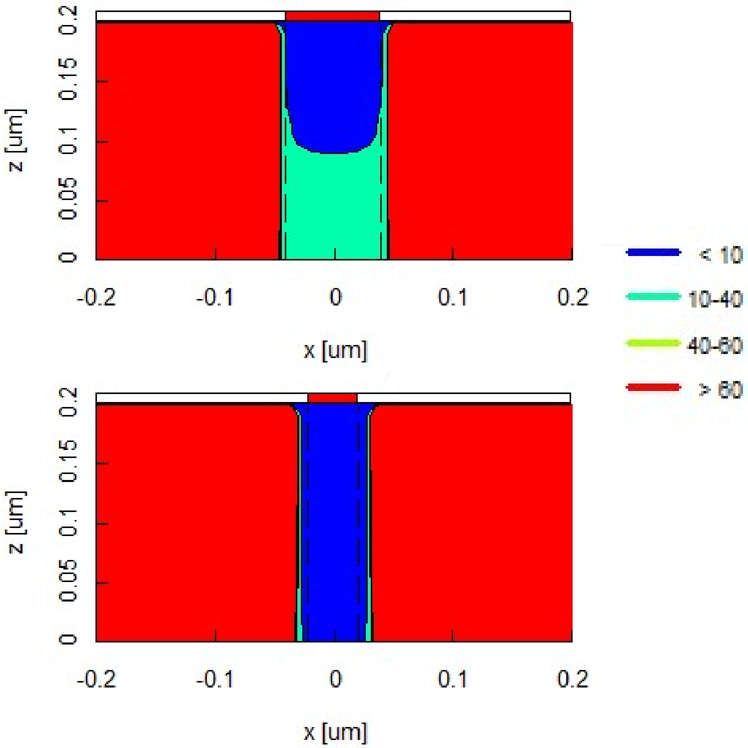


Pattern Density

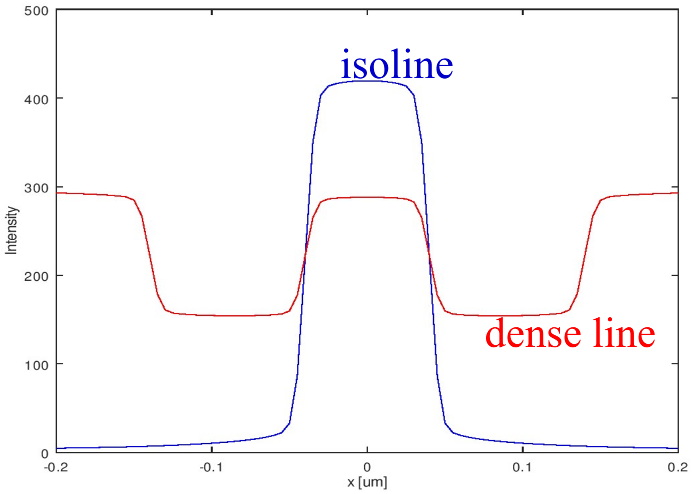
- What matters for the resist development: pattern density
  - Developer front for isoline pattern is moving faster in comparison to dense line.
  - The lateral development is less for isoline with smaller background energy in unexposed area.

Dose PEC

ODUS (overdose = 2)



Energy across the line



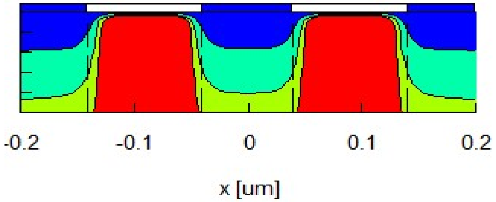
Resist Thickness

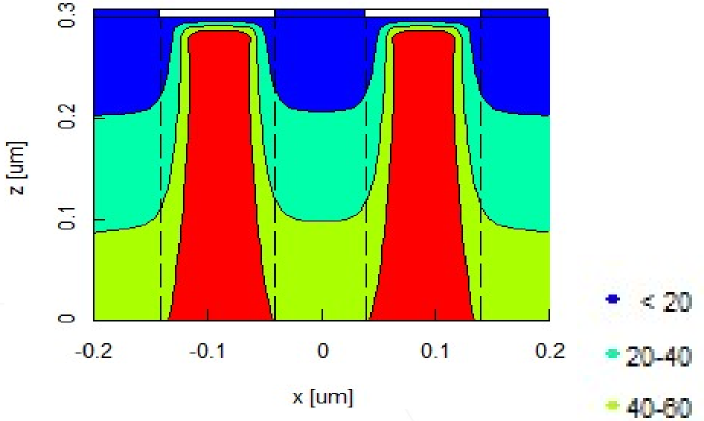
- What matters the resist development: resist thickness
  - The ODUS enhancement on resist profile is more apparent for thicker resist.

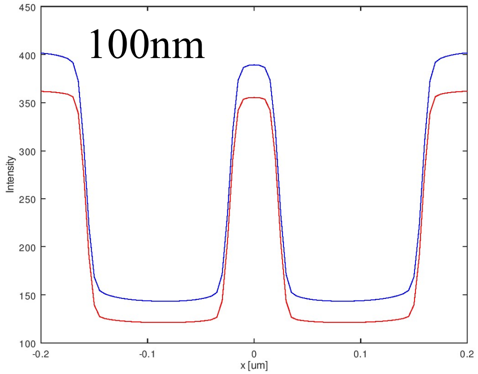
300nm

100nm

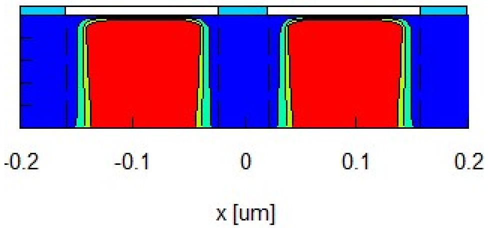
Dose PEC

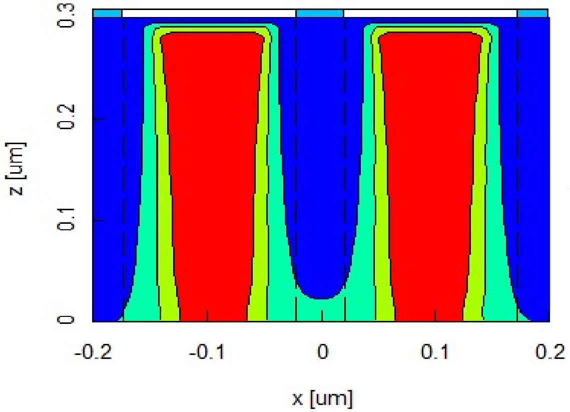


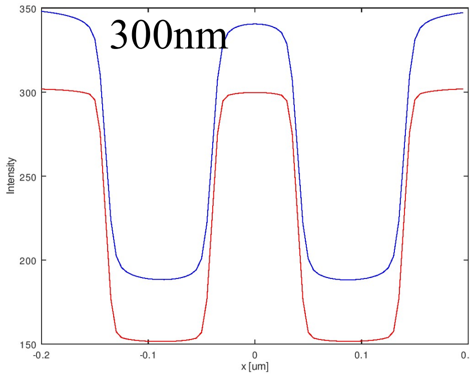




ODUS (overdose = 2)





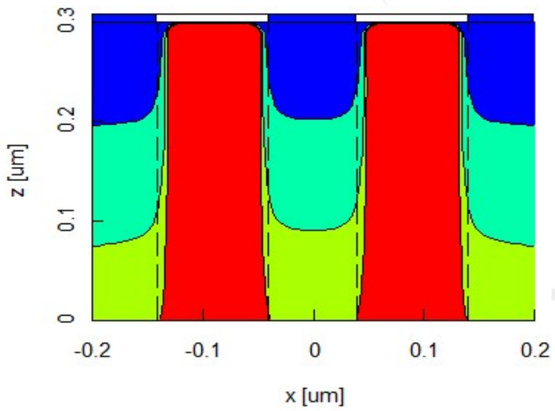


Substrate

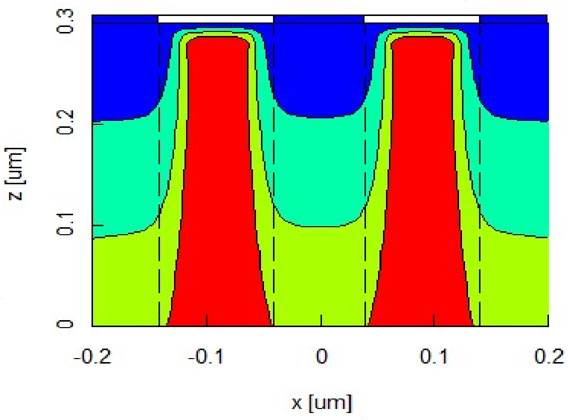
- What matters the resist development: substrate material
  - The resist profile enhancement is more apparent for GaAs substrate.

Dose PEC

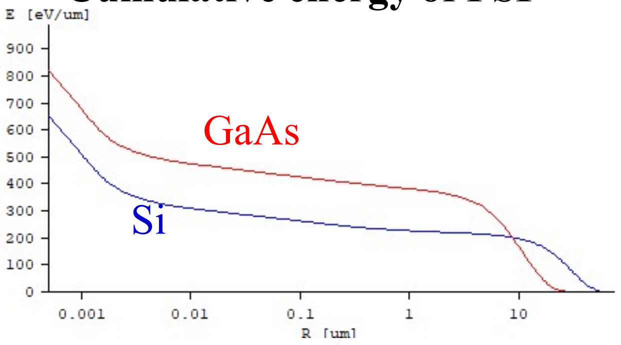
Si



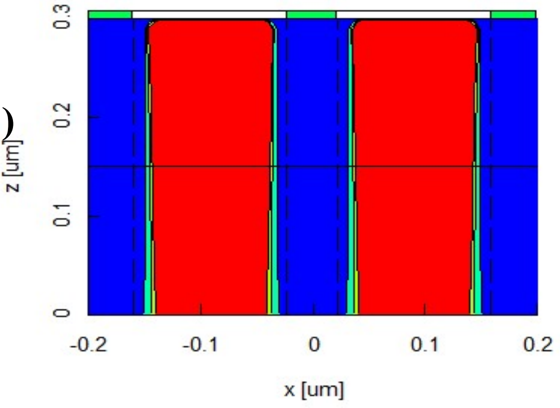
GaAs

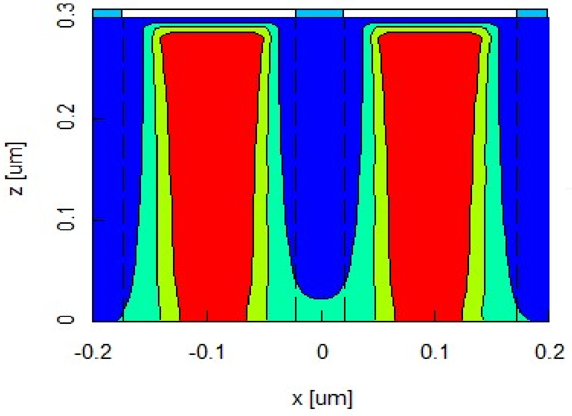


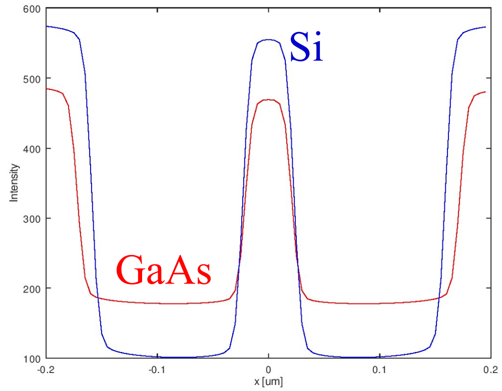
Cumulative energy of PSF



ODUS (overdose = 2)







GenISys
Advancing the Standard

Outline

- Part 4 Summary: Process Effects, Calibration and Correction
- Shape vs. Dose
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- Application Example
  - Single layer Lift-Off
  - Enhance feature fidelity (resolution)
- Summary
- Q&A

Single Layer Lift-Off

Better metal edge (liftoff) after EBL on single layer resist / PEC vs. ShapePEC

Developer

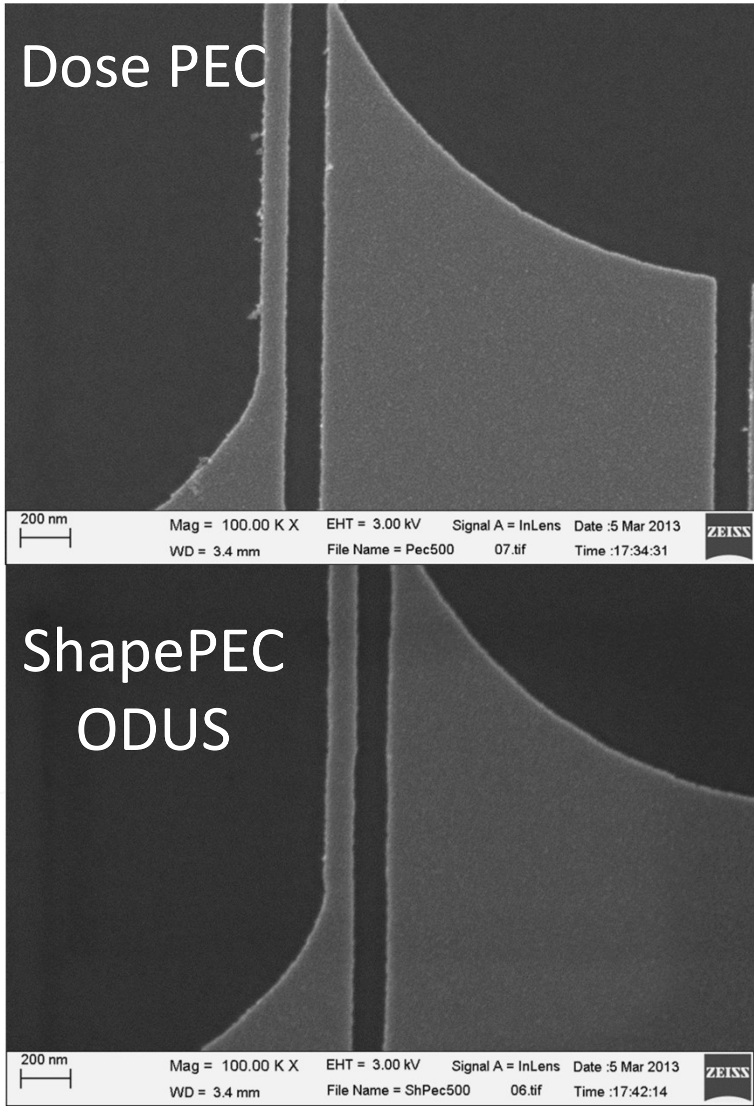
PEC vs ShapePEC overdose/ undersize

Lift-Off

BD

PSF

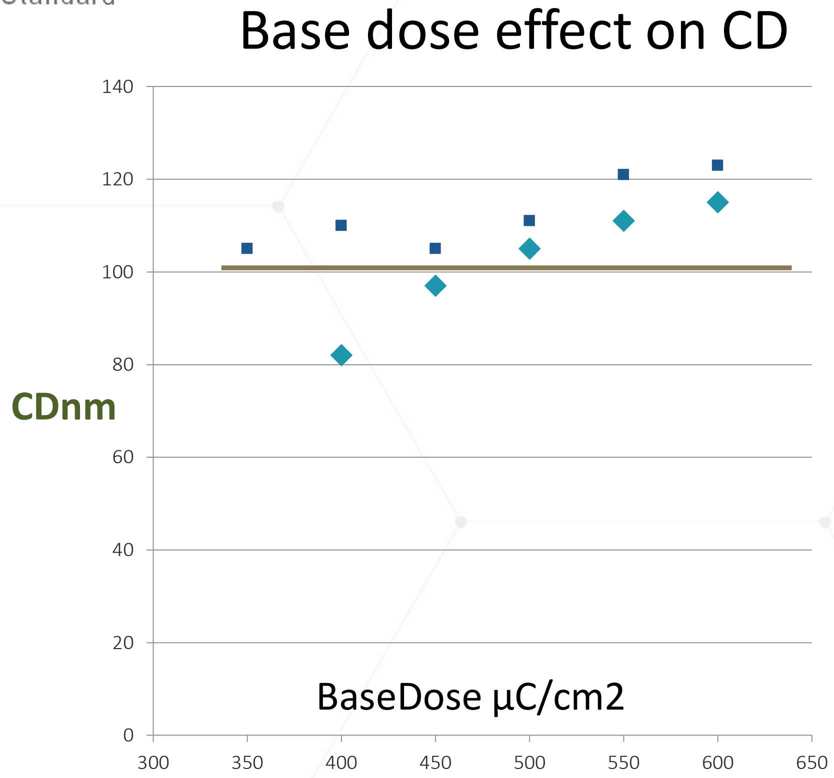
Plasma



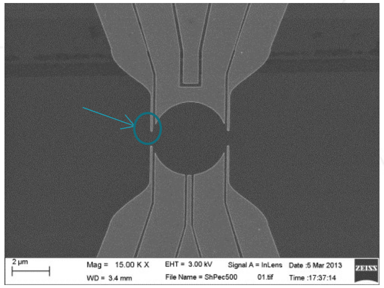
Why is ShapePEC With OD better?

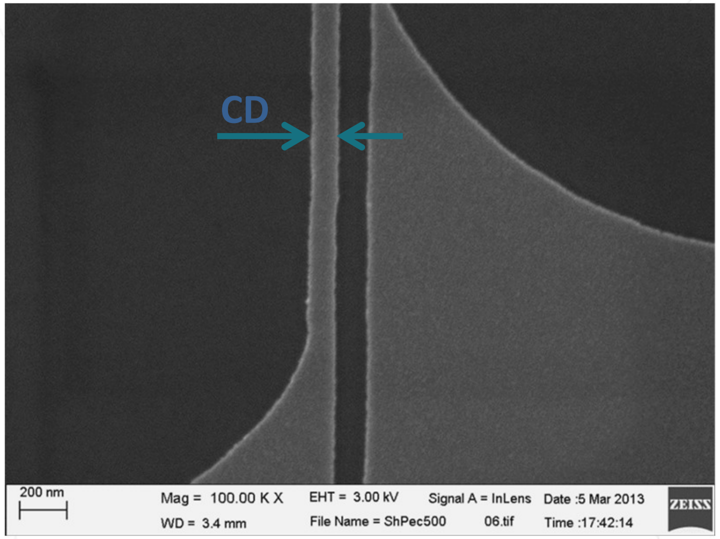
Presented at BEAMeeting Freiburg 2013:
Diana Mahalu – Compare Shape PEC and Dose PEC

CD Sensitivity



CD design 100nm

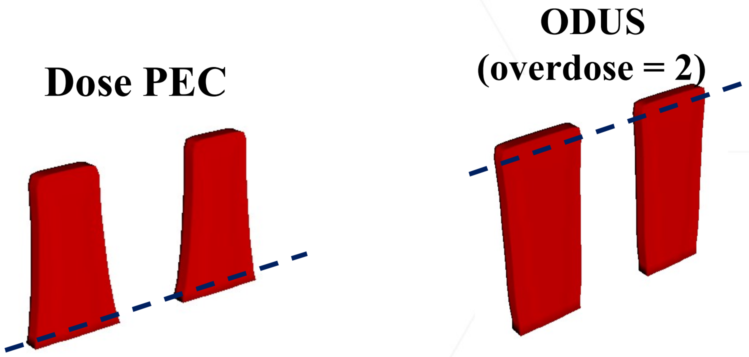




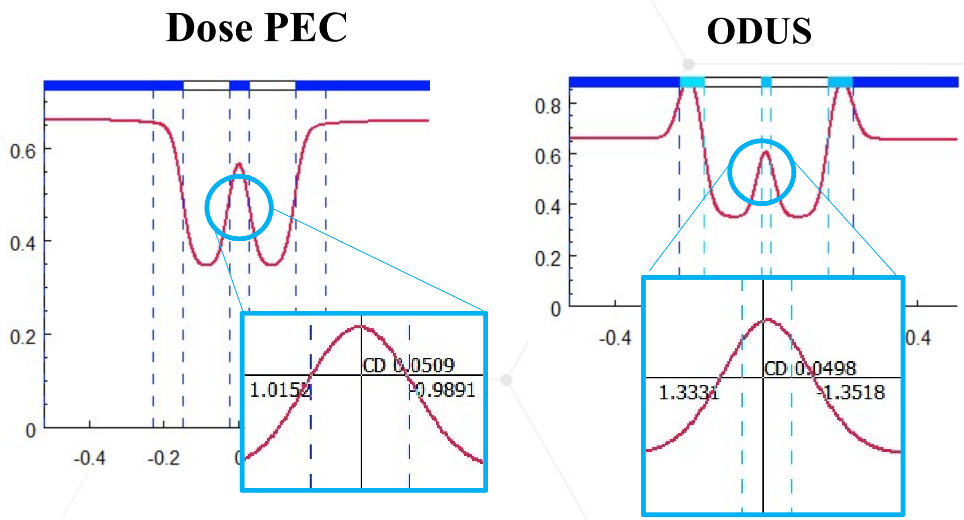
Bigger lift-off process window when using ODUS (resist edge-slope)

Simulated CD Sensitivity

- In theory, the enhanced image contrast results in enhanced CD sensitivity.
- The CD change with 5% exposure dose is compared for PEC and ODUS.
- With negative resist profile for ODUS(overdose = 2), the CD change at the resist top is responsible for patterns from lift-off technique. The CD change for positive resist profile (PEC) is decided at the resist bottom.



	Position	Simulated CD change
Dose PEC	Resist bottom	16 nm
ODUS (overdose = 2)	Resist Top	6 nm



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Application Example for ODUS

Photonic Device Patterning Optimization

Improving Process Window via Contrast Enhancement

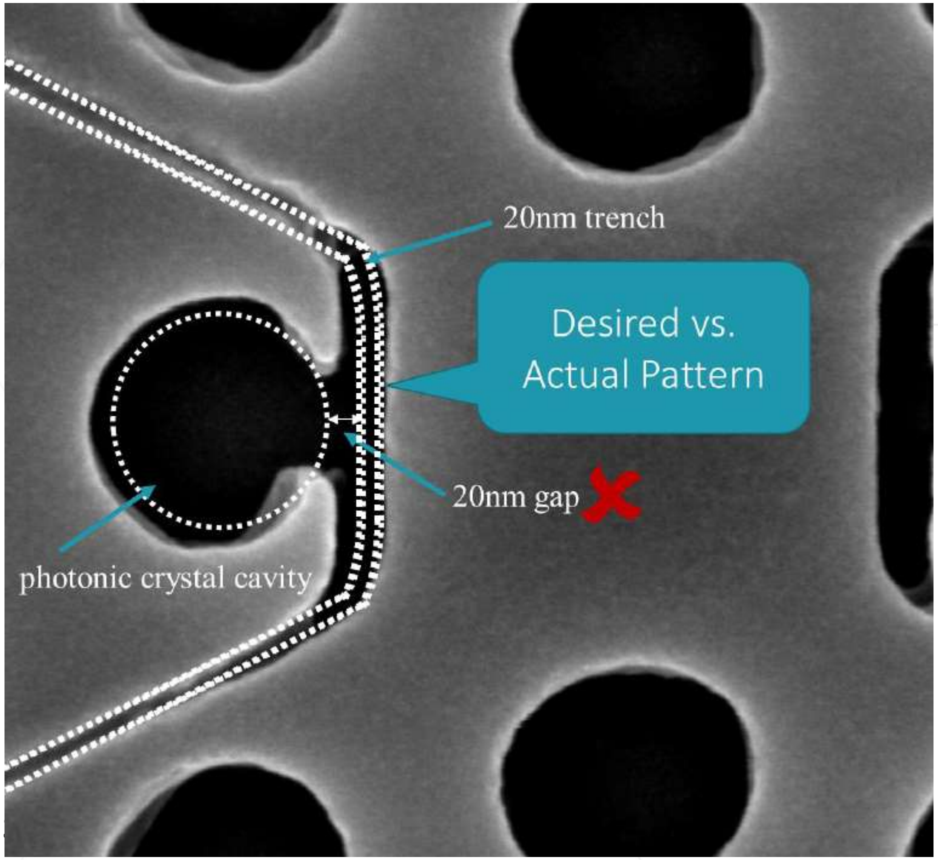
Kashif Masud Awan and Gerald Lopez
University of British Columbia and University of Pennsylvania

Presented at BEAMeeting EIPBN 2019

JEOL 8100 at 100kV + 500nm ZEP520A

- Challenges
- Attempting to resolve a 20 nm gap between a photonic crystal cavity and trench (NEMS + Photonic circuit)
- PEC initially did not yield any intuitive results.

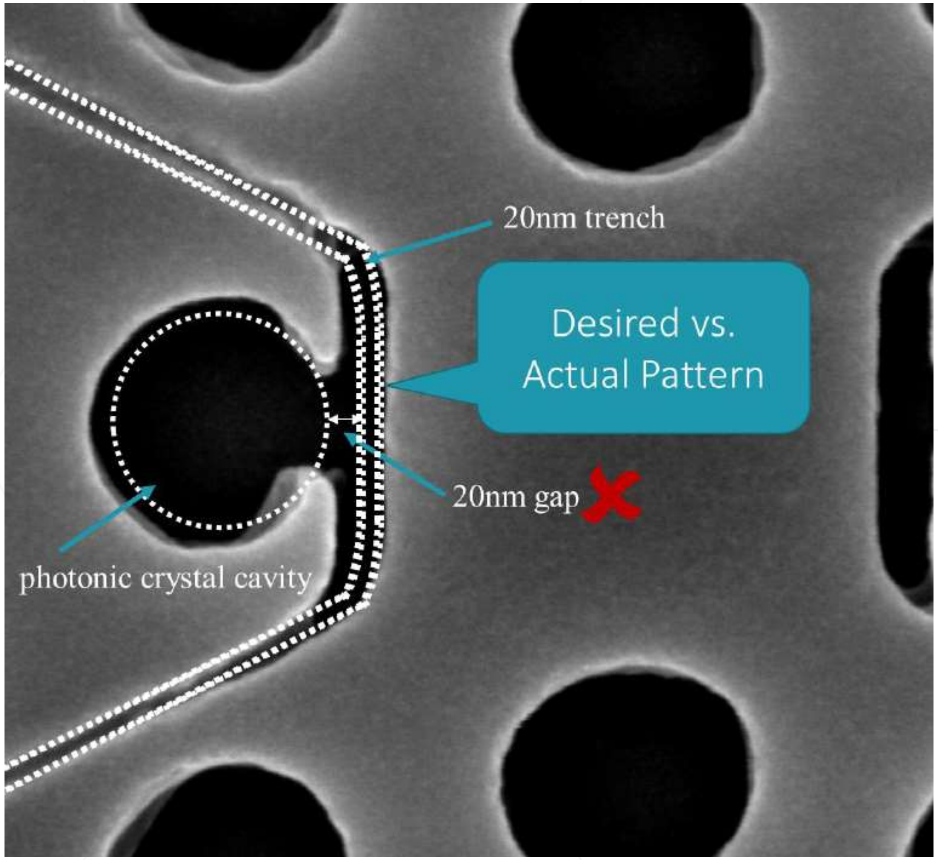
- Limitations:
- Cannot reduce resist thickness due to etch requirement
- Anything near 20 nm does not resolve



Application Example for ODUS

Critical Design Elements:
- **Trench:** 20 nm wide
- **Gap:** 20 nm wide
- **Photonic crystal cavity:** 200 nm (diameter)
- Resolving this **trench** and **gap** combination has proven to be elusive when using PEC.

Experiment
- An exposure was done on structures with 50 nm gaps with 30 and 50 nm wide trenches. Pattern was PEC'edusing only long range correction.
- Simulations were performed to match exposure latitude and observed phenomenon.



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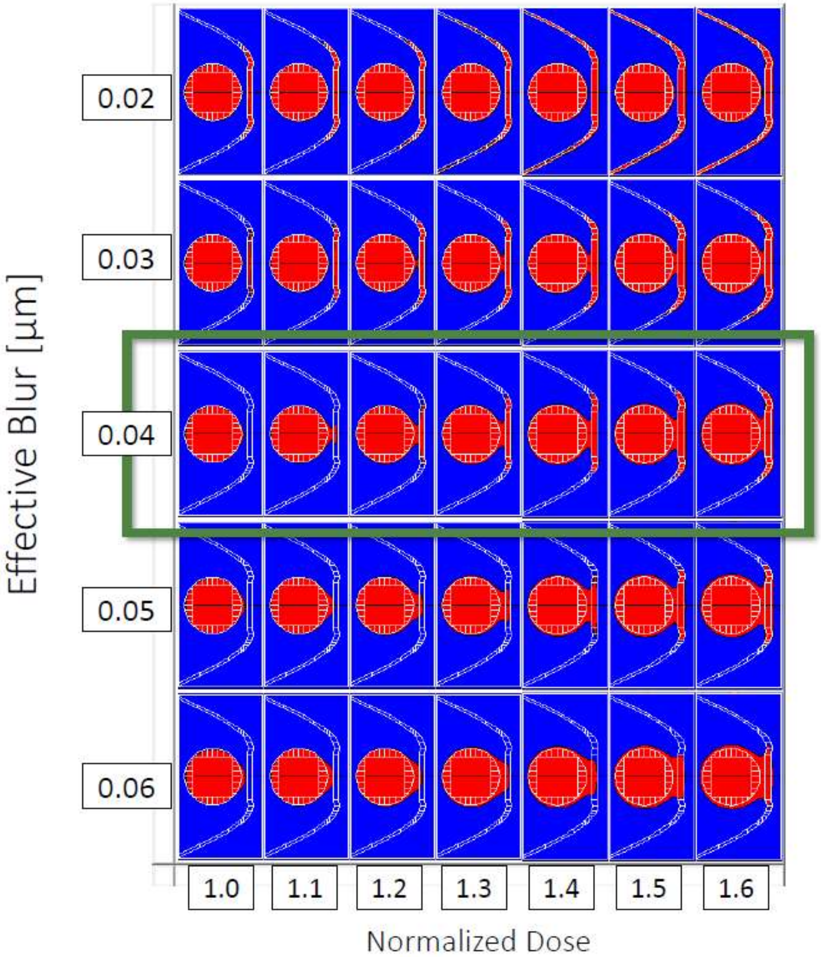
Determination of Effective Blur by Simulation

Simulation: 20 nm Trench

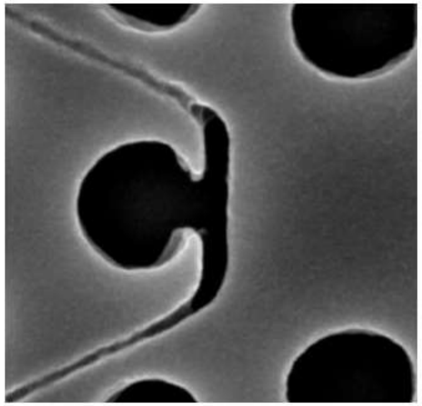


Threshold analysis

- Pattern was corrected with only long range correction.
- The absorbed energy at 50% is shown.
- This is the threshold of the resist or the constant energy that is tied to the resist development to where the resist edge will land.

Key Observation

Large blurs$_{eff}$ (i.e., 50 and 60 nm) do not closely describe the observed phenomenon.



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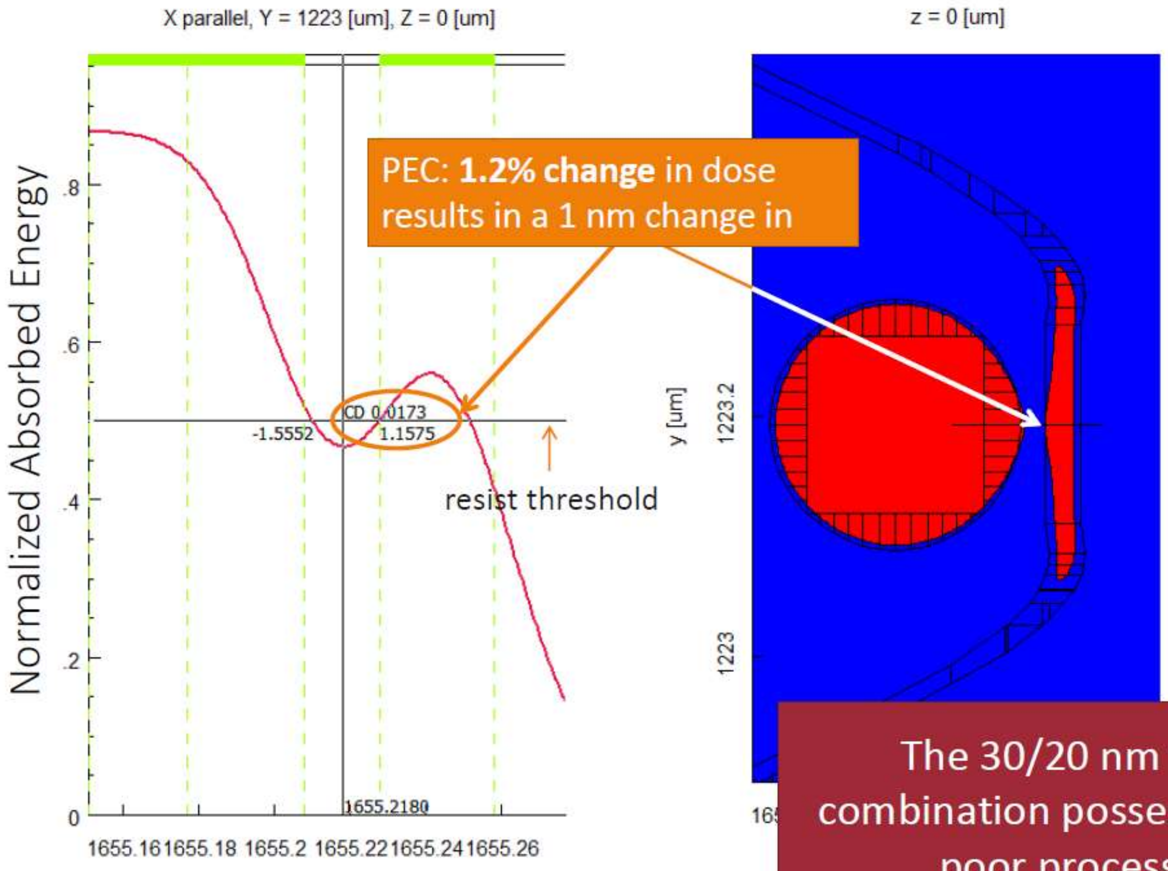
Dose PEC – Poor Process Window



PEC: **1.2% change** in dose results in a 1 nm change in

Design

Trench: 30 nm

Gap: 20 nm

The 30/20 nm trench/gap combination possesses a relatively poor process window

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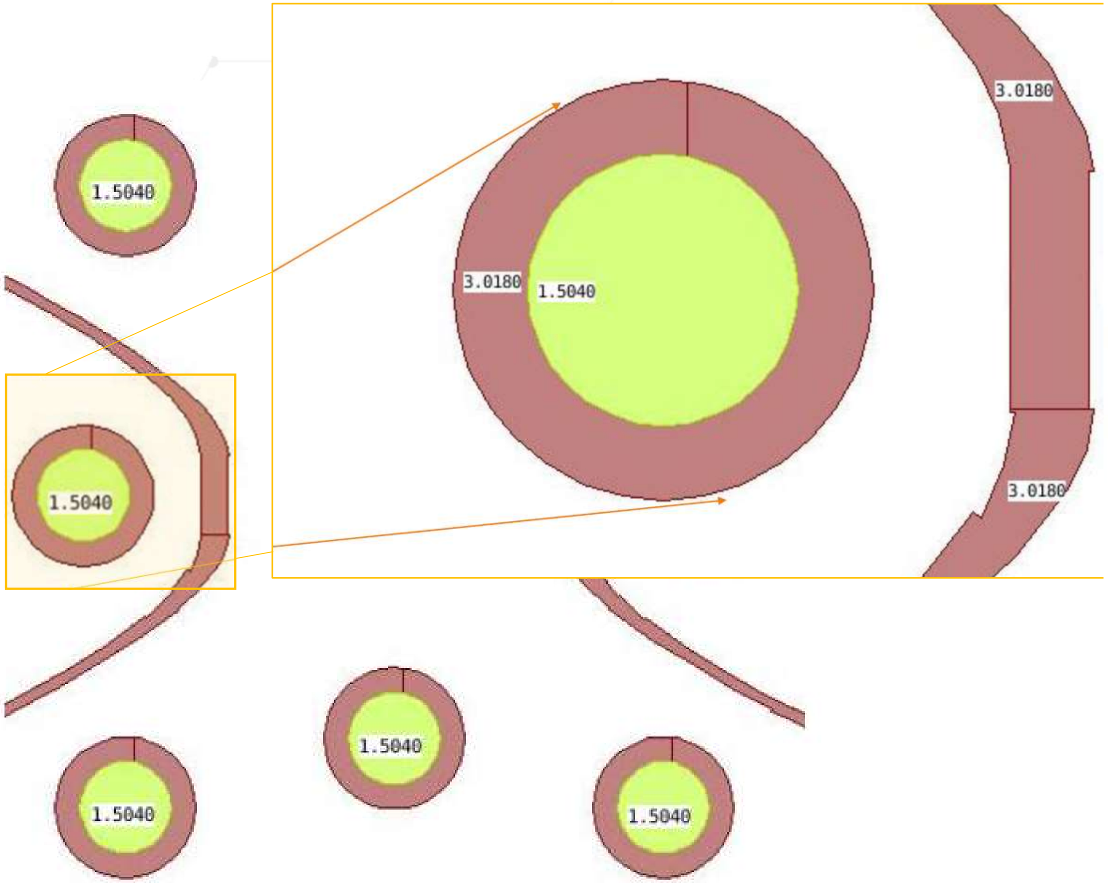
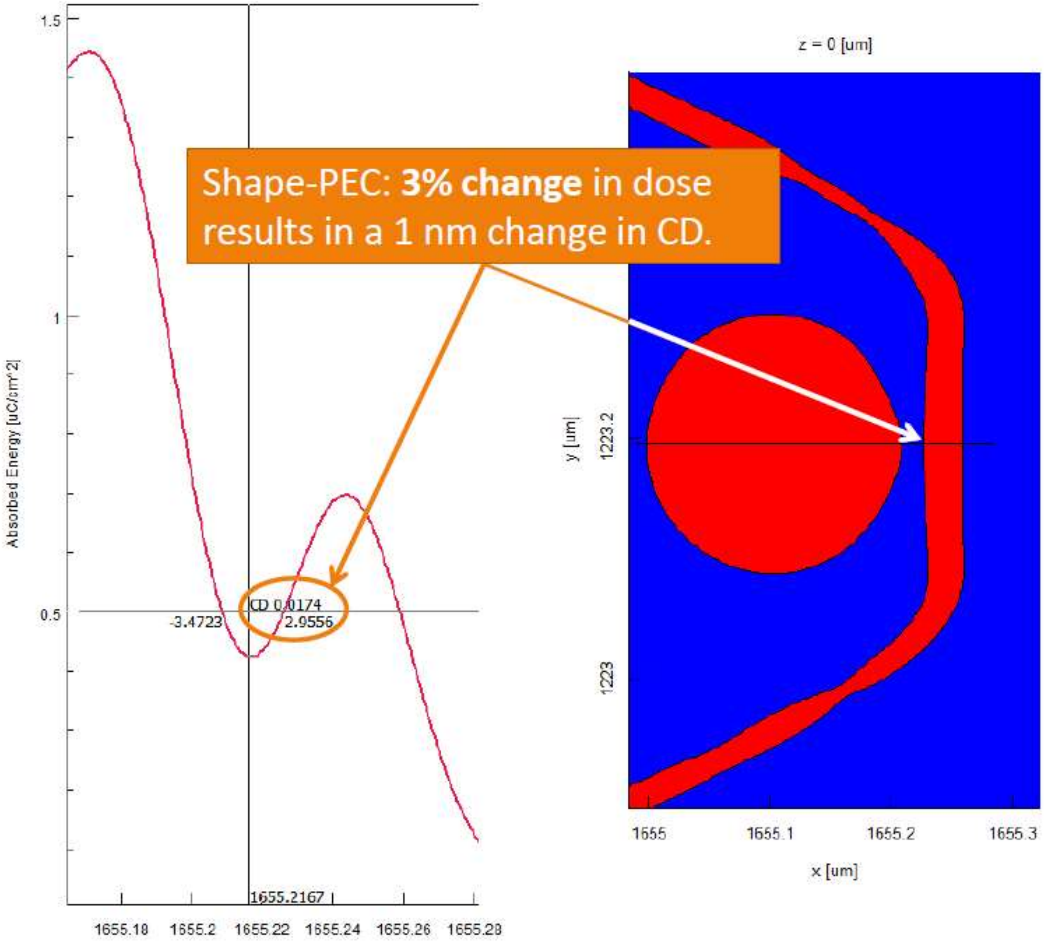
ShapePEC with OD 2.0





Shape-PEC: **3% change** in dose results in a 1 nm change in CD.

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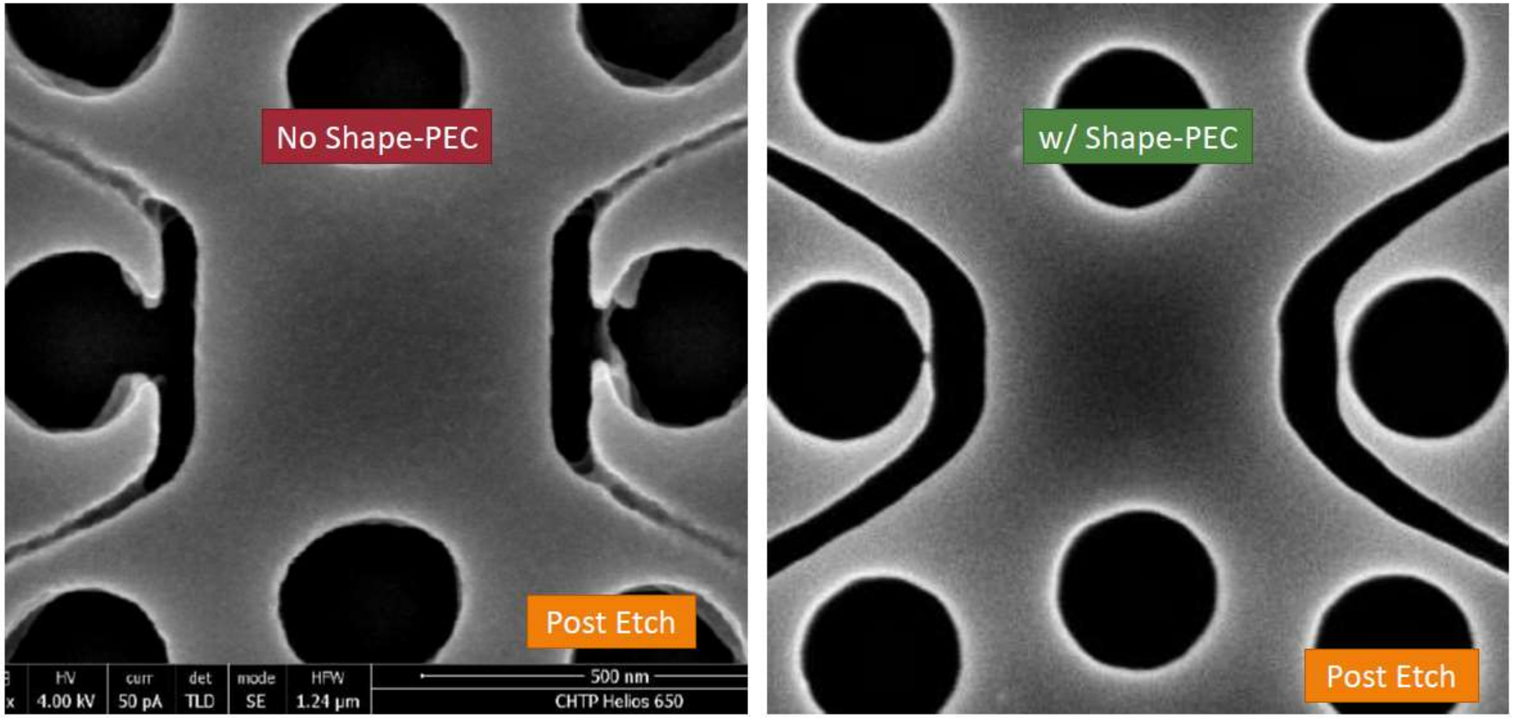
GenISys
Advancing the Standard

Application Example for ODUS

Shape-PEC Applied



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Gap: 20nm
Trench: 30nm

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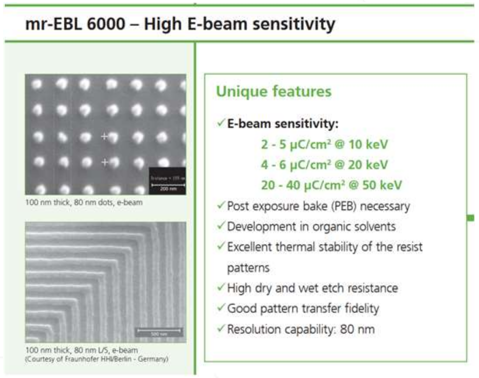
mr-EBL 6000

- Resolution study of e-beam resist mr-EBL 6000
  Courtesy of Adriaan Taal & Shriddha Chaitanya at Columbia University
- Problem: Not able to reach 80 nm resolution limit. 100 nm+ features printing okay
  - 100 pA exposure
    PEB: 80C 60 S
    Developer: Propylene carbonate 60s



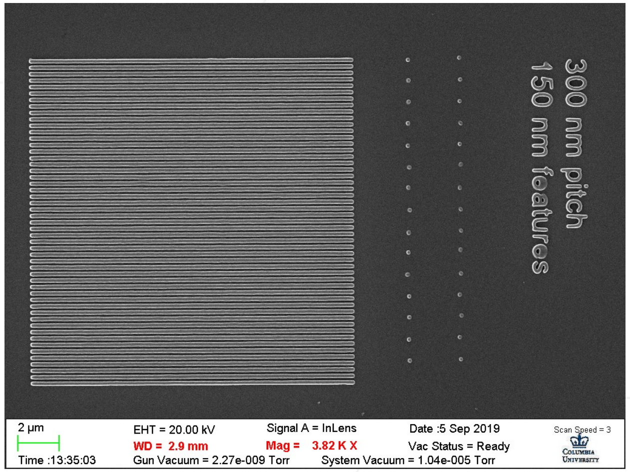
mr-EBL 6000 – High E-beam sensitivity

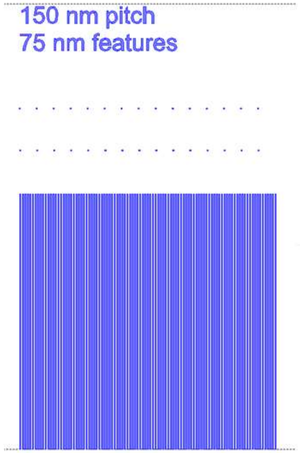
100 nm thick, 80 nm dots, e-beam

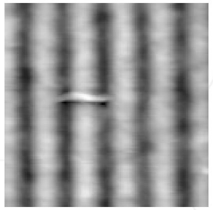
100 nm thick, 80 nm L/S, e-beam
(Courtesy of Fraunhofer HHI/Berlin - Germany)

Unique features

- ✓ **E-beam sensitivity:**
  - 2 - 5 μC/cm² @ 10 keV
  - 4 - 6 μC/cm² @ 20 keV
  - 20 - 40 μC/cm² @ 50 keV
- ✓ Post exposure bake (PEB) necessary
- ✓ Development in organic solvents
- ✓ Excellent thermal stability of the resist patterns
- ✓ High dry and wet etch resistance
- ✓ Good pattern transfer fidelity
- ✓ Resolution capability: 80 nm





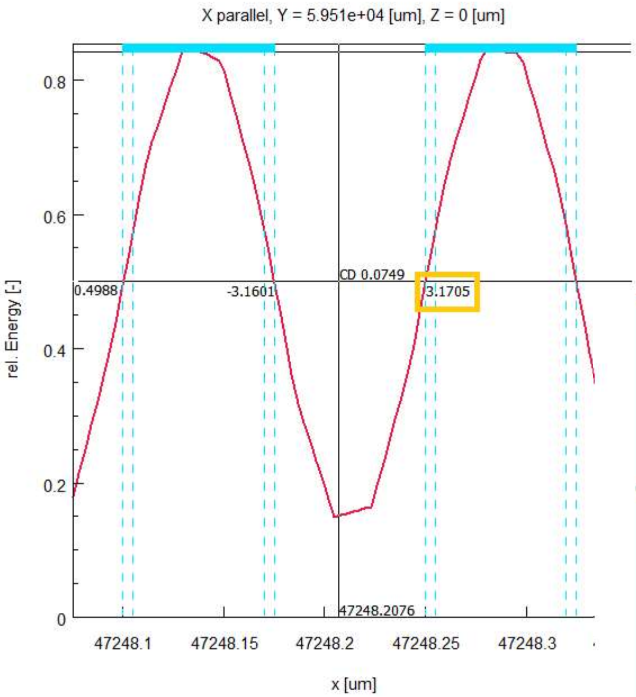


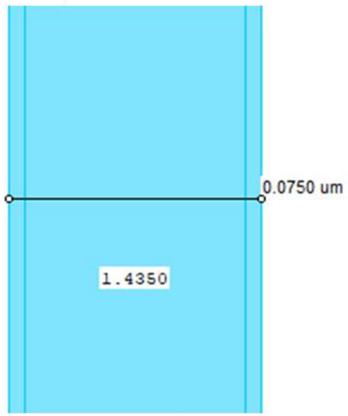
75 nm lines not printing well, remaining resist in gaps

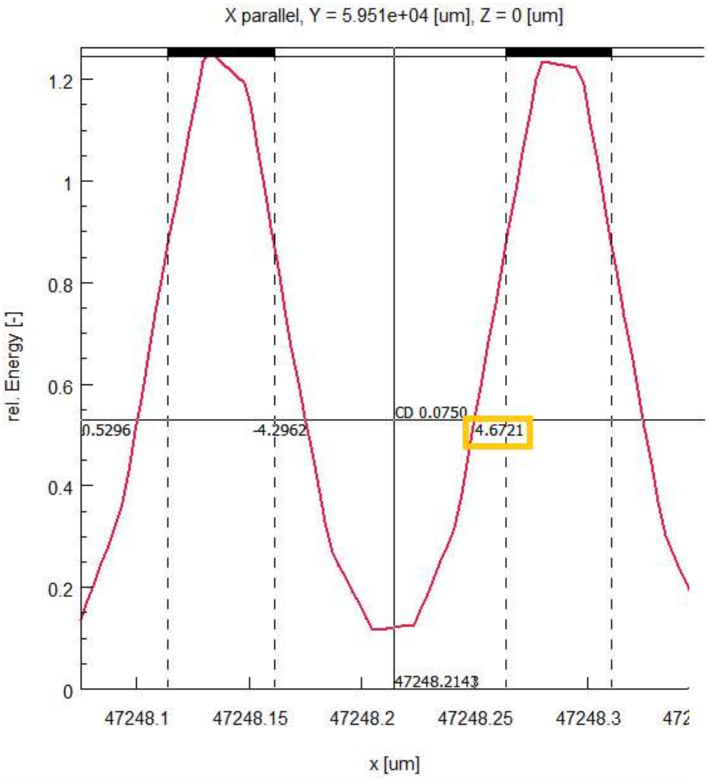
https://www.microresist.de/en/produkt/mr-ebl-6000-series/

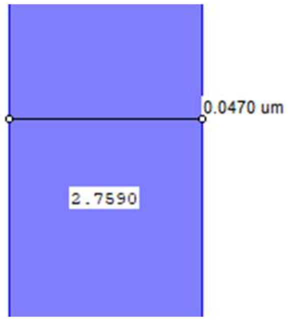
mr-EBL 6000

- Strategy: Shape-PEC ODUS for contrast enhancement



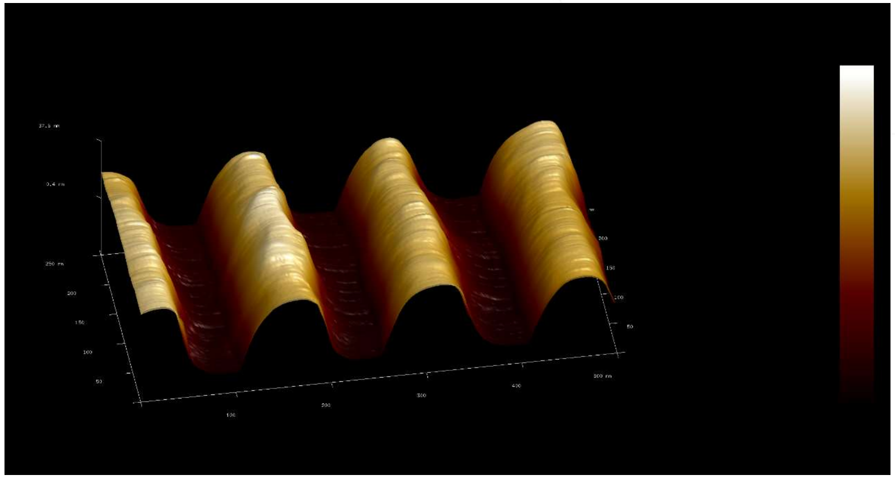


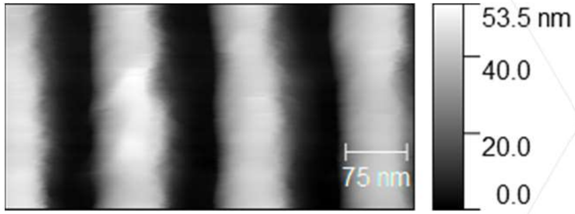




mr-EBL 6000

- Contrast enhancement with overdose undersize resulted in clearly resolving 75 nm 1:1 line:space pattern





Outline

- Part 4 Summary: Process Effects, Calibration and Correction
- Shape vs. Dose
- OverDose-UnderSize (ODUS)
- Resist Profile with ODUS
- Application Example
- Summary
- Q&A

Summary

- Short- and mid-range effects may be compensated by dose or shape
  - Dose - Pro: Higher Contrast and more stable for complex shapes
  - Dose – Con: Symetric correction, not optimal for non-symetric scenario (e.g. line end, different distance at edges)
  - Shape – Pro: Enables non-symetric correction, allows ODUS (s. below)
  - Shape – Con: Lower contrast (without ODUS), limitation for complex curved shapes
- Shape with ODUS
  - Enabling to push image contrast (litho quality) beyond Dose PEC
  - Higher edge quality, steeper resist profile
  - More stable process (larger process window)
- Application example
  - Single layer resist lift-off process by achieving negative resist profile
  - Resolving features & gaps in the order of the blur
- Warning:
  - Dose PEC is method of choice (effective and stable) for most application
  - ODUS offers advanced solution for some application, but needs special attention on complex layouts