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GenISys Team
October 28th, 2020

Proximity Effect in E-Beam Lithography

Overview and Agenda

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BEAMER LAB TRACER ProSEM MASKER

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…

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Rick Bojko, Ulrich Hofmann
October 28th, 2020

Proximity Effect in E-Beam Lithography

Part 4: Process Effect Calibration and Correction

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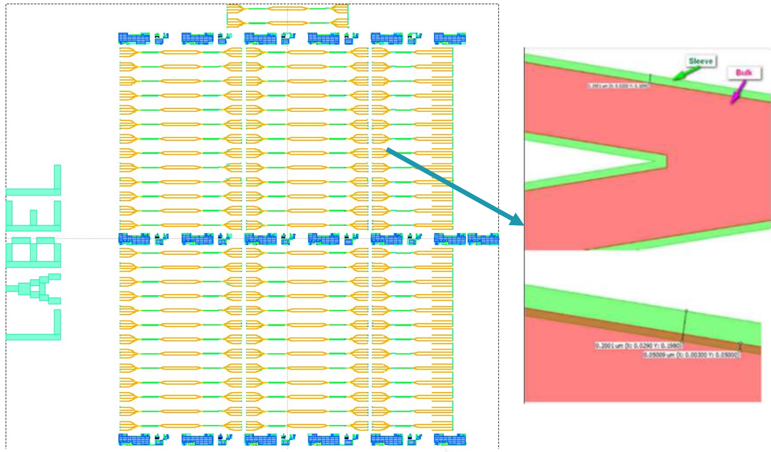
Outline

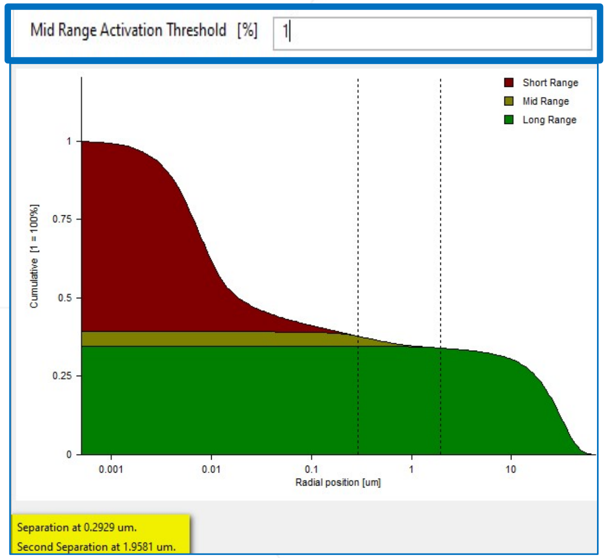
- Part 3 Summary: Dose PEC Parameters
- Process Effects and Major Parameters
- Calibration Procedure
- Advanced Model Parameters
- Summary
- Q&A

General Dose PEC Parameters

- Include all (and only) pattern to be exposed into the resist
  - PEC does maintain layers (e.g. for bulk-sleeve, writing order control)
  - Include non-critical layer in PEC, but exclude LR fracturing assigns on dose to the feature and considers energy contribution
  - Non critical out of influence range (pads, label, ….) may be excluded

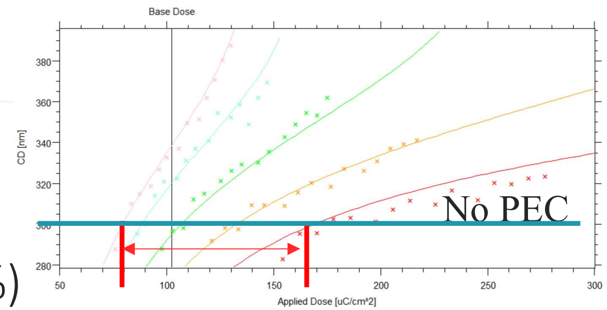


- PEC can be only as good as the correction function (PSF)
  - Monte-Carlo (table defined) PSF is preferred
  - Including Short Range correction requires “Effective Short Range Blur” (calibrated by TRACER)
  - Adding an additional midrange process blur (e.g. for HSQ) is possible (can be calibrated by TRACER)

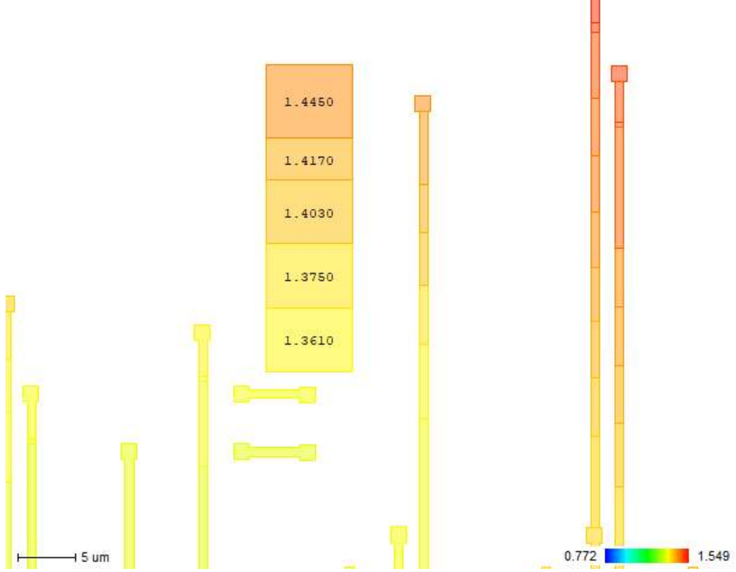


Dose Factor Accuracy

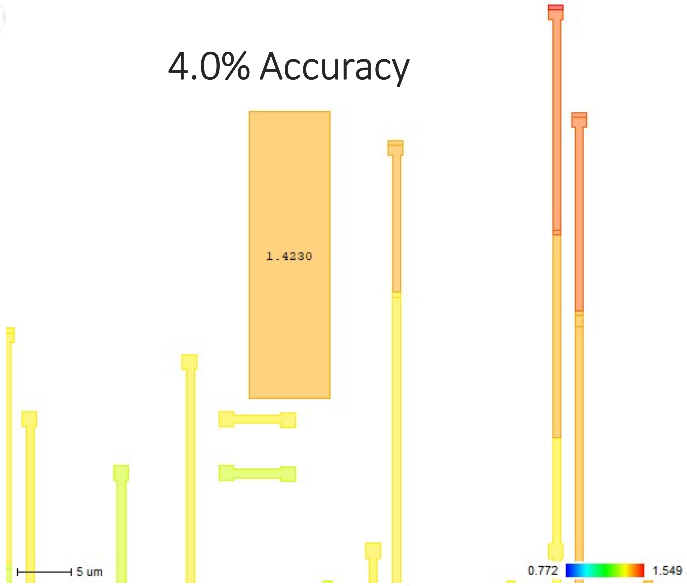
- The required **dose range** (PSF dependent) is split to “Dose Classes”
- Dose classes are automatically generated
  - Either via dose accuracy or manually by predefined dose classes
- Tradeoff between litho quality and shape count (write time)
  - Dose accuracy lower limited set by the system capability (typically 1%)

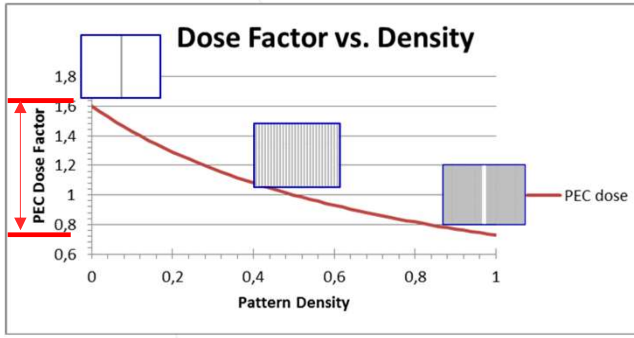


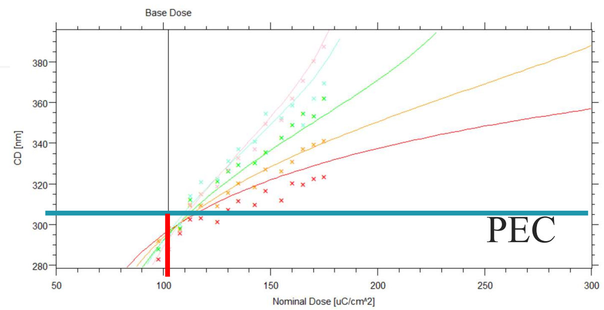
1.0% Accuracy



4.0% Accuracy





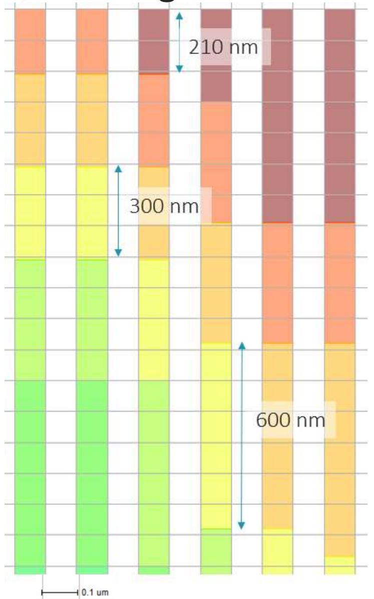


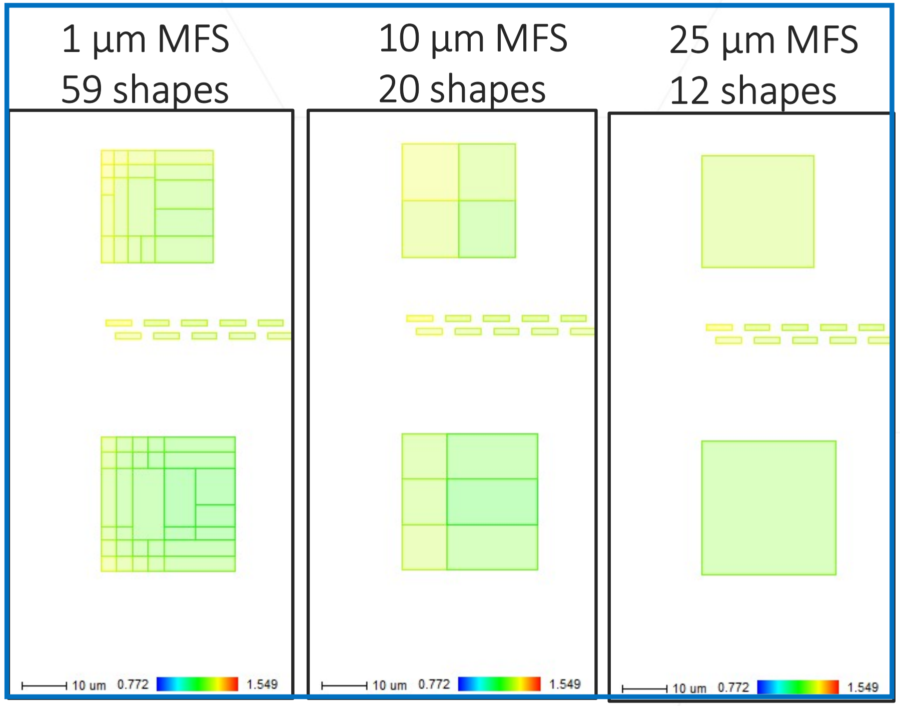
Physical PEC Fracturing

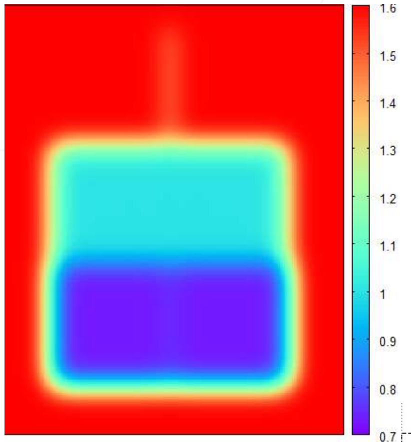
- The layout is locally fractured along the discretized dose map (iso-dose lines from dose classes)
  - “Iso-Dose” grid and Minimum Fracture Size (MFS) control location of cuts and number of shapes
  - Pre-fracturing allow to optimize number of shapes vs. accuracy

MFS = 100 nm

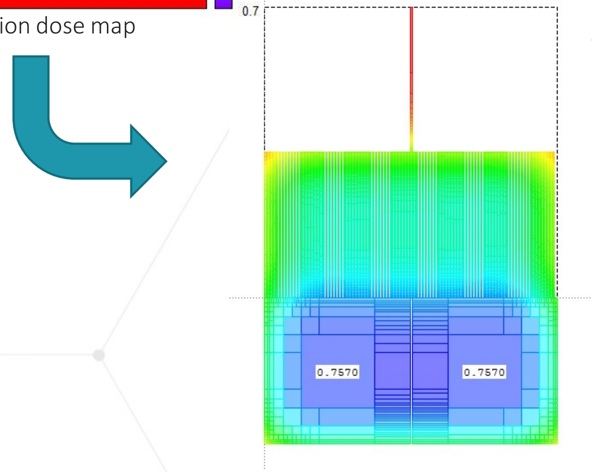
Isodose grid = 30 nm





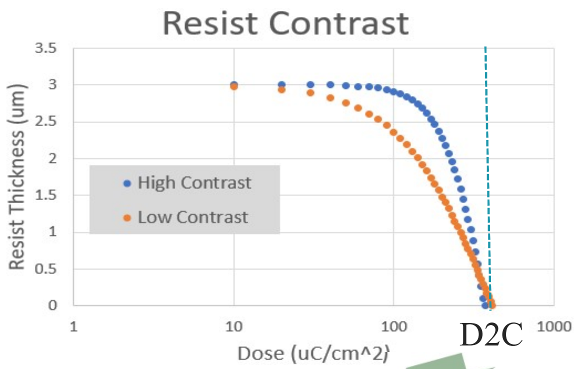


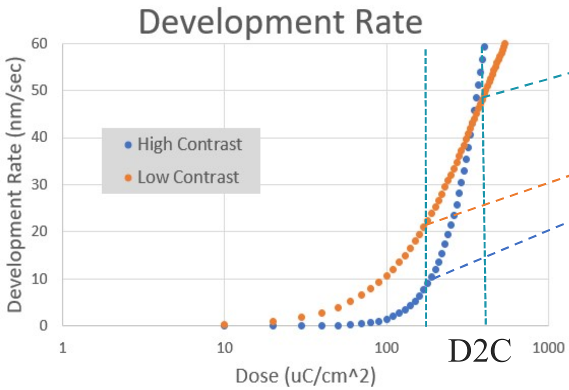
Correction dose map



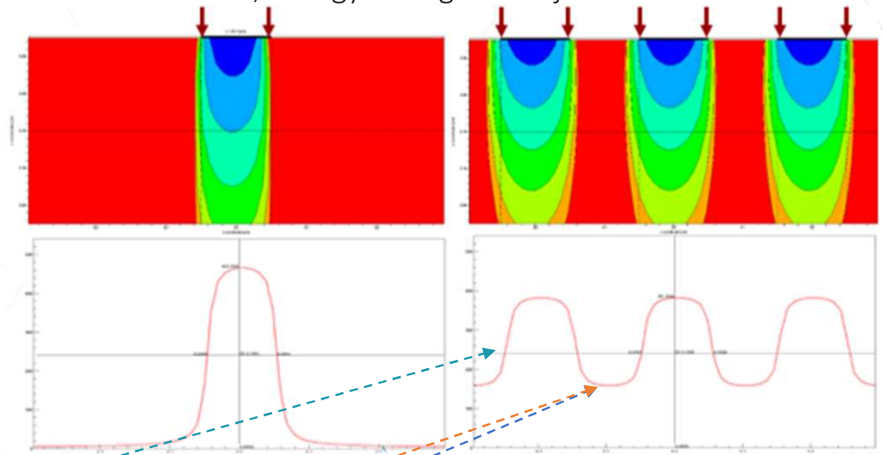
Origin of Lateral Development

- Energy scatters beyond the pattern edges, leading to unintended partial exposure
- Practical resists have finite contrast; resist develops even for doses well below the dose to clear





In PEC, Energy at edges is adjusted to dose to clear

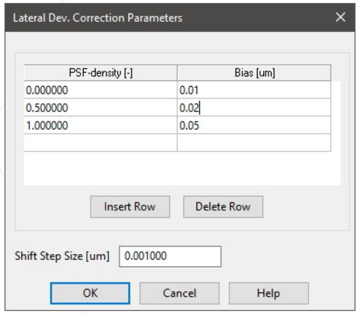


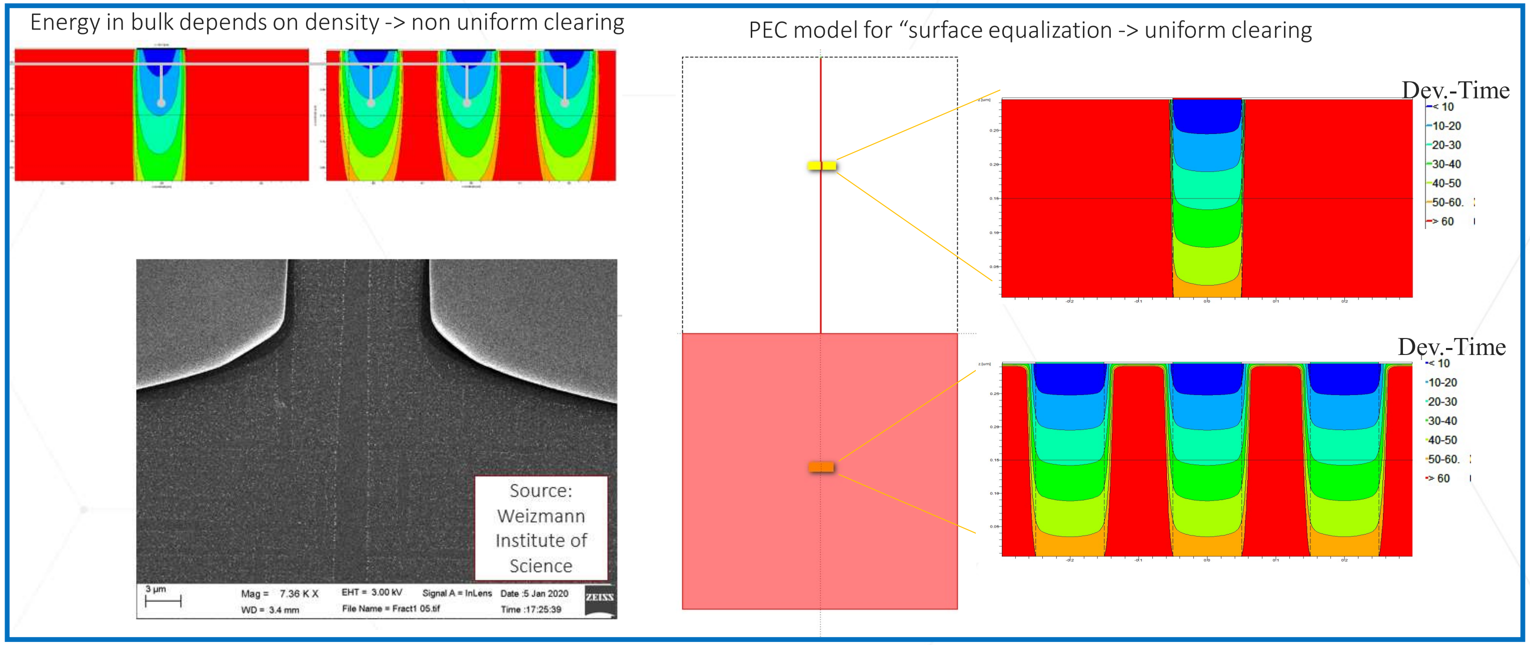
Background energy in unexposed area

- Together, these lead to development beyond exposed features, and features grow wider
- This is known as “Lateral Development”, and is an effect of the resist process

Advanced Process Correction Parameters

- Resist development effects require additional correction
- Lateral development is corrected by density-dependent bias
- Resist residues due to low energy in areas of high density (large pads) may require correction towards “uniform clearing”, a mix of OC/UC
- These are calibrated from experimental measurements using TRACER

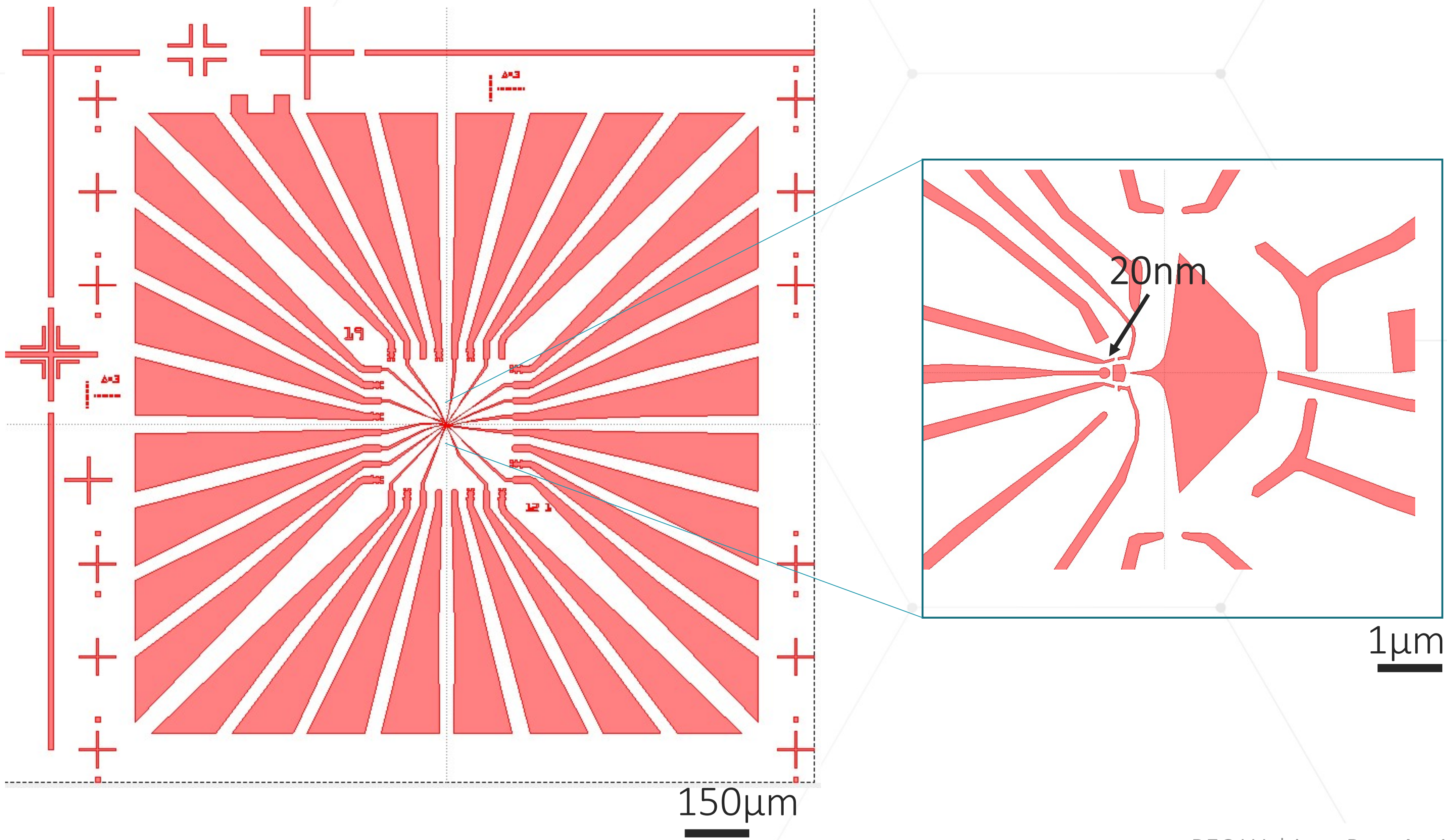




Outline

- Part 3 Summary: Dose PEC Parameter
- Process Effects and Major Parameter
  - From Design to Sample
  - Base Dose, Process Biases, Effective Blur and their Coupling
  - Calibration Strategy
- Calibration Procedure
- Advanced Model Parameter
- Summary
- Q&A

From Design To Sample



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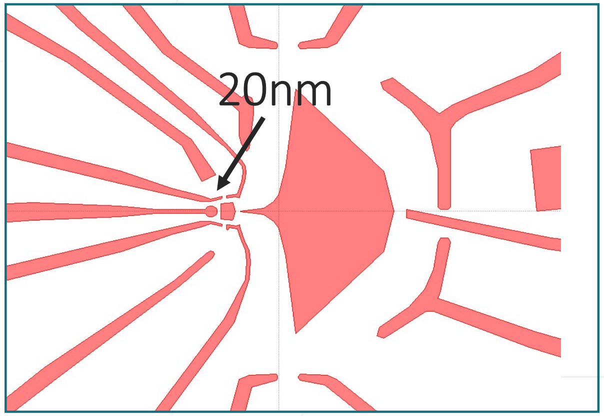
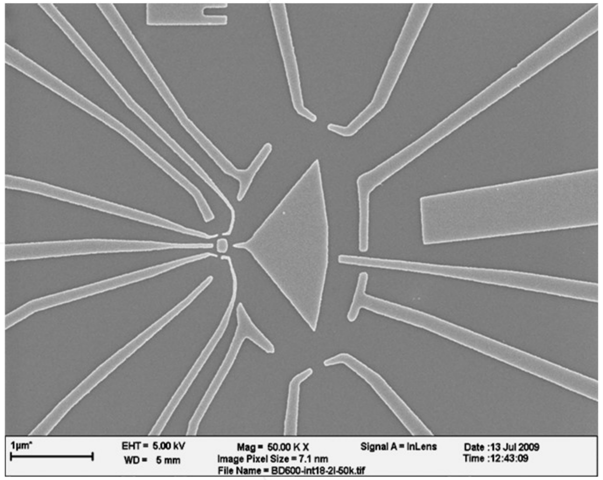
From Design To Sample

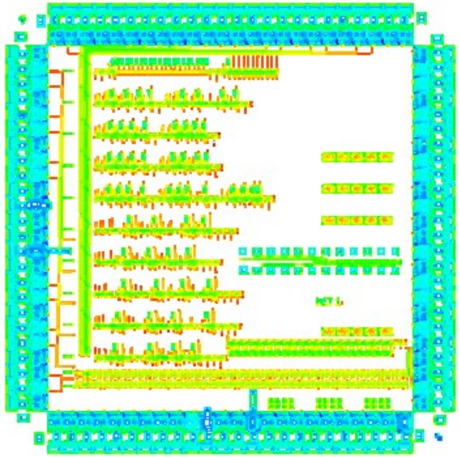
- What we see on SEM is the result of a complex process
  - Dataprep
  - Exposure
    - Writing strategy (fields, shape filling , ...)
    - Electron Scattering (spread of energy in 3D)
  - Resist development
    - Transfer of energy to dissolution rate
    - Resist development process (single layer, multi layer)
    - Post development process (baking, descum,...)
  - Pattern transfer
    - Lift off
    - Etching (wet, RIE)
  - Inspection
    - SEM imaging

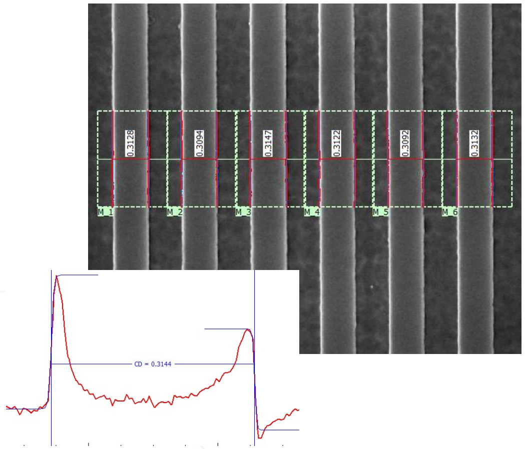




How do we Choose Exposure Parameters?

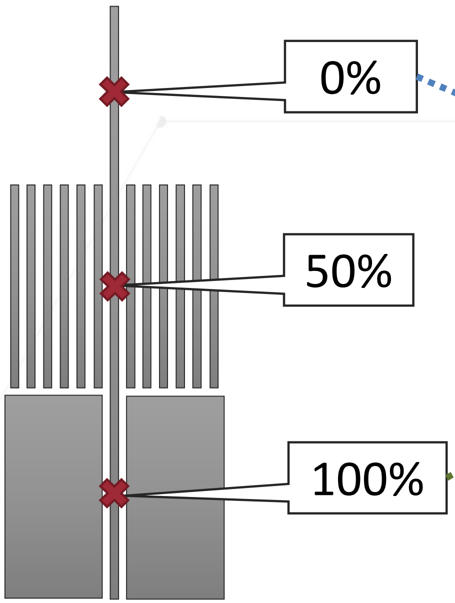
- Base Dose
  - Expose dose matrix
    - a „typical“ PEC‘ed pattern
    - large 50% L/S pattern with dose matix
  - Process (develop, pattern transfer)
  - Find „right dose“ with SEM measurement

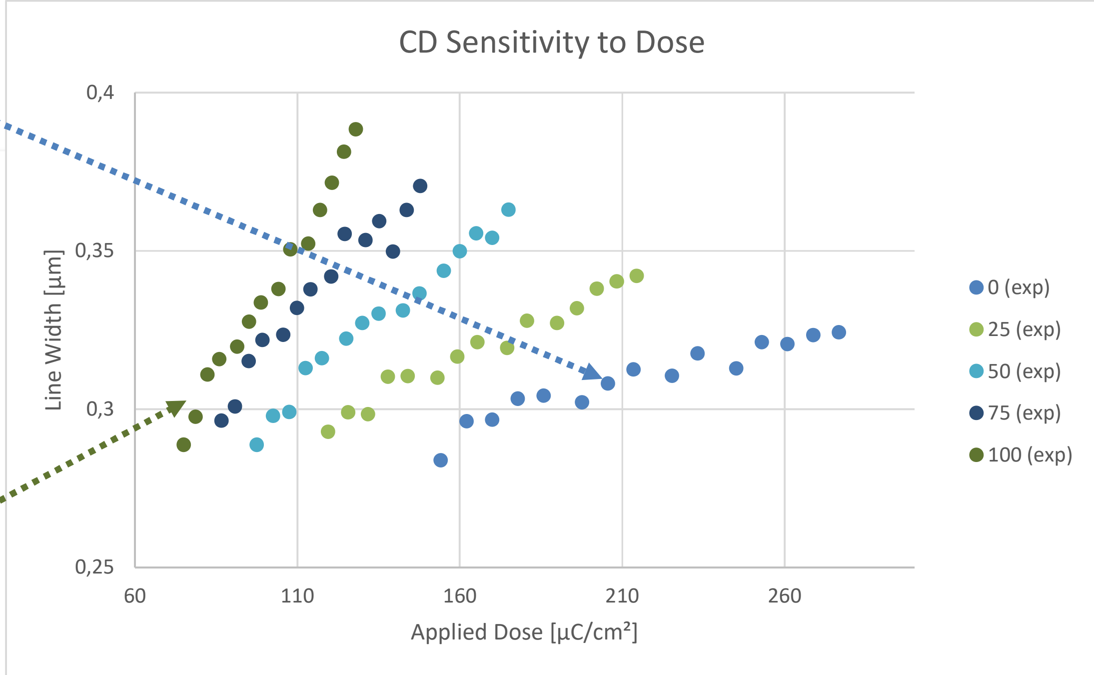




- **Good as a starting point**
- **Does not include process effects across densities**
- **May not be the „best base dose“**

Typical Experimental Result





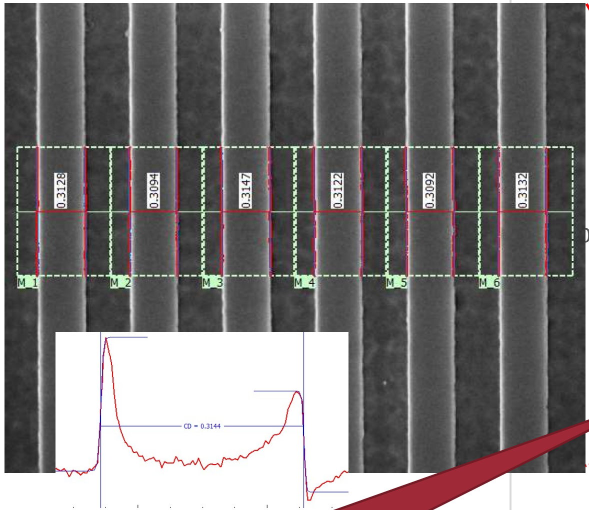
U.Penn:
200nm ZEP520A on Si

Accel. Voltage: 50 kV

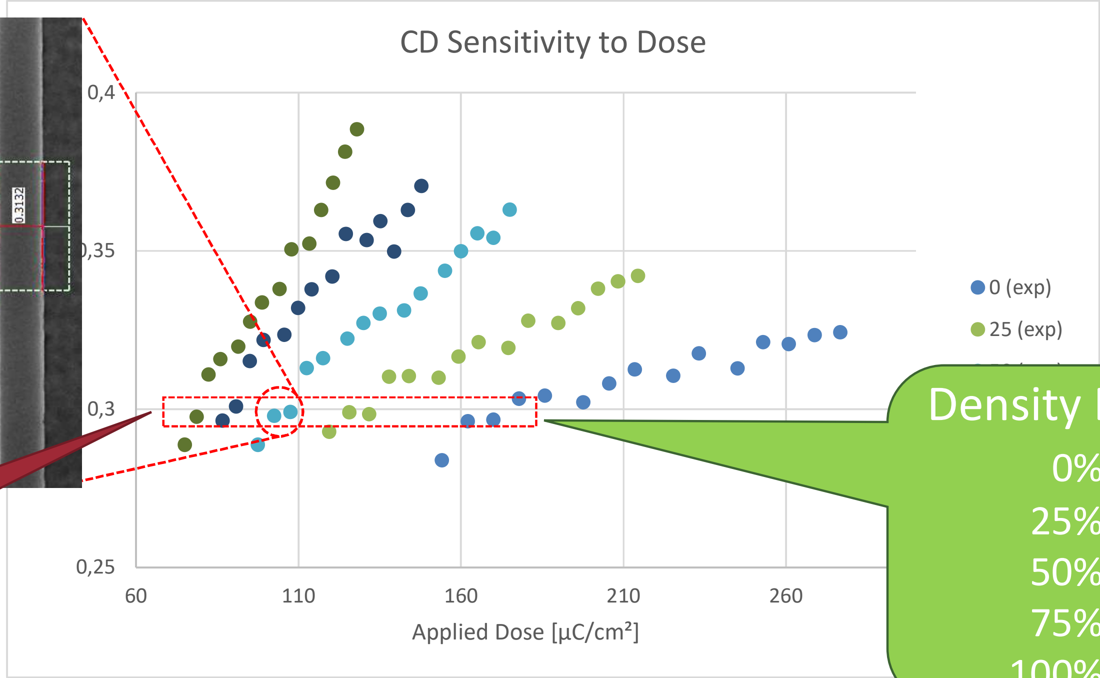
Target CD: 300nm

- For a given stack, $CD_{measured}$ is a function of dose and pattern density
  - Iso- and dense lines require very different doses to get to the same CD
  - Iso lines show „best“ CD response with dose (big changes in dose -> CD varations)
- Base Dose and Bias is coupled

„Typical“ Process Optimization: Dose to Size



Target CD: 300 nm



U.Penn:
200nm ZEP520A on Si

Accel. Voltage: 50 kV

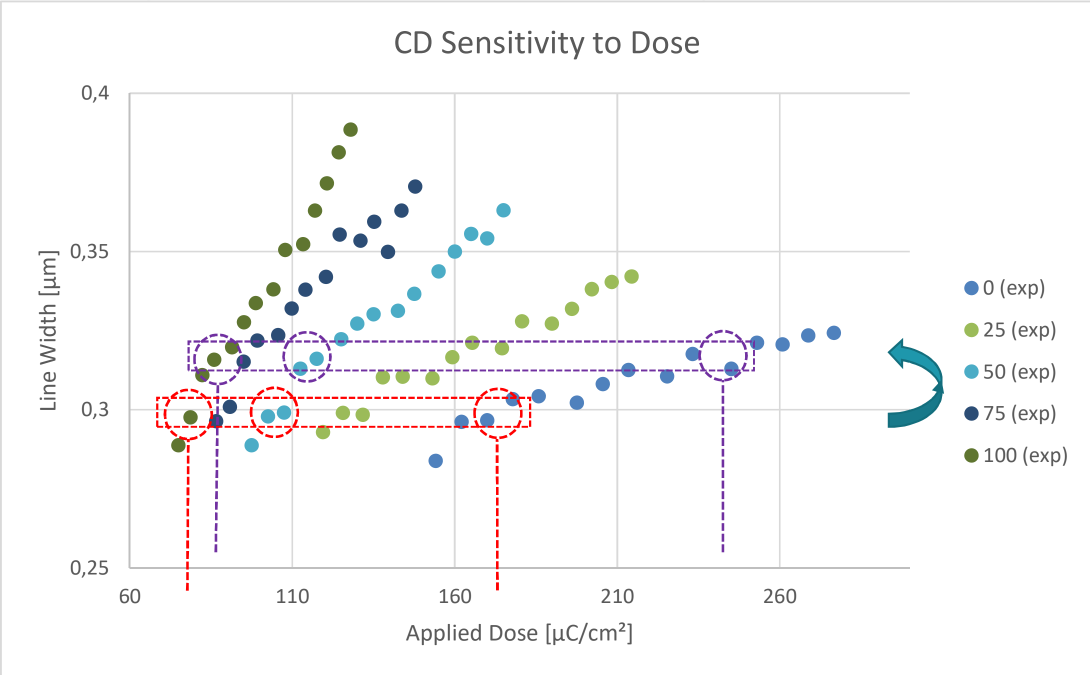
Target CD: 300nm

Density Dependent Doses

0%	170µC/cm²
25%	130µC/cm²
50%	107µC/cm²
75%	95µC/cm²
100%	80µC/cm²

- Typical base dose calibration picks „line width == space width“ for 1:1 L&S
  - Results in 107 µC/cm² Base Dose for this example
  - Results in Dose Range 80 (100%) .. 170 µC/cm² (0%)

Impact of „a" Bias



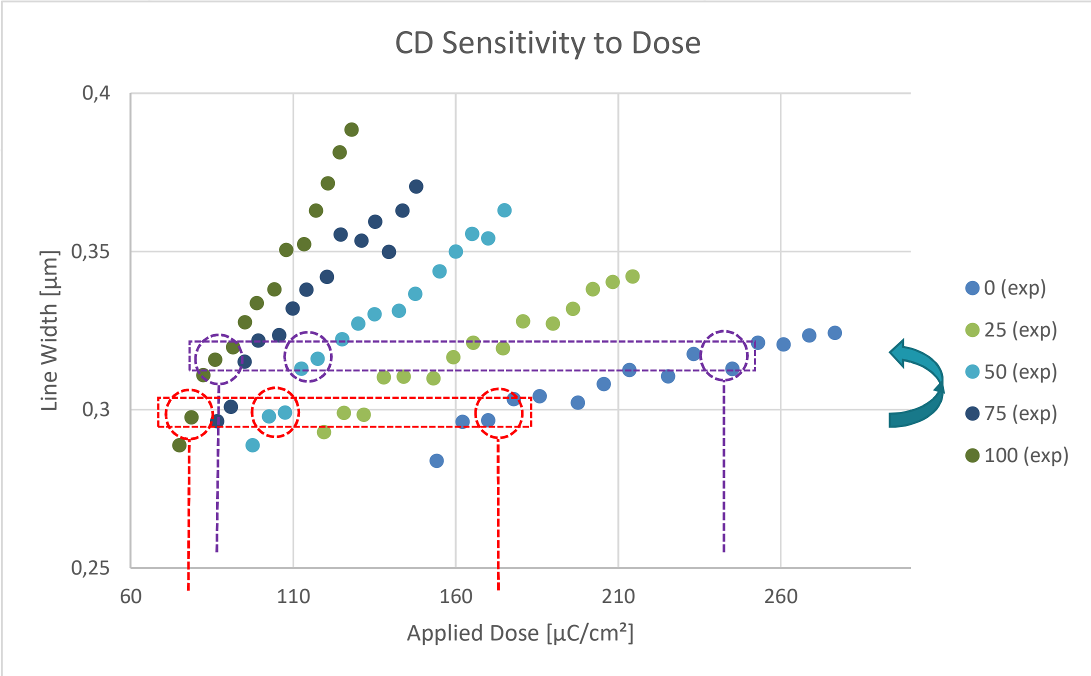
U.Penn:
200nm ZEP520A on Si

Accel. Voltage: 50 kV

Assume 20nm process bias
e.g. from development, etch, metrology

- Target CD (= Zero Bias) results in Dose Range 80 (100%) .. 170 µC /cm² (0%)
- 20nm Bias ⇒ Applied dose: 91µC (100%) .. 233µC /cm² (0%)

Impact of „a" Bias



U.Penn:
200nm ZEP520A on Si

Accel. Voltage: 50 kV

Assume 20nm process bias
e.g. from development, etch, metrology

- Target CD (= Zero Bias) results in Dose Range 80 (100%) .. 170 µC /cm² (0%)
  - PEC would need to deliver a dose ratio D_{iso} / D_{dense} = 170 / 80 = 2.12
- 20nm Bias ⇒ Applied dose: 91µC (100%) .. 233µC /cm² (0%)
  - PEC would need to deliver a dose ratio D_{iso} / D_{dense} = 233 / 91 = 2.56

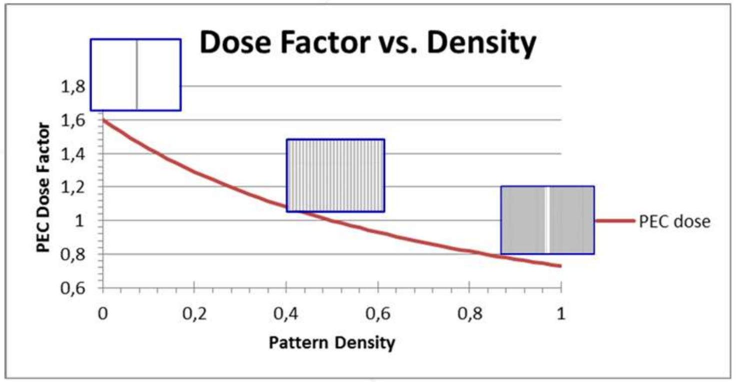
Key Learning

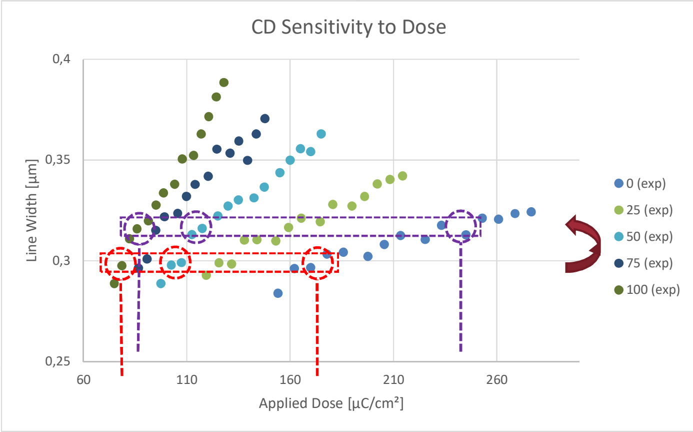
- PEC computes (density dependent) dose factors
  - The dose ratio D_{iso} / D_{dense} only depends on back-scattering (NOT on process point)
  - For Si at 50keV, D_{iso} / D_{dense} = 2.4

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

BE = 0.4
ρ = 1 for dens / 0 isolated

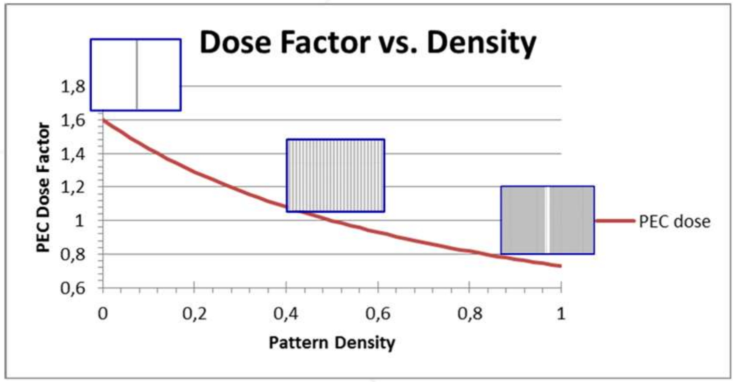
$$\frac{D_{iso}}{D_{dense}} = \frac{\frac{1}{1 + 0.412\,(2 * 0 - 1)}}{\frac{1}{1 + 0.412\,(2 * 1 - 1)}} = 2.4$$

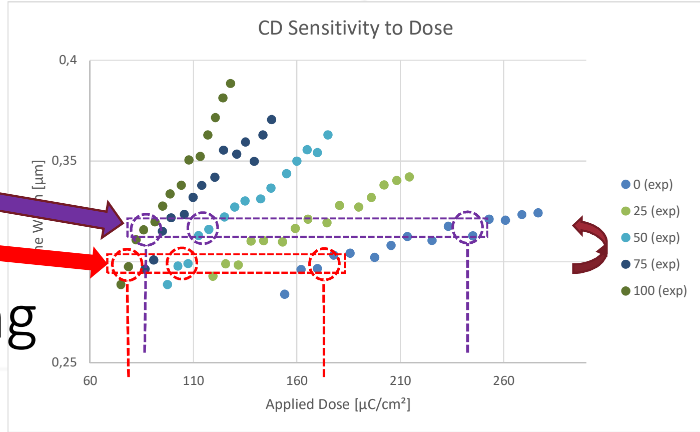




Key Learning

- PEC computes (density dependent) dose factors
  - The dose ratio D_{iso} / D_{dense} only depends on back-scattering (NOT on process point)
  - For Si at 50keV, D_{iso} / D_{dense} = 2.4
- However, process data shows varying dose ratios
  - For the sample data shown
  - D_{iso} / D_{dense} = 2.56 (20nm bias)
  - D_{iso} / D_{dense} = 2.12 (0 bias)
- Adjustment to proper dose range enable decoupling
  - Base Dose, Process Bias (global & density dependent), effective blur





Process point with smallest spot-size (blur) sensitivity: the iso-focal

Iso-Focal Calibration

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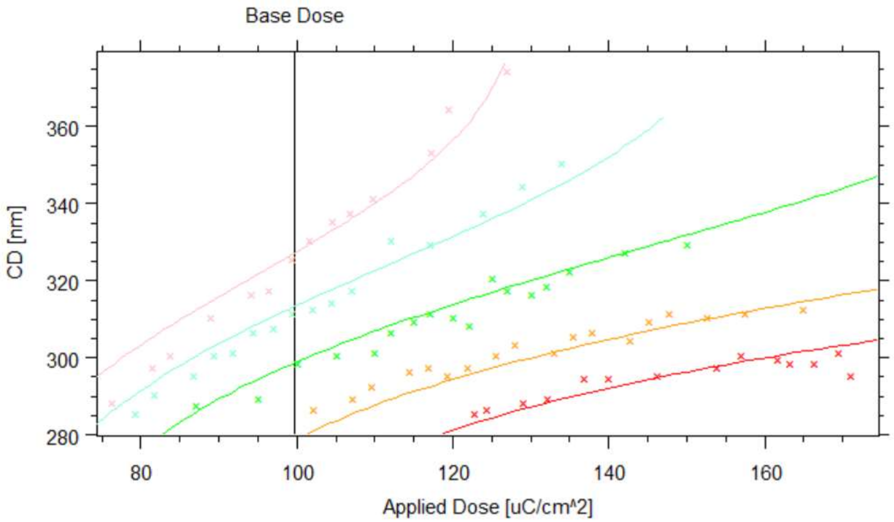

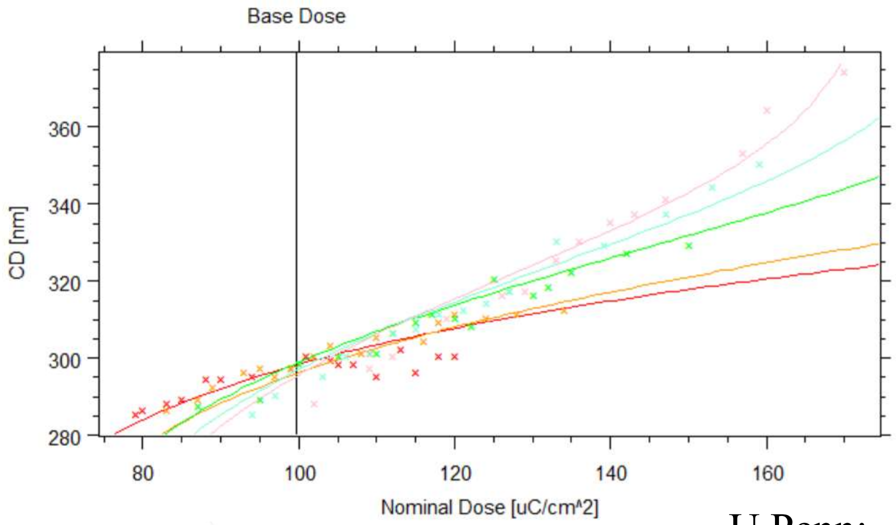

U.Penn:
300nm ZEP520A on Si

Accel. Voltage: 50 kV

Applied Dose = Base Dose * D_f

Please Note: Both graphs show the same process!
Line Width vs. Applied Dose ⇔ Line Width vs. Base Dose

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References

1. Chris Mack, Electron-beam lithography simulation for maskmaking, part IV, proceedings of Photomask and X-Ray Mask Technology VI, SPIE Vol. 3748, pp. 27-40
2. K.Keil et al, Determination of best focus and optimum dose for variable shaped e-beam systems by applying the isofocal dose method, Microelectronic Engineering 85 (2008) 778–781
3. U.Hofmann, N.Ünal, S.Sayan, G.Lopez, D.Mahalu, A novel method to find the best (iso-focal) process point in electron beam lithography, GenISys White Paper
4. G. Lopez et al, Isofocal Dose Based Proximity Effect Correction - Tolerance to the Effective Process Blur. Journal of Vacuum Science & Technology B 35, 06G505, 2017
5. Application Note in GenISys download area, Full Process Calibration using TRACER: Experimental Procedure

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Outline

- Part 3 Summary: Dose PEC Parameter
- Process Effects and Major Parameter
- Calibration procedure
  - GaAs example
  - High contrast resist vs. low contrast resist
- Advanced Model Parameter
- Summary
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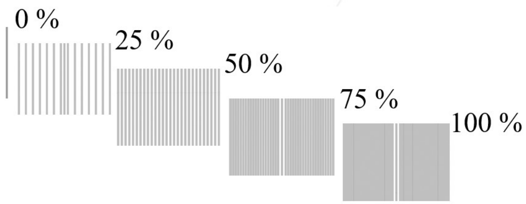
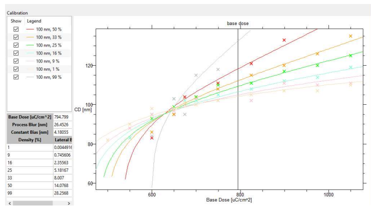
Process Calibration Procedure

Expose Dose Matrix, Process, & Measure Calibration Pattern

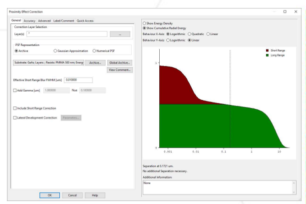


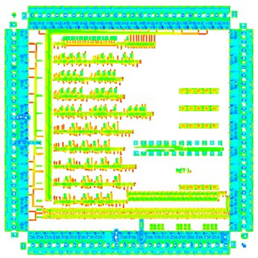
Use TRACER to fit the data and determine correction parameters



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

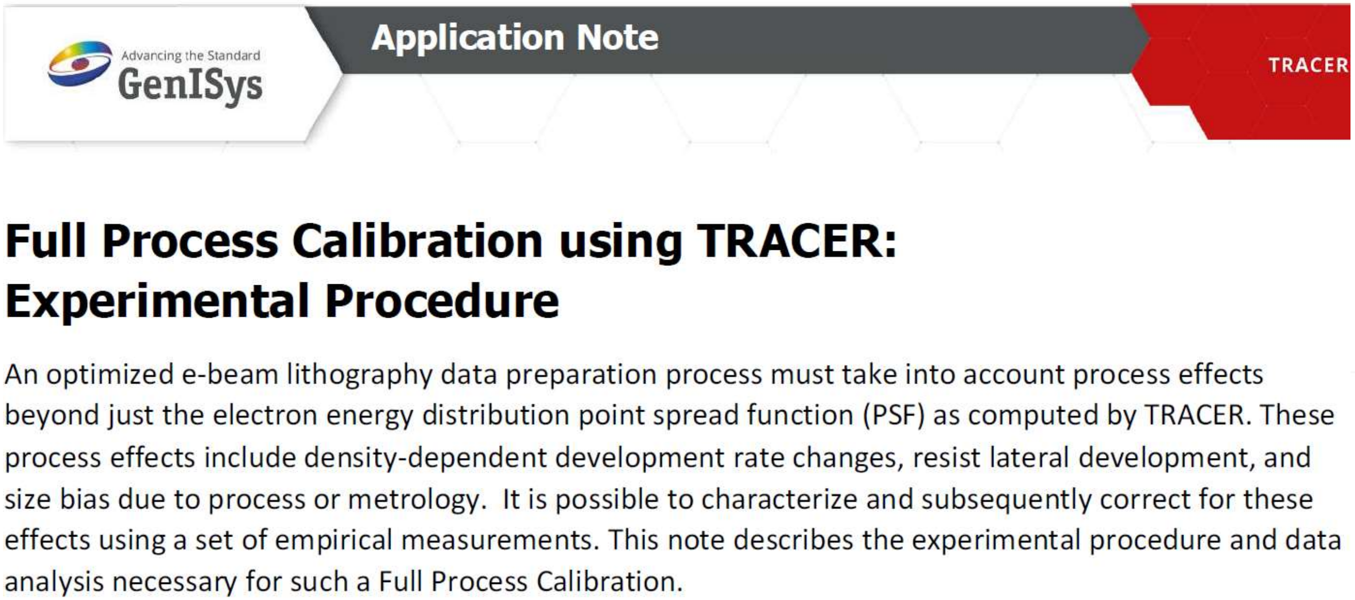
Apply correction parameters using BEAMER's PEC module





Documentation and Materials

- Calibration patterns are in BEAMER example folder
- Application Note in download area
- Help: support@genisys-gmbh.com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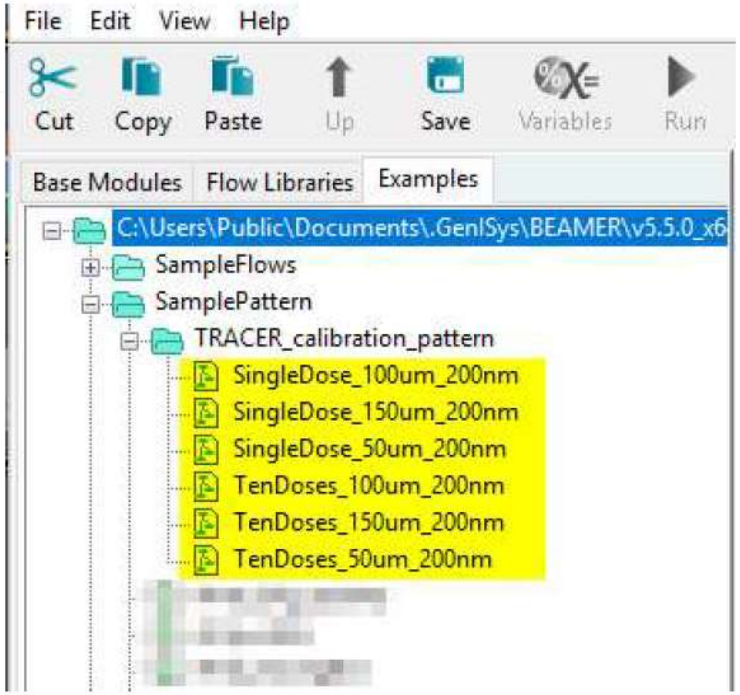
Application Note
TRACER

Full Process Calibration using TRACER: Experimental Procedure

An optimized e-beam lithography data preparation process must take into account process effects beyond just the electron energy distribution point spread function (PSF) as computed by TRACER. These process effects include density-dependent development rate changes, resist lateral development, and size bias due to process or metrology. It is possible to characterize and subsequently correct for these effects using a set of empirical measurements. This note describes the experimental procedure and data analysis necessary for such a Full Process Calibration.



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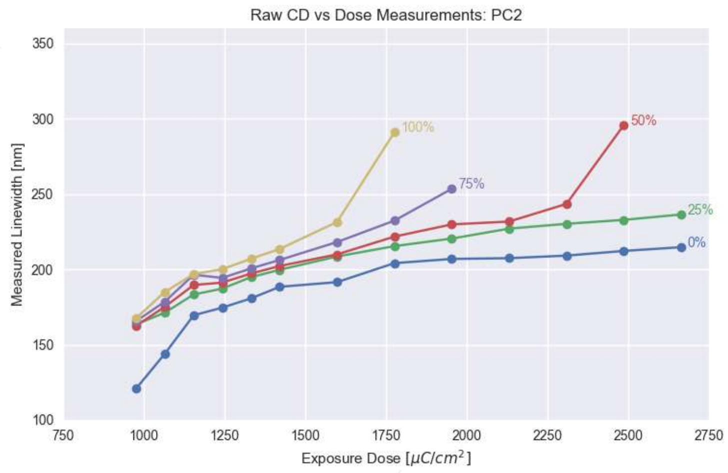
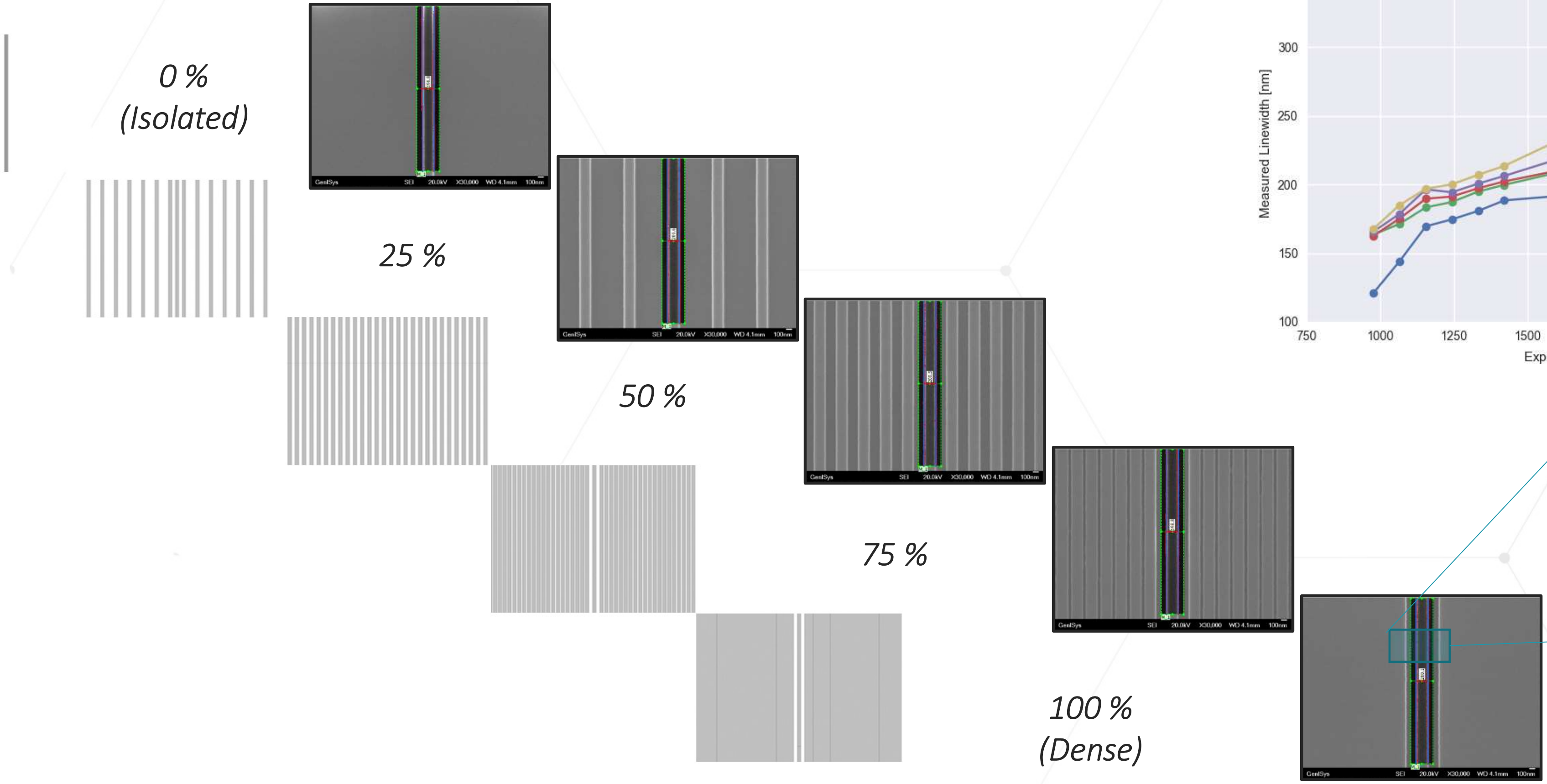
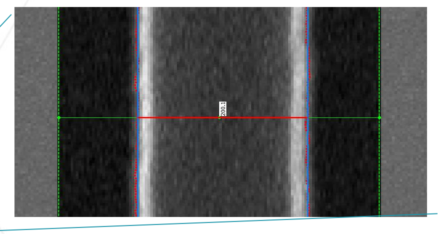
Measuring Process Effects of Pattern Density

- Expose lines over a range of doses, with local pattern density varying from isolated to fully dense.







Fast and Consistent Measurements

- Consistent and reliable SEM measurements are critical for process calibration
  - Hand-drawn cursors are subjective, tedious, time-consuming, inconsistent
- ProSEM offers stable, consistent, fast CD measurements from saved SEM images
- Recipes, Batch Processing and Scripting enable automation

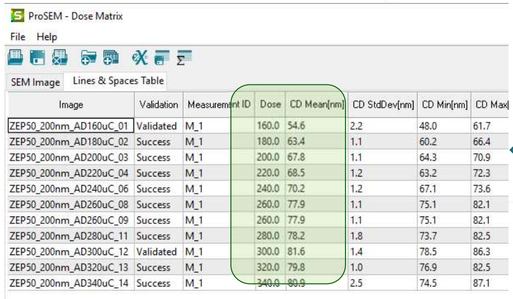
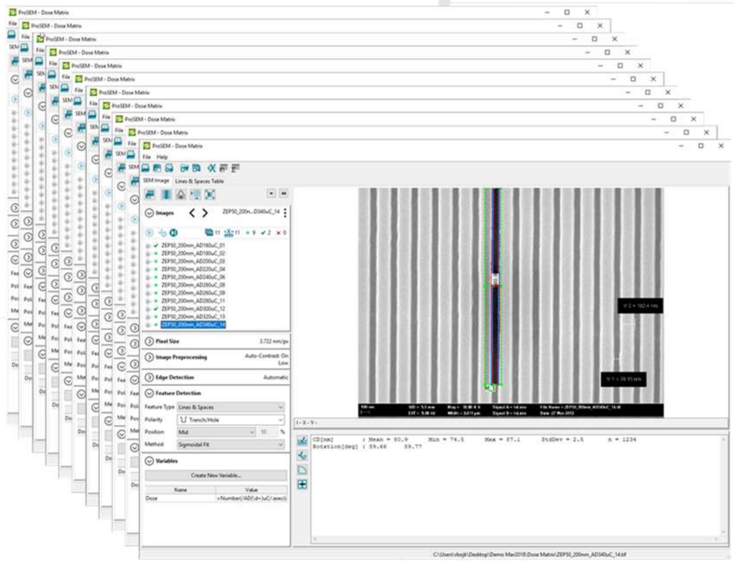


Image	Validation	Measurement ID	Dose	CD Mean[nm]	CD StdDev[nm]	CD Min[nm]	CD Max[
ZEP50_200nm_AD160uC_01	Validated	M_1	160.0	54.6	2.2	48.0	61.7
ZEP50_200nm_AD180uC_02	Success	M_1	180.0	63.4	1.1	60.2	66.4
ZEP50_200nm_AD200uC_03	Success	M_1	200.0	67.8	1.1	64.3	70.9
ZEP50_200nm_AD220uC_04	Success	M_1	220.0	68.5	1.2	63.2	72.3
ZEP50_200nm_AD240uC_06	Success	M_1	240.0	70.2	1.2	67.1	73.6
ZEP50_200nm_AD260uC_08	Success	M_1	260.0	77.9	1.1	75.1	82.1
ZEP50_200nm_AD260uC_09	Success	M_1	260.0	77.9	1.1	75.1	82.1
ZEP50_200nm_AD280uC_11	Success	M_1	280.0	78.2	1.8	73.7	82.5
ZEP50_200nm_AD300uC_12	Validated	M_1	300.0	81.6	1.4	78.5	86.3
ZEP50_200nm_AD320uC_13	Success	M_1	320.0	79.8	1.0	76.9	82.5
ZEP50_200nm_AD340uC_14	Success	M_1	340.0	80.9	2.5	74.5	87.1



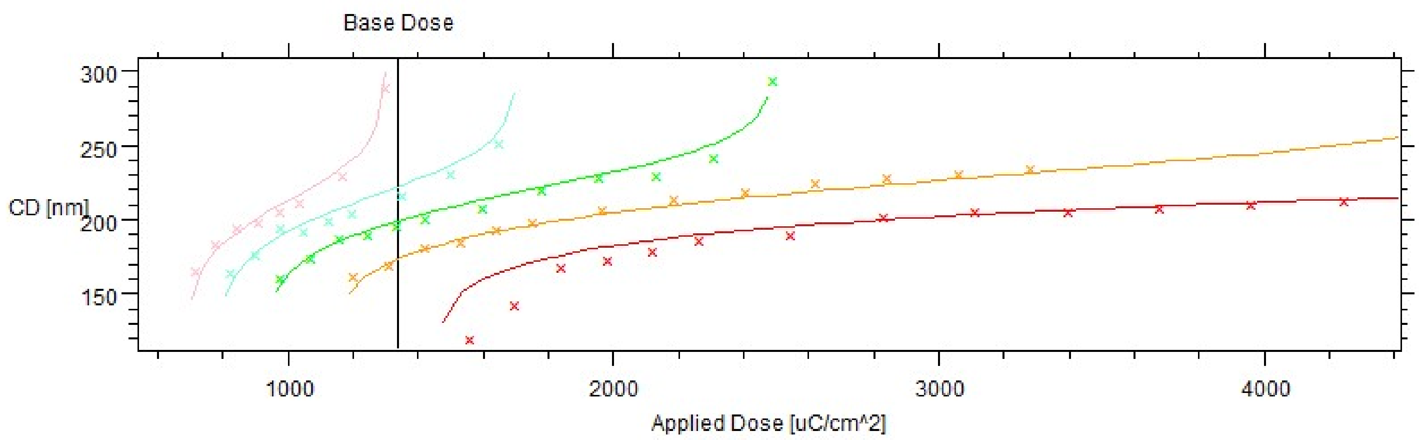
Fitting the Measured CD Data

- The data is fitted to determine additional correction terms needed to compensate for process effects

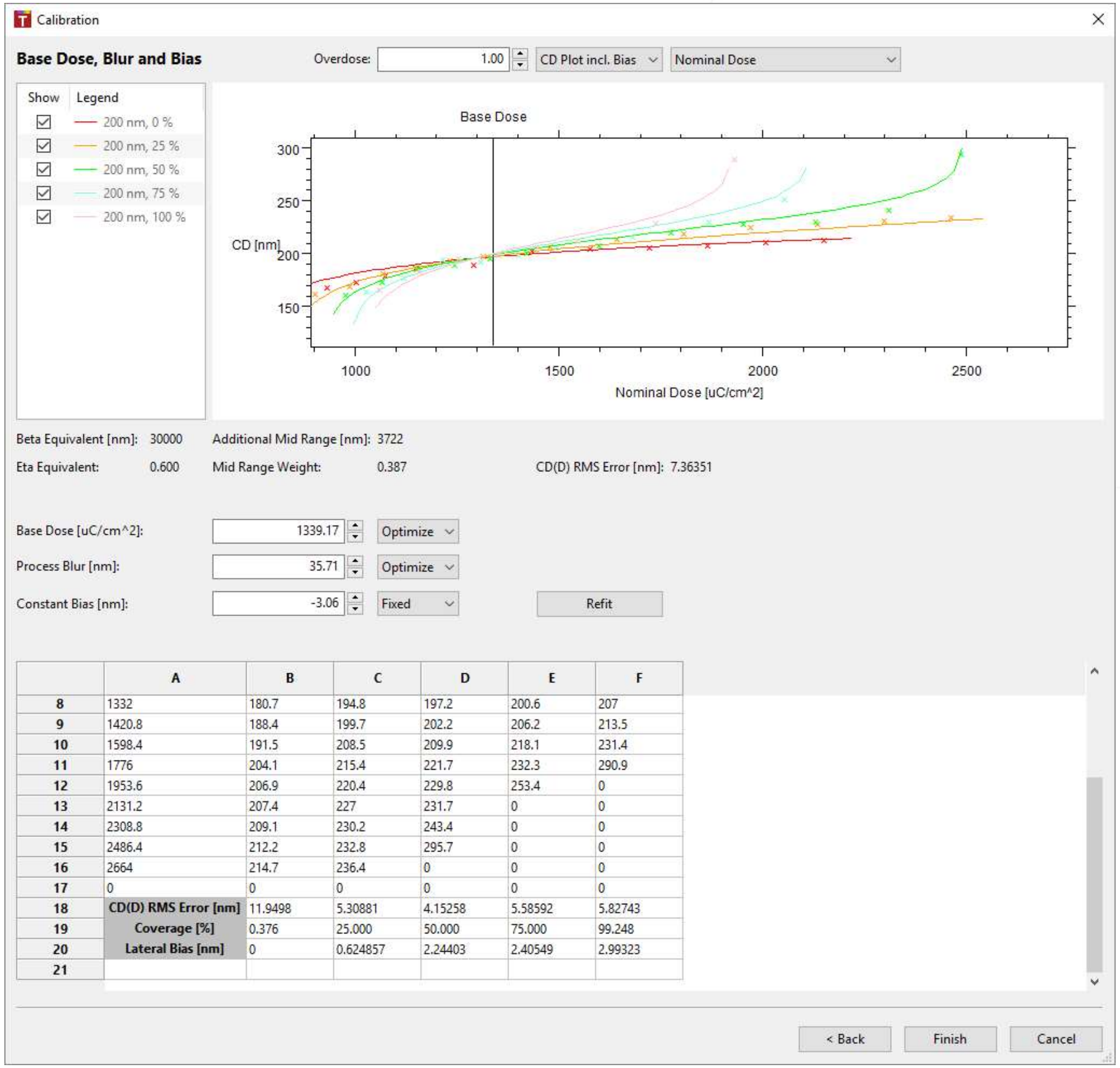
$$CD = CD_0 + Bias_{Lat.Dev} + \frac{ProcessBlur}{\sqrt{\ln(2)}} * Erf^{-1}\left[\left(\frac{D2C}{D} - BE - Dens_{long-range} * BE\right) * (1 - BE)\right]$$

Where the $Bias_{Lat.Dev}$ is determined using the development rates derived from the contrast curve and iterating the integral:

$$t_{lat} = \int_{x0}^{x1} \frac{dx}{r_{lat}(x)}$$



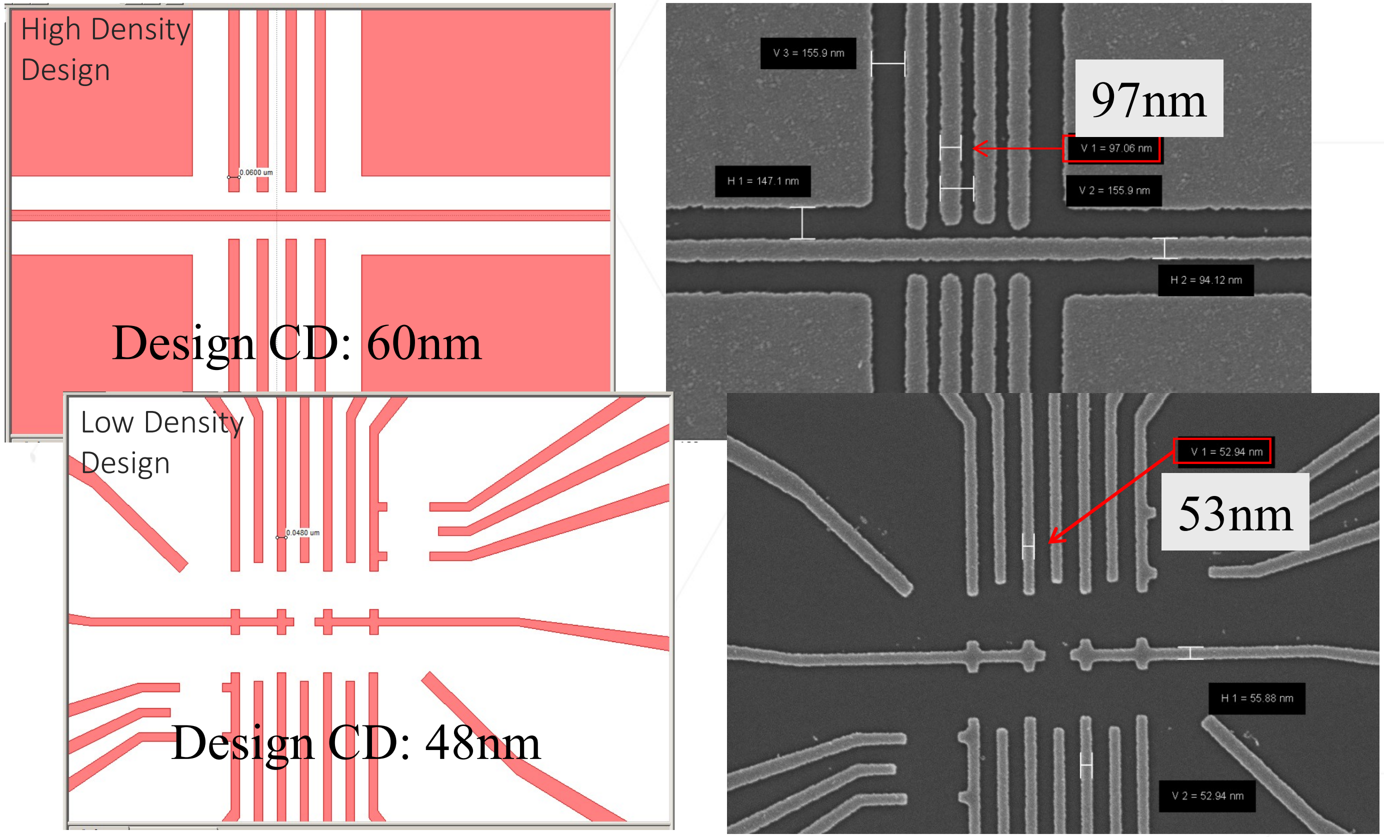
Fit Results



	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						

- The fitting procedure results in an "Extended Point Spread Function", adding terms to the scattering PSF for:
  - Optimal Base Exposure Dose
  - Process Blur
  - Overall Process Bias
  - Density-dependent Bias to compensate for lateral development
  - Midrange Gaussian term for additional process effects, such as diffusion
  - OC/UC Mix Factor

Quantum Device w/o Process Calibration



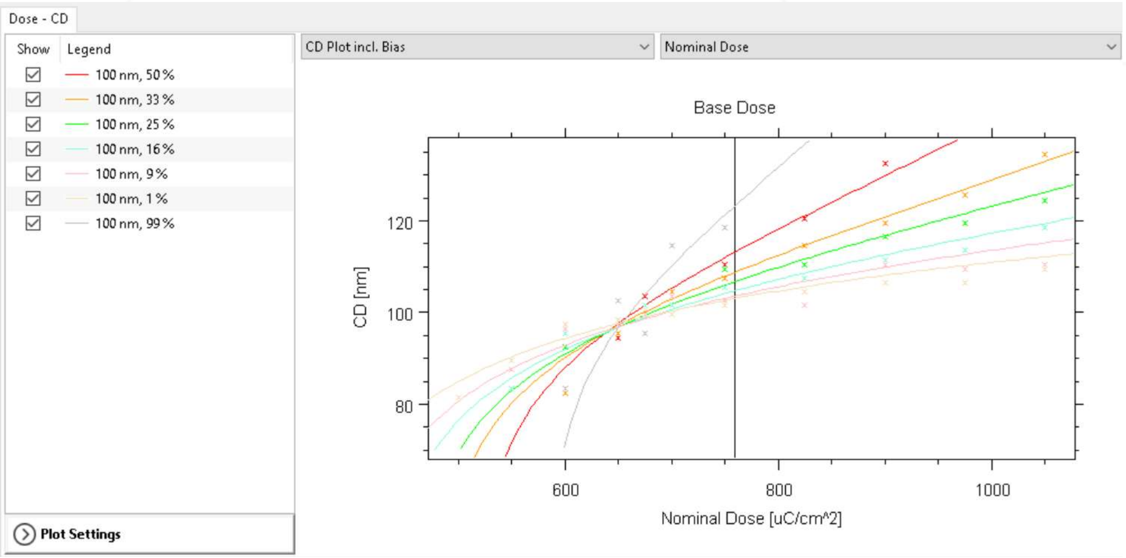
Conventional PEC Only

- The 48 nm line almost on target – 60nm line far away from target

Source: מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE

Calibration for 100keV on GaAs

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

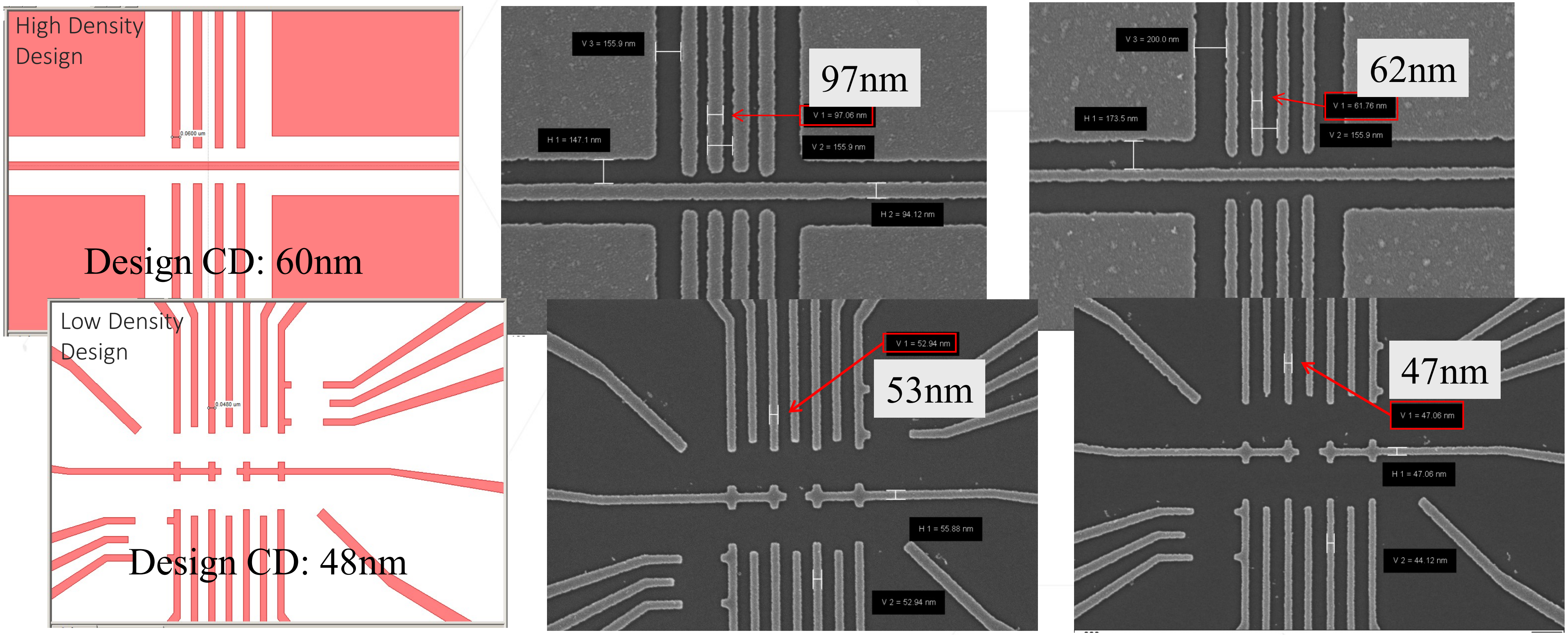


12⁰C (tool set point) development 2 minutes							
Dose factor / Pattern Ratio	1:1	1:2	1:3	1:5	1:10	1:1000	100:1
1050 µC/cm²	--	135.6	125.9	119.1	111.3	110.8	--
975 µC/cm²	--	126.2	120.6	114	110.8	107.4	--
900 µC/cm²	132.9	120.9	117.6	112.1	111.8	107.9	--
825 µC/cm²	121.6	115.5	111.5	108.5	102.5	105	--
795 µC/cm²	118	112	110	106	105	104	132
750 µC/cm²	111.5	108.2	110	105.6	102.9	102.5	118.7
700 µC/cm²	104.7	104.7	104.1	102	103.7	100.4	115.1
675 µC/cm²	104.1	100.9	100.3	102.2	100	101	95.6
650 µC/cm²	95	95.7	99.1	103.4	97.8	98.9	103.7
600 µC/cm²	81.6	89.7	93	95.6	94.1	98.1	--
550 µC/cm²				83.8	88.2	90.4	
500 µC/cm²						82.5	

Process:
200nm PMMA on GaAs
Exposure @ 100 kV
Development: 2 minutes at 12⁰C (tool set point)

Source: מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE

Quantum Device Result



Conventional PEC Only

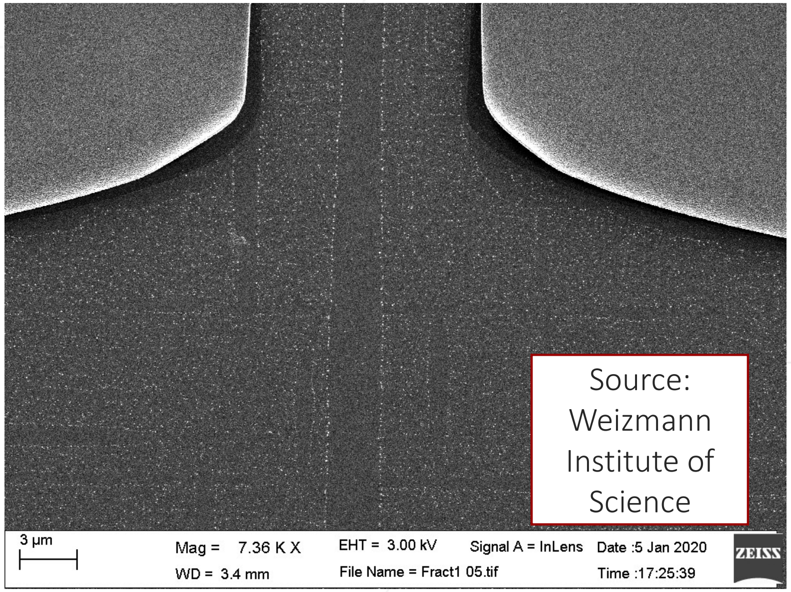
PEC with Process Calibration

- Excellent Results on different CDs at different densities

Source: מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE

Resist Residues

- In some cases, resist residues are left in large exposed areas
- This is especially found with:
  - Low contrast resists
  - On Higher Z materials, such as III-V semiconductor substrates



Outline

- Part 3 Summary: Dose PEC Parameter
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- Advanced Model Parameters
  - Low-contrast resists in combination with III-V materials
  - HSQ peculiarities
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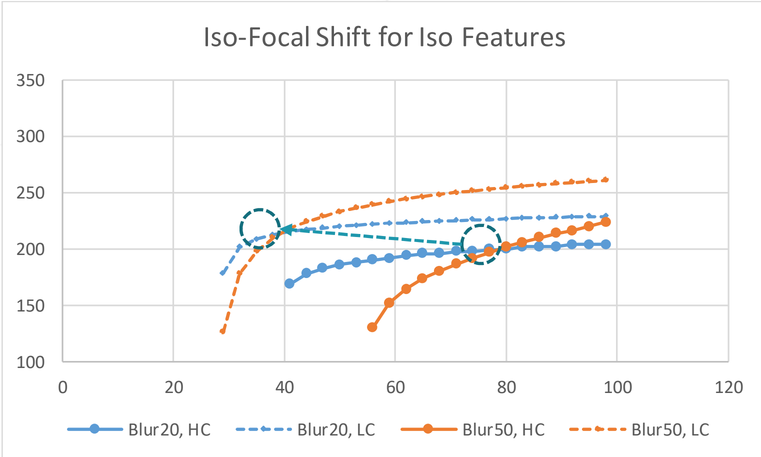
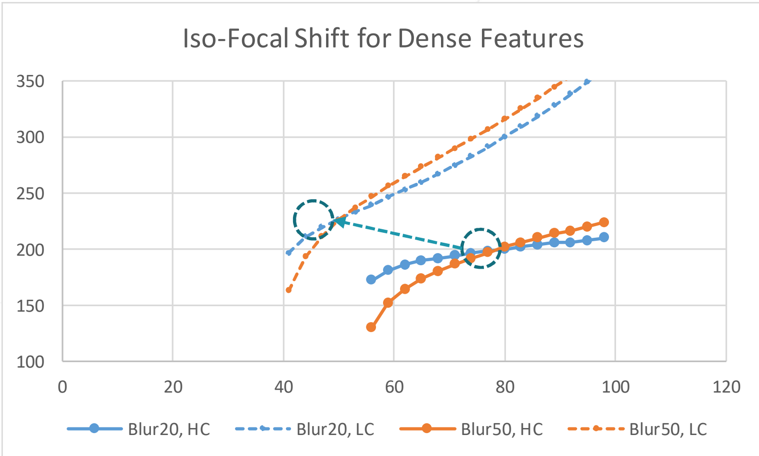
Lateral Development ⇒ Iso-Focal Shift

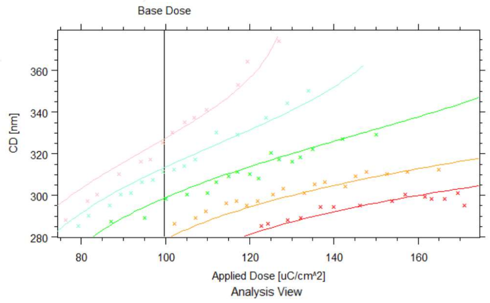
- Low-contrast resists develop also at lower doses
  - Iso: development into the blur (e.g. spot size)
    - Si example: 80µC -> 40µC, 12nm Bias
  - Dense: development into the blur and backscatter
    - Si example: 80µC -> 50µC, 25nm Bias
- Net effect: the process iso-focal shifts to lower doses
  - Stronger with more back-scattering (III-V materials)
  - Stronger with lower contrast resists (e.g. PMMA)
  - Stronger for thicker resist
- Key Learnings
  - For III-V on GaAs, this can shift the iso-focal below D2C
  - Since the amount of shift is density dependent, it will change the required PEC dose range

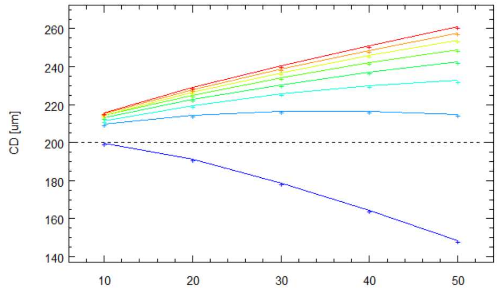


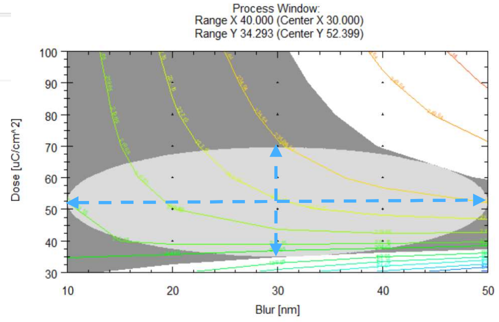


Blur-Dose Matrix

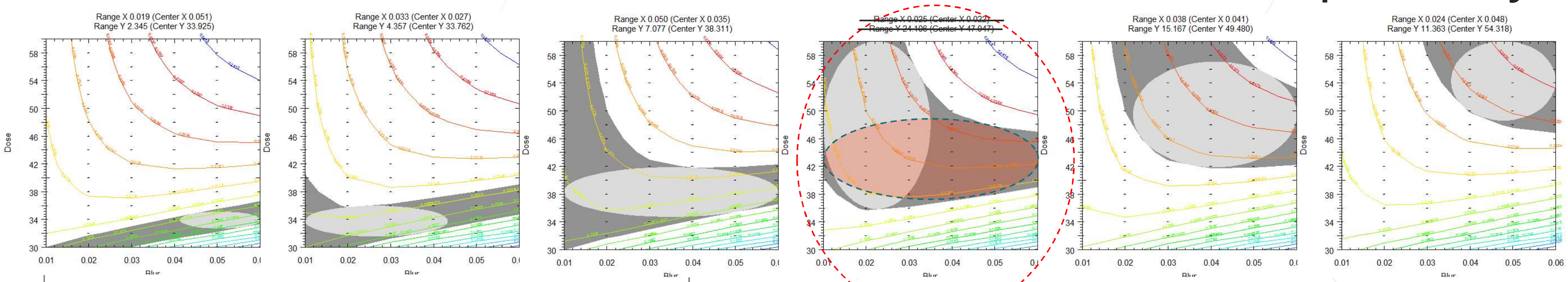
- Different ways to plot CD / Dose / Density / Blur Dependency
  - CD as function of Dose, with Density Iso-Lines
  - CD as function of Blur, with Dose Iso-Lines
    - Individual plots for the different densities
    - Already gives an indication of „iso-focal“ dose (horizontal trend)
  - Dose as a function of Blur, with CD iso-Lines
    - ± 5% CD tolerance from target provides CD limits (gray area)
    - Fit elliptical Process Window into CD limits
    - Horizontal axis is „blur latitude“
    - Vertical axis is „dose latitude“

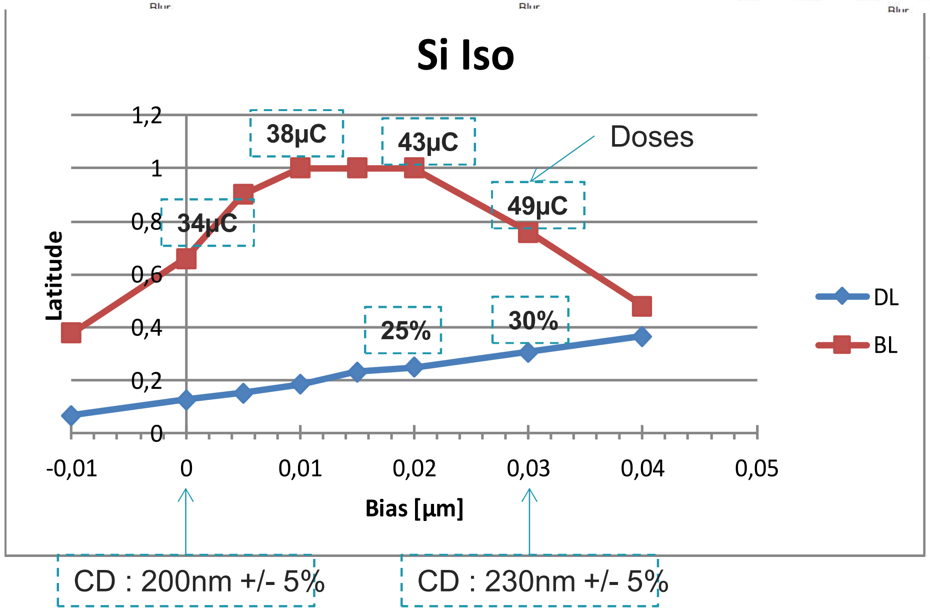






Concept Study

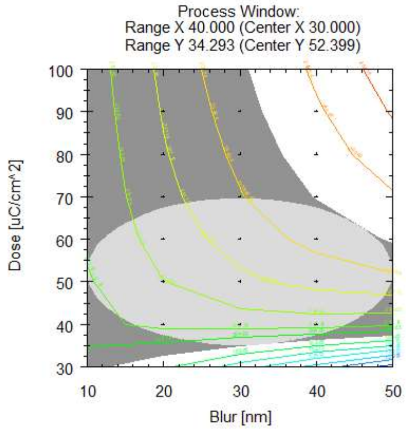


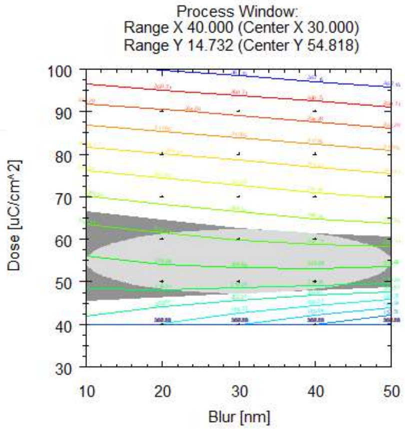


- Iso-Line, Si, Low-contrast Resist
- „Best“ Process Point @ ~20nm Bias
  - „Largest“ Process Window
  - Smallest Bias Value
  - Base Dose = 40µC

Process Iso-Focal

- For each density, search a large enough „blur latitude“
  - This guarantees good CD control also at the corners of the field
    - In the high-contrast case, this is equivalent to the optical iso-focal
  - TRACER searches for a large enough blur latitude (up to 2.5*ProcessBlur)
    - Under constraints (BaseDose * $PEC\_Dose_{100\%}$ > D2C, small Bias values)

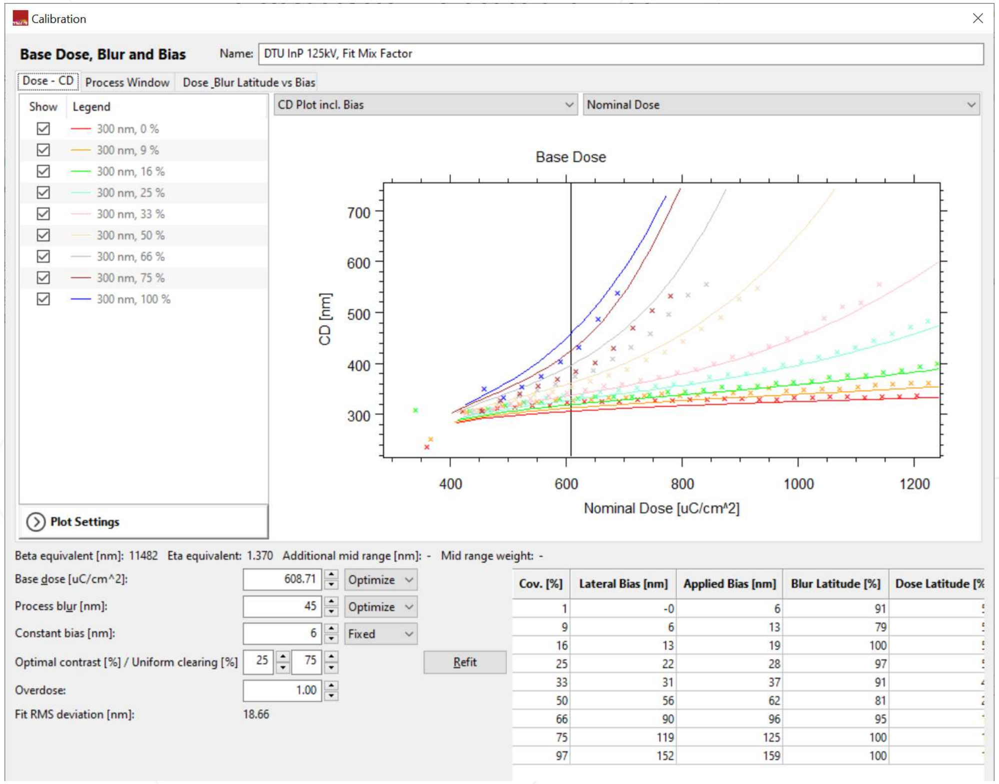


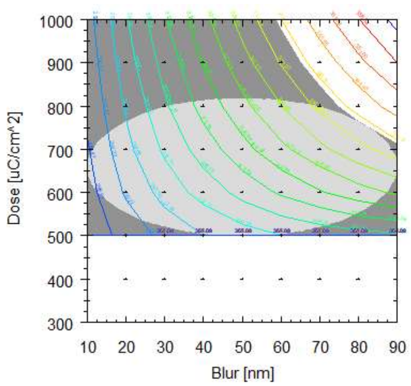


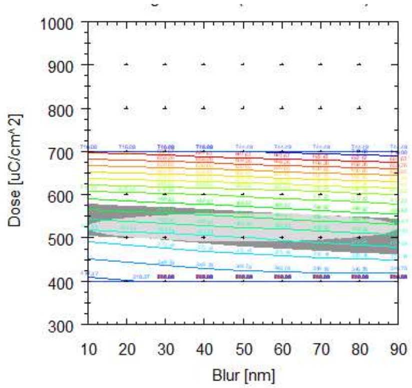
- Please Note: blur cross-over (= iso-focal) and density cross-over are different points
  - Therefore, a density dependent Bias becomes essential

Low Contrast InP Example, Process Iso-Focal

- Customer Case
  - InP, 125kV, PMMA (γ=3)
  - D2C known as 480µC/cm²
- Process Iso-focal at 609µC/cm²
  - Mix-Factor at 25/75
  - Above D2C (609*0.88 = 538µC/cm²)

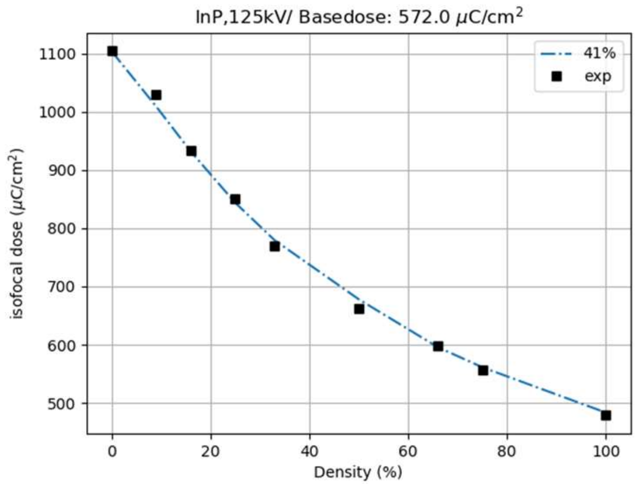






Low Contrast InP Validation

- Customer measured 572µC/cm²
  - Mix-factor of 41/59
- Pretty close to model prediction at 609µC/cm²
  - Mix-Factor of 25/75



- Not bad for just one dataset with one spot-size
  - Measuring process iso-focal requires at least two data sets with different spot sizes
  - TRACER criteria optimizes for „large enough“ blur latitude

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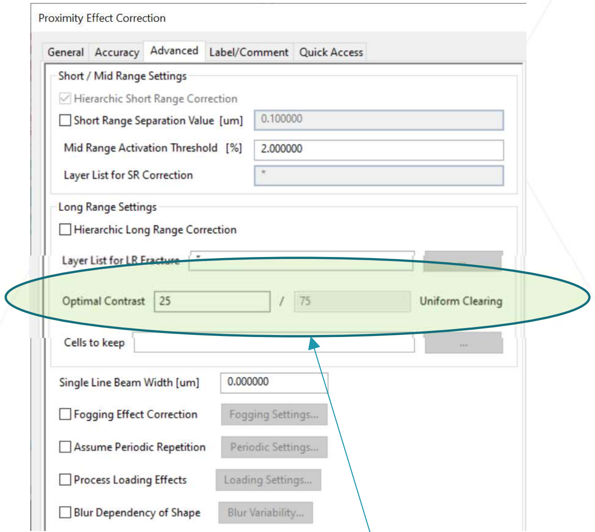
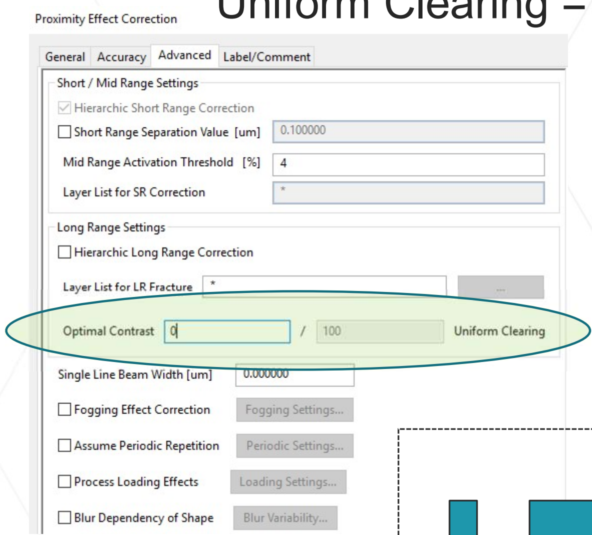
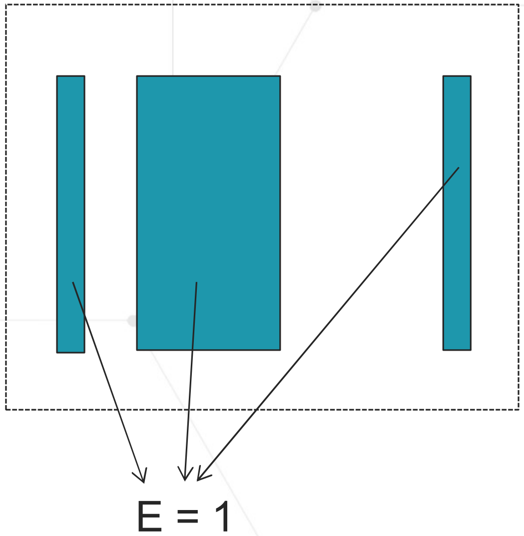
PEC – Mix Factor

Uniform Clearing = Surface Equalization





Automatically transferred via extended PSF



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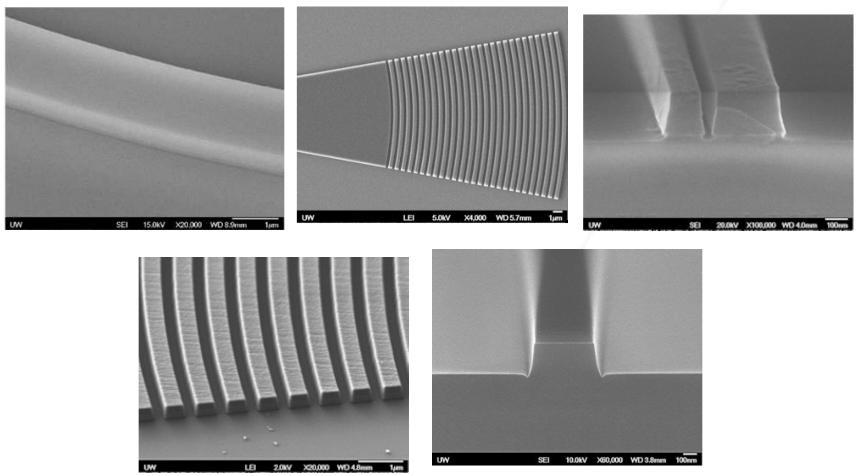
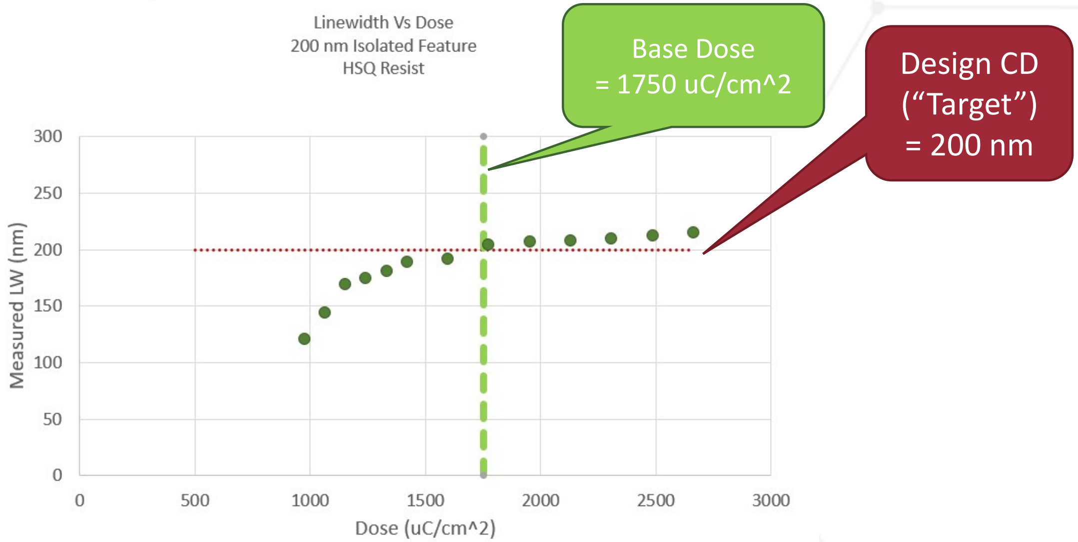
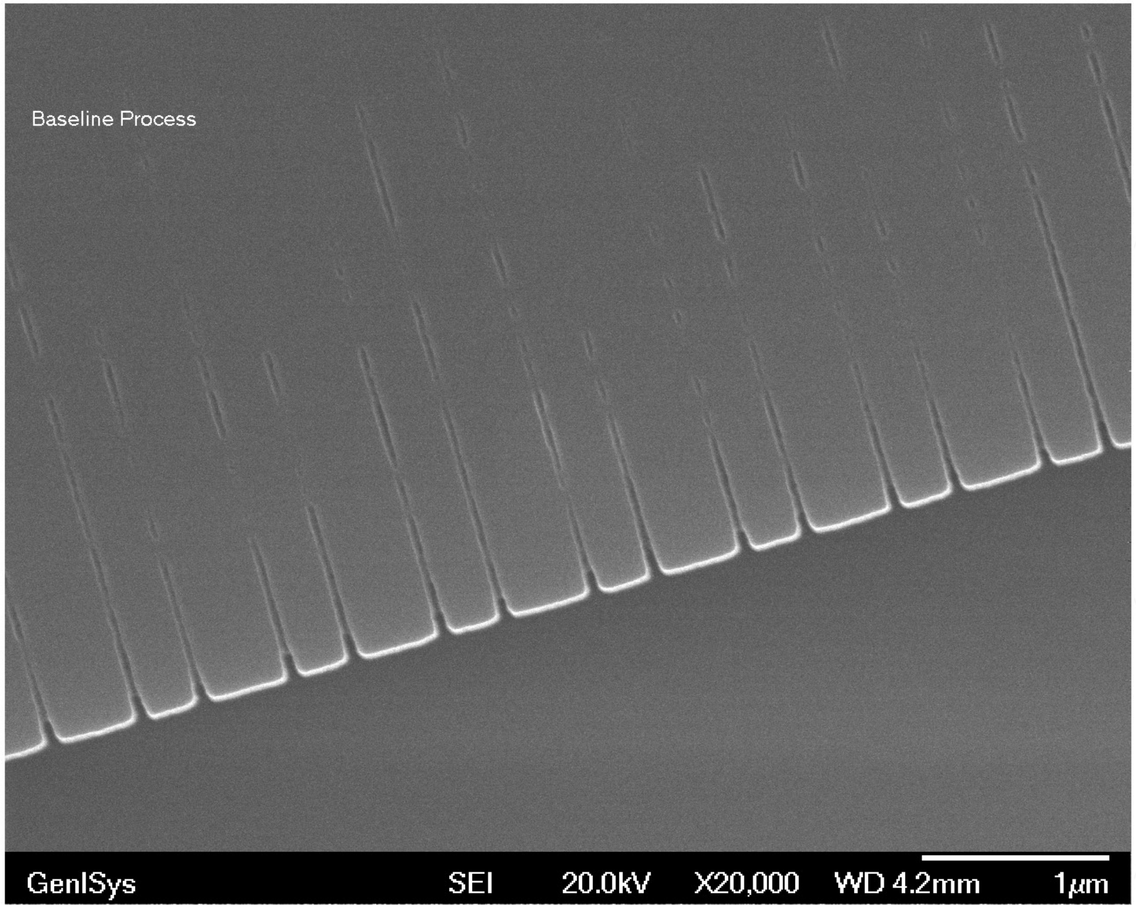
HSQ Silicon Photonics

- An HSQ process for Silicon Photonics has been in use for 9+ years.
- The process point was determined in a "traditional" way.
  - Use a baseline PSF for 100 kV electrons on Si.
  - Expose a dose matrix of the patterns, which were low-density waveguides (0-25%)
  - Choose base dose by observation, what dose gives proper size for a waveguide
- Hundreds of successful wafers have been built with this process.





… until they needed higher-density patterns

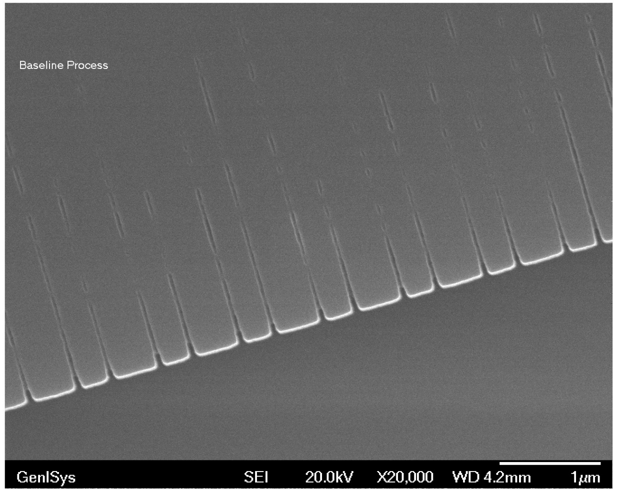


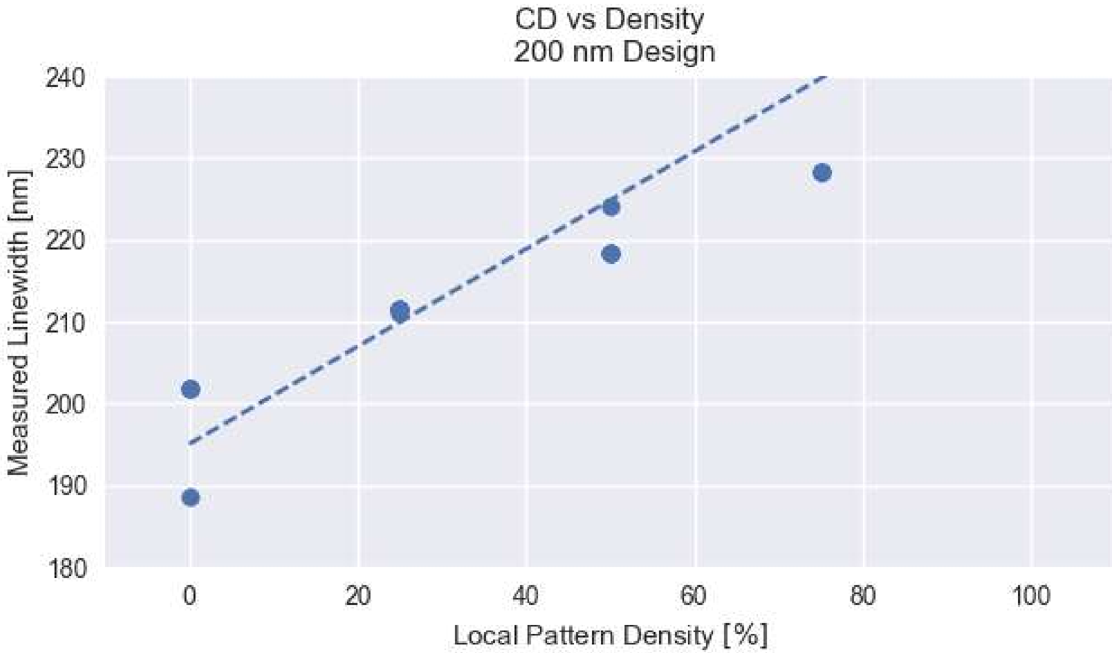
"Giant" subwavelength surface grating coupler.

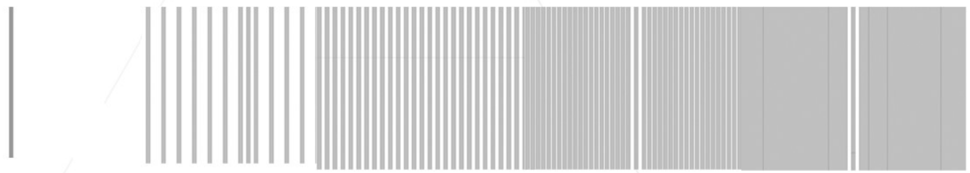
Local density in the middle ~ 82%

CD versus Local Pattern Density

- Strong dependence of linewidth on pattern density, even using baseline proximity effect correction.
- Dense patterns with small spaces are impossible.

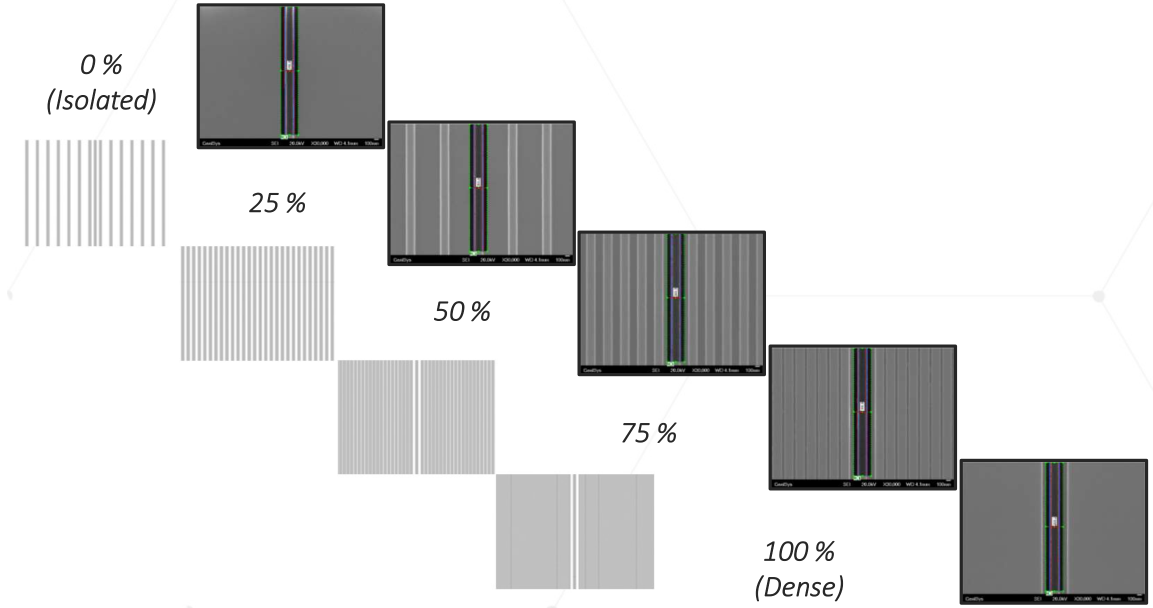


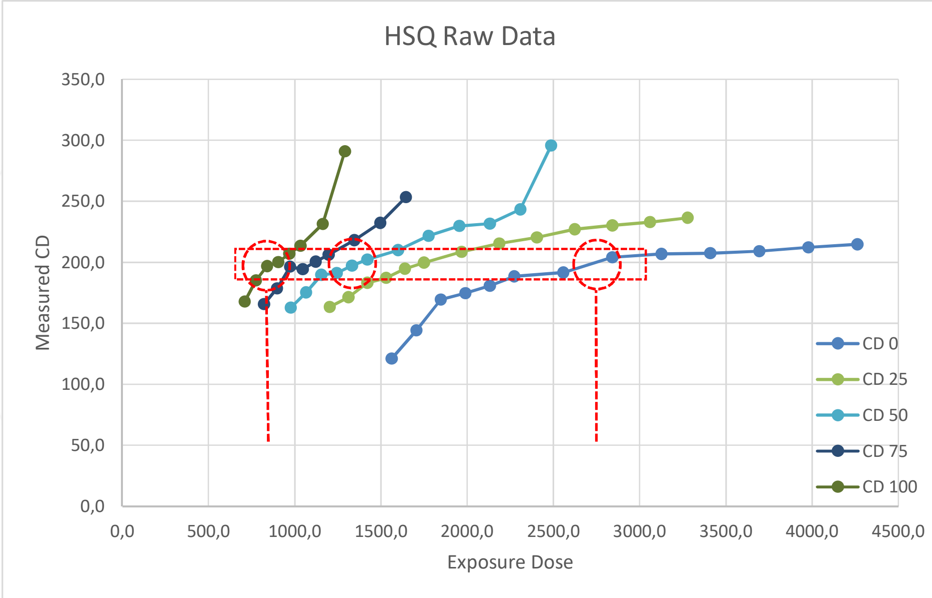




Measuring Effect of Pattern Density

- Expose lines over a range of doses, with local pattern density varying from isolated to fully dense.





Indicator: dose ratio D_{iso} / D_{dense} highly unusual: 2800 / 850 = 3.3 (expected would be 2.2)
→ something in addition to scattering effects

What is 'special' about HSQ?

- Many researchers have reported exposure effects such as neighboring-shape interactions beyond electron scattering, non-reciprocity(writing order) effects, or have observed the utility of adding an additional midrange Gaussian energy term to the dose-based PEC to improve results.
- Examples include: Liddle (2003), Olynick (2006), Brown (2013)
- Olynick 2006 speculates these are due to diffusion of hydrogen released during the exposure, which increases the HSQ sensitivity (lower the dose) of nearby shapes.
- However, no known published description of systematically quantifying and correcting for these effects.

Nanoscale topography control for the fabrication of advanced diffractive optics

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Scanning x-ray microscopy investigations into the electron-beam exposure mechanism of hydrogen silsesquioxane resists

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Pattern exposure order dependence in hydrogen silsesquioxane

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Hydrogen diffusion can be modeled by additional mid-range Gaussian

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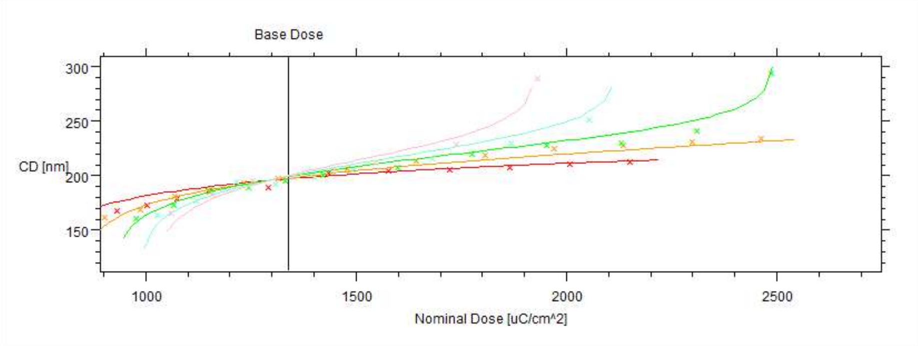
Fit Results

Calibration

Base Dose, Blur and Bias

Overdose: 1.00 | CD Plot incl. Bias | Nominal Dose

Show	Legend
☑	200 nm, 0 %
☑	200 nm, 25 %
☑	200 nm, 50 %
☑	200 nm, 75 %
☑	200 nm, 100 %



Beta Equivalent [nm]: 30000
Additional Mid Range [nm]: 3722
Eta Equivalent: 0.600
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
Refit

	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
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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						

< Back | Finish | Cancel

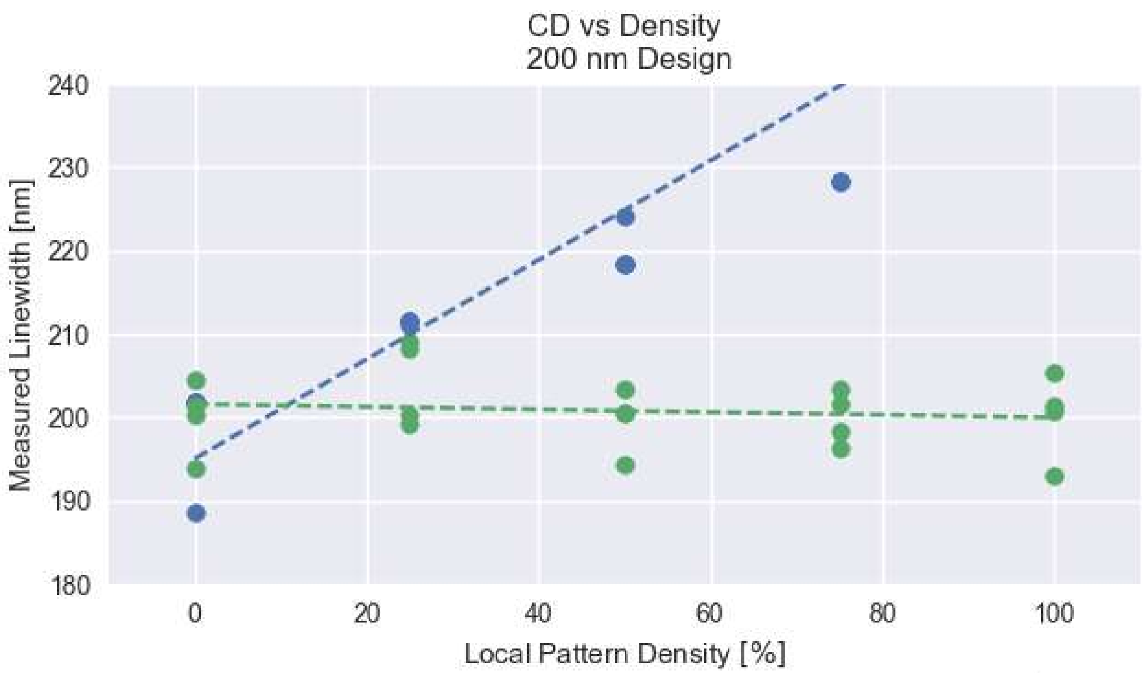
- The fitting procedure results in an "Extended Point Spread Function", adding terms to the scattering PSF
  - Additional Midrange Gaussian term to compensate for hydrogen diffusion effects
  - Overall Process Bias
  - Density-dependent Bias terms to compensate for lateral development
  - Optimal Base Exposure Dose
  - Process Blur term

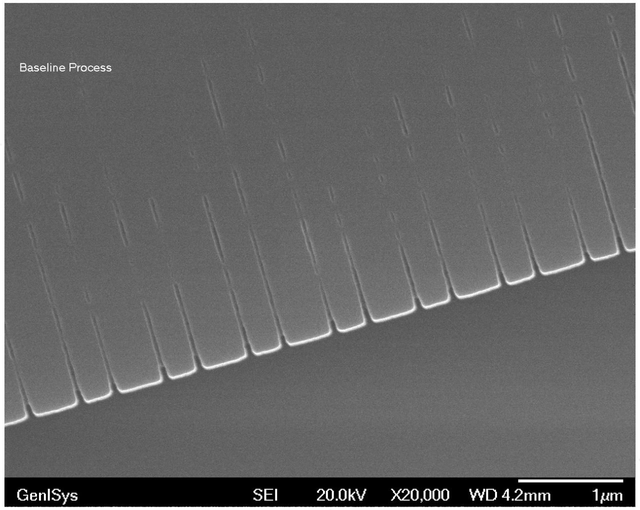
Extended PSF Calibration

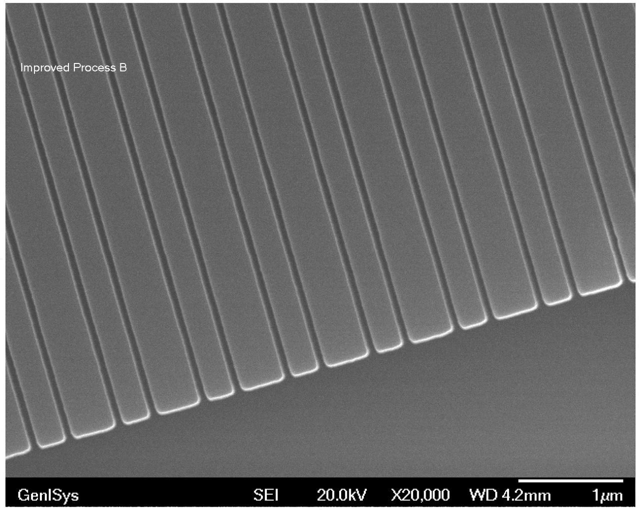
	Before Calibration Chosen by 'Traditional Method'	Calibration Parameters Determined by TRACER fit to Measured CD Data
Base Dose	1750 $\mu C/cm^2$	1340 $\mu C/cm^2$
Process Blur	50 nm	36 nm
Process Bias	None	-3 nm
Density-dependent Bias	None	0% = 0 nm, 25% = 1 nm, 50% = 2 nm, 75% = 2 nm, 100% = 3 nm
PEC Parameters	Standard Si PSF	Additional Mid-range Gaussian γ= 3722* nm, ν=0.38*

Success

- With the enhanced correction:
  - Features are nominally the design size through the full range of density
  - Devices not previously successful with standard PEC correction are now fabricated successfully







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HSQ Summary

- HSQ exposures show (among other challenges):
  - Significant additional proximity effect, where exposed shapes can be affected by prior exposure of nearby shapes, above what is explainable by electron scattering
  - The effective dose for exposure is lowered when nearby shapes have been exposed
  - This effect can be measured and compensated for using dose proximity-effect correction, by treating the neighborhood exposures as an additional mid-range proximity effect term

- Not discussed here, but still true:
  - This also causes a significant “write-order” effect, so the sequence in which nearby shapes are written affects the resulting dimension
  - This write-order effect can be mostly mitigated by using multi-pass writing strategy

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Summary

- “Real” processes have many effects beyond electron scattering
  - Process / metrology bias
  - Lateral development from finite resist contrast (density dependent)
  - Additional midrange process effects

- PEC Dose Range 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, one PMMA required D_{iso}/D_{dense} = 1 + 1.2*BS/FS
  - Additional terms such as resist sensitivity changes (e.g. coming from catalytic reactions)

- TRACER can plot and fit the experimental data, providing the necessary process correction parameters
  - Maximizing the blur latitude to minimize process variation, e.g. across field
  - May include mix factor strategies, between Optimum Contrast and Uniform Clearing
    - Substrate and contrast dependent
  - Ability to adjust with parameters & see effects on process window, e.g. Undersize/Overdose

- BEAMER can be used to correct for not only the “Proximity Effect” but also these additional process effects

TRACER Model

- Considers contrast curve
- Supports OC / UC
- Fit Additional mid-range term
- Fit „mix factor“