GenISys
Advancing the Standard

Doc Daugherty, Thomas Michels
Oct 21st, 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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Proximity Effect in E-Beam Lithography

Part 3: Optimization of Dose PEC Parameter

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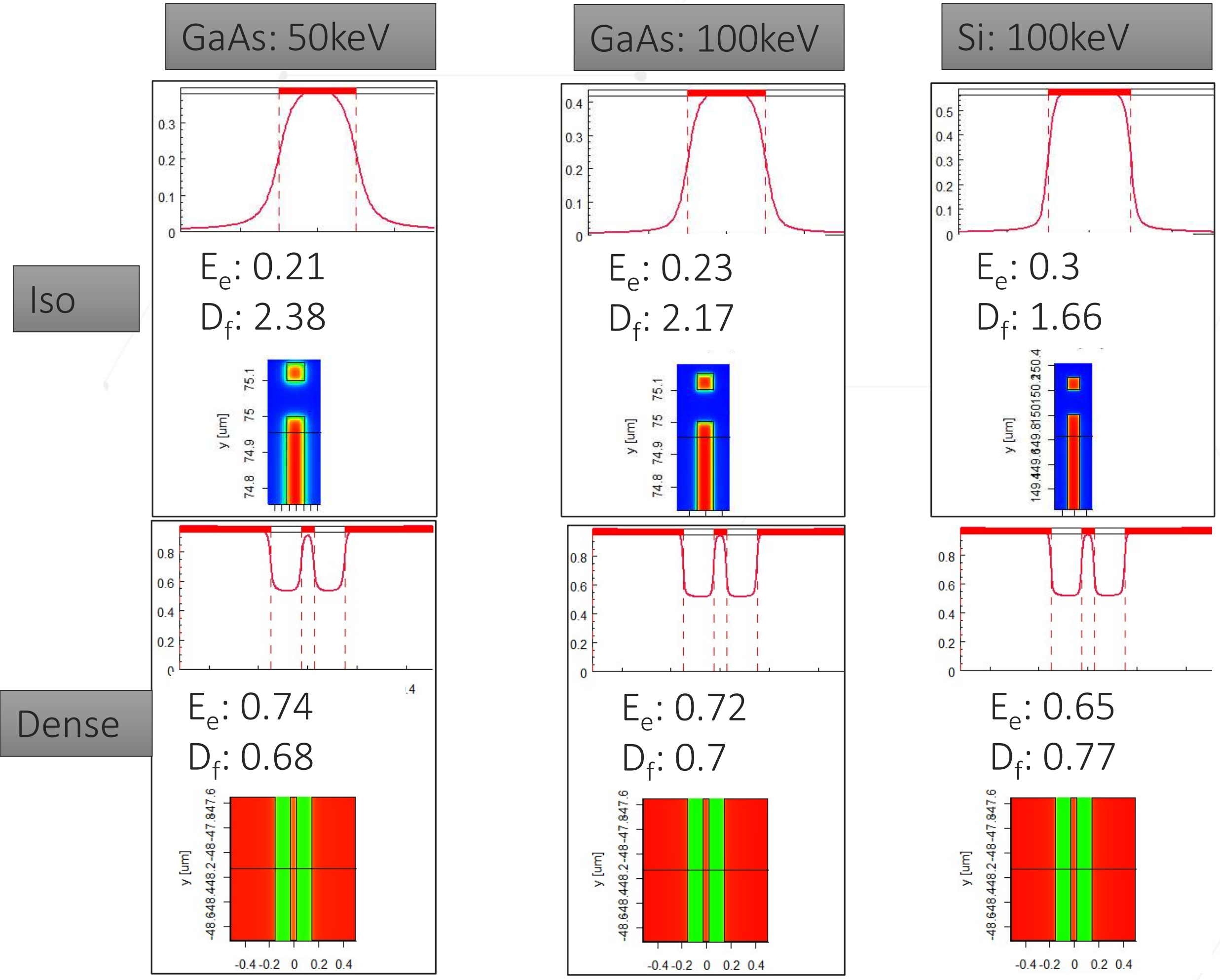
Outline

- Part 2 Summary: PEC Principle & Algorithm
- General Dose PEC Parameter
- Accuracy Control Parameter
- Advanced Model Parameter
- Summary
- Q&A

Proximity Effect - Summary

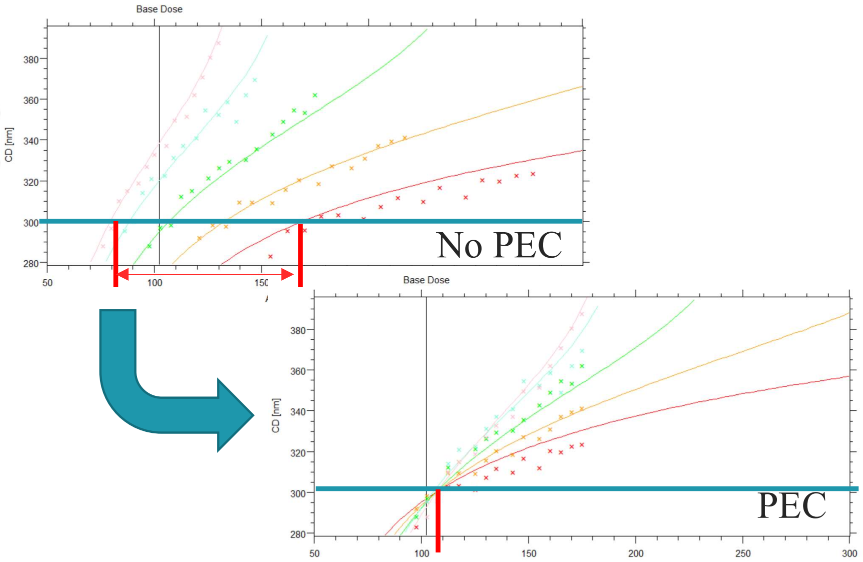
- Electrons always scatter and spread energy over long distances

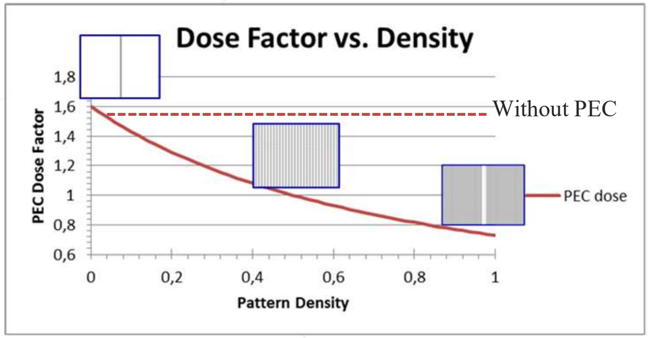


- **Absorbed energy** is varying depending on **layout density** (iso and dense), leading to CD variation
- Layout density dependent **dose factor** is needed to adjust all feature to the same absorbed energy (dose to clear)
- The dose factors depend on **acceleration voltage** and **stack** (mainly substrate material density)

Always Use PEC

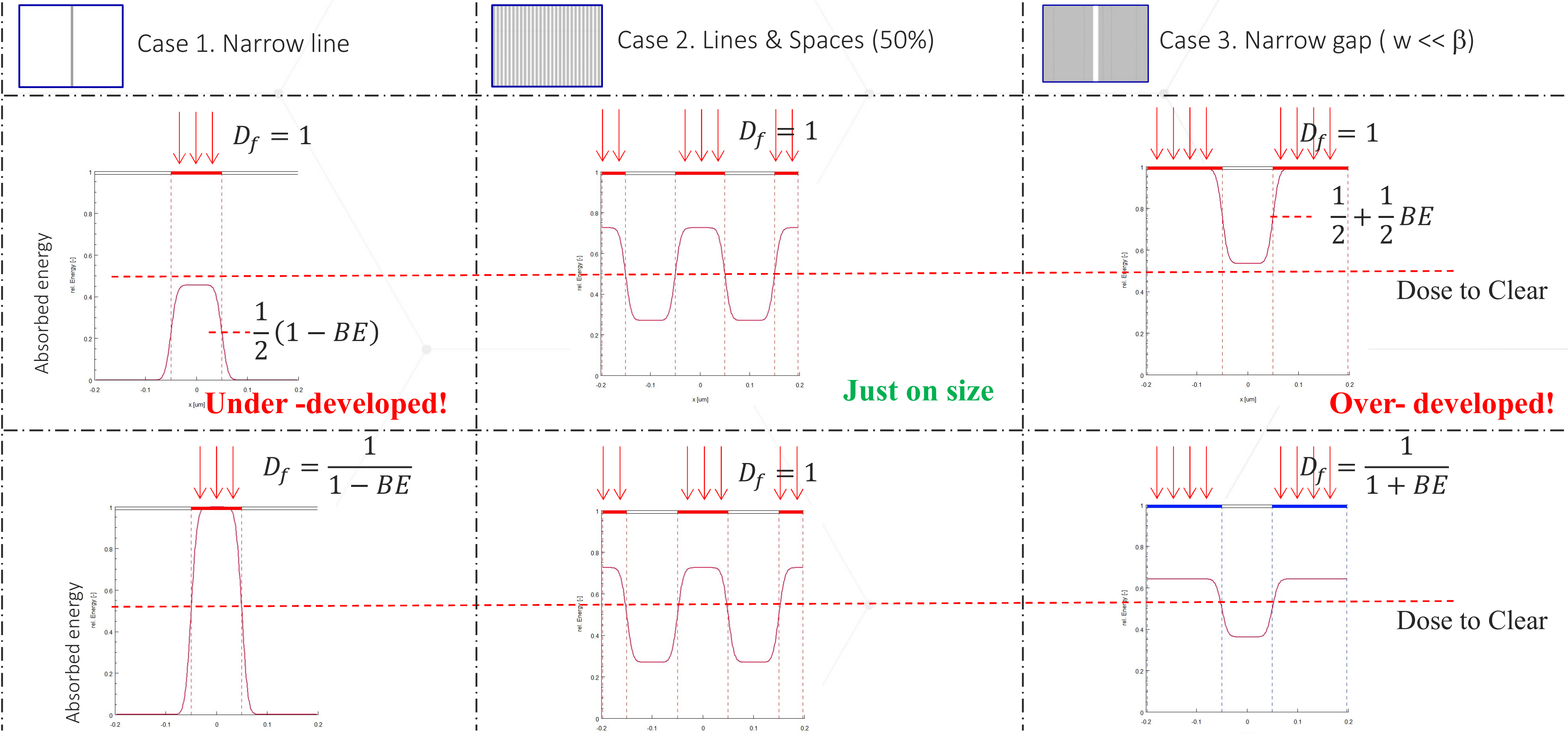
- Avoids Dose Matrices
  - Takes out pattern dependence
  - Easily transferable to other stacks / voltages
- Improves Litho Quality
  - CD linearity (also density dependent)
  - Opens / enlarges process window
  - Dose Latitude (Contrast) enhancement for sparse features
- Minimizes Beam-On Time





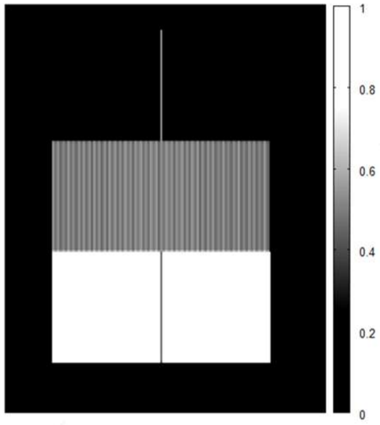
Edge Equalization

PMMA on GaAs at 100keV

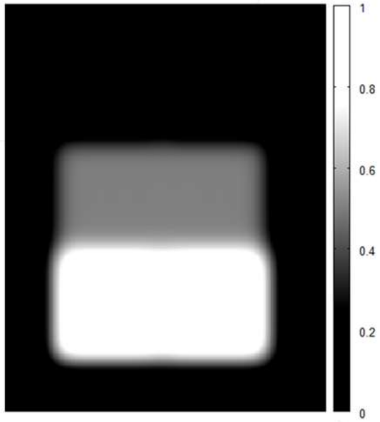


Iso-focal (blur independent) → Best CD control across Field → Stable and Robust

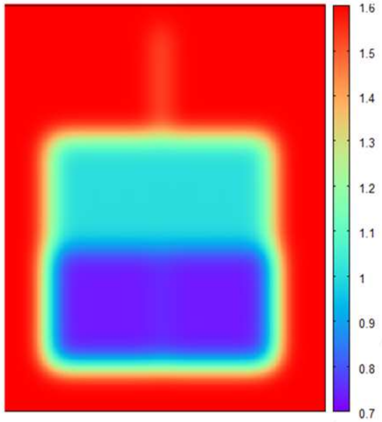
Influence Range ⇔ Algorithm Choice



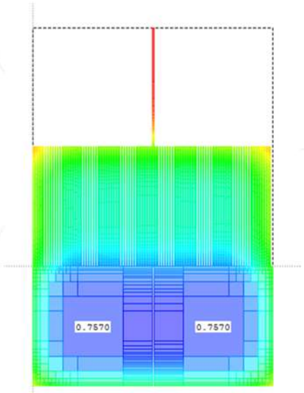
A. Original Layout as bitmap



B. Convolved pattern density



C. Correction dose map

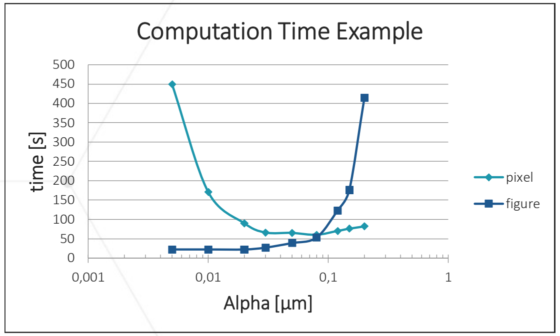


C. Dose transfer to polygonal data including physical fracturing

- Fast and robust back-scatter PEC through pixel based convolution algorithm
  - Also enables Physical Fracturing

- For short-range PEC, shape-based convolution is a better choice
  - Coupled with DRC (find SR PEC relevant areas) to boost performance

- Mid-range effects are include either in SR or LR
  - For large mid-range energies, this needs to be separated out as its own correction using a finer grid -> performance hit



Main PEC Parameters

- PSF
  - Use Monte Carlo PSF’s
- Effective Blur
  - Including: forward scattering (α), beam blur and resist effects.
  - 1st order estimate:
    - FWHM = 0.76 * ΔCD / Δ%dose
- Base Dose
  - ~ 2 x Dose to Clear
  - Simple way: Dose Matrix on one PEC’d pattern
- Dose Classes / Fracturing
  - Recommended Dose Accuracy: 3%
  - Min. Fracturing Size

Main Parameters can be obtained pretty simple

Mix Factor

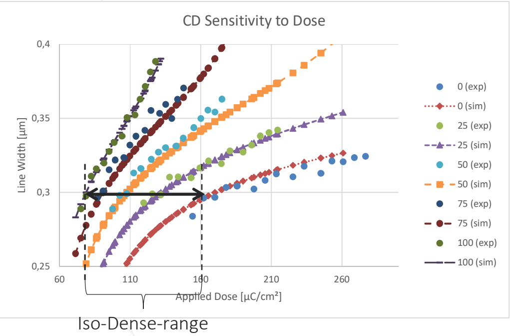
- Edge equalization (iso-focal) works well for high-contrast resists

- Low contrast resists (γ ≤ 3) add additional effects specifically with high density material
  - E.g., lateral development changes CD
  - Effects get stronger with high-backscatter materials (e.g. III-V)

- PEC can take into account lateral Biases

- Alternatively, adopt dose range towards uniform clearing

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



Courtesy of Pennstate Univ.

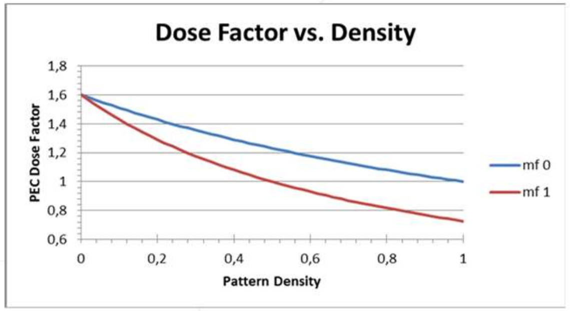


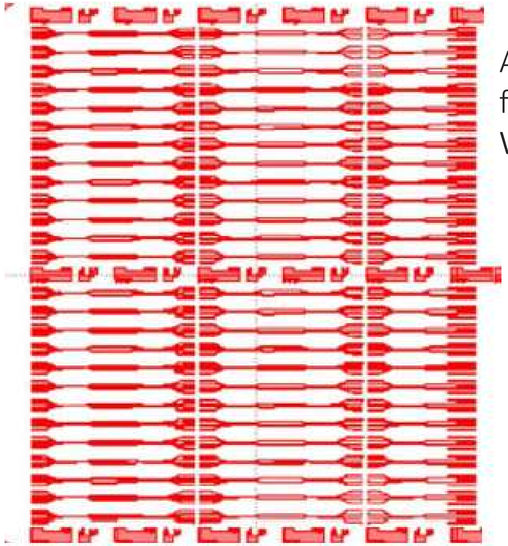
Fig. Dose factor vs. density for the limiting mix factors. (BE = 0.375)

Outline

- Part 2 Summary: PEC Principle & Algorithm
- General Dose PEC Parameter
    - Layout
    - Point Spread Function (PSF)
- Accuracy Control Parameter
- Advanced Model Parameter
- Summary
- Q&A

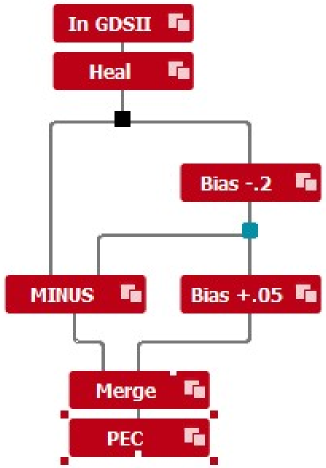
Which part of the layout?

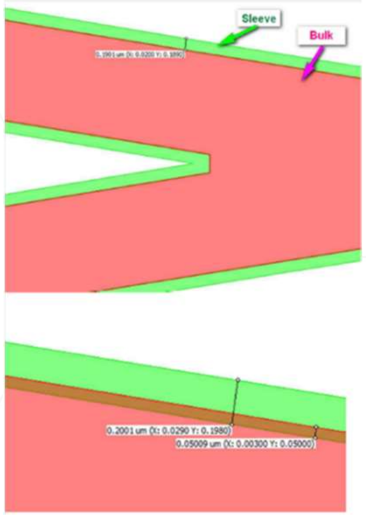
- All (and only) pattern being exposed into the resist before development
  - May use different layer for writing order control, or exposure with different currents
  - Application example for multi-layer: Bulk / Sleeve
    - Exposure of large waveguide pattern needs small beam and BSS for high quality (low loss)
    - Exposing all pattern at 1nA takes 6 days
    - Exposing only the edge with 1nA (fine beam) and bulk with 50nA (large beam) takes only 4 hours
    - Split of layout to bulk-sleeve in different layer, PEC maintaining both layer
    - Generate separate exposure file of both layer including proper dose factors



Area: ~ 2.5 cm²
for I = 1 nA, D = 200 µC/cm²
Write Time: ~ 6 days

Source:
HHI - Berlin

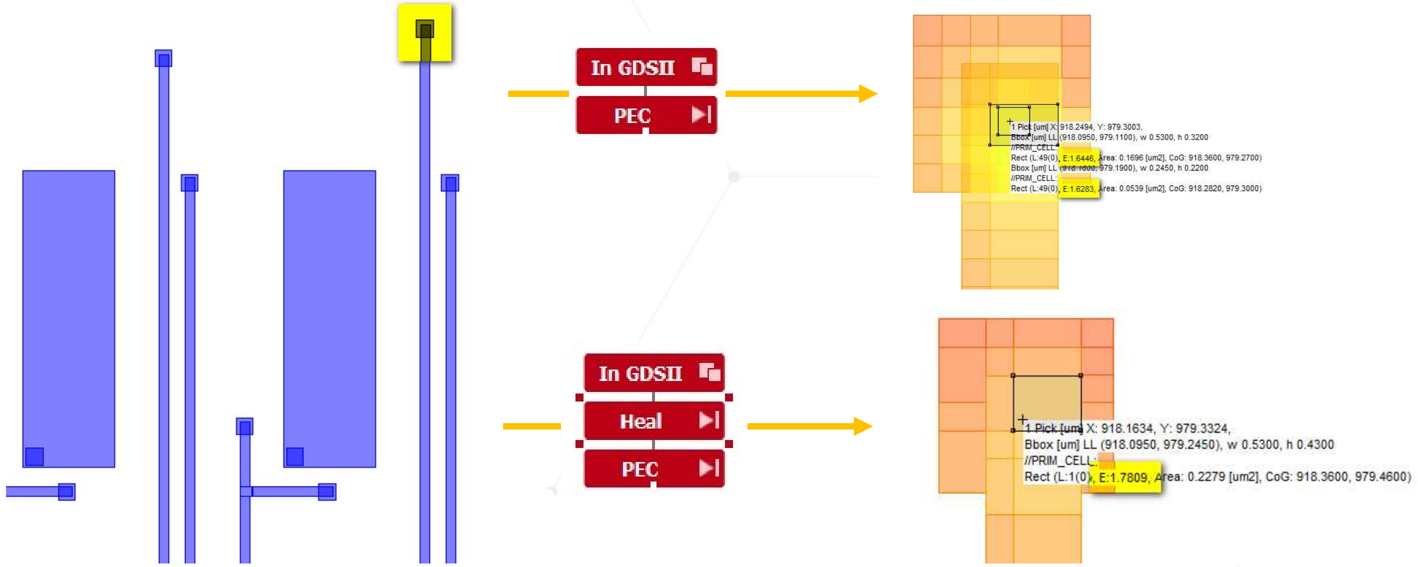




Bulk Write Time: ~ 3 hours
for I = 50 nA, D = 200 µC/cm²
Bulk Write Time: ~ 3 hours
Sleeve Area: ~ 0.01 cm²
Sleeve Write Time: ~ 0.5 hours
for I = 1 nA, D = 200 µC/cm²
Total write time: ~ 4 hours (35x faster)

Which part of the layout?

- Remove overlaps
  - The energy of the energy will be considered in the background energy, but the local double exposure is not removed

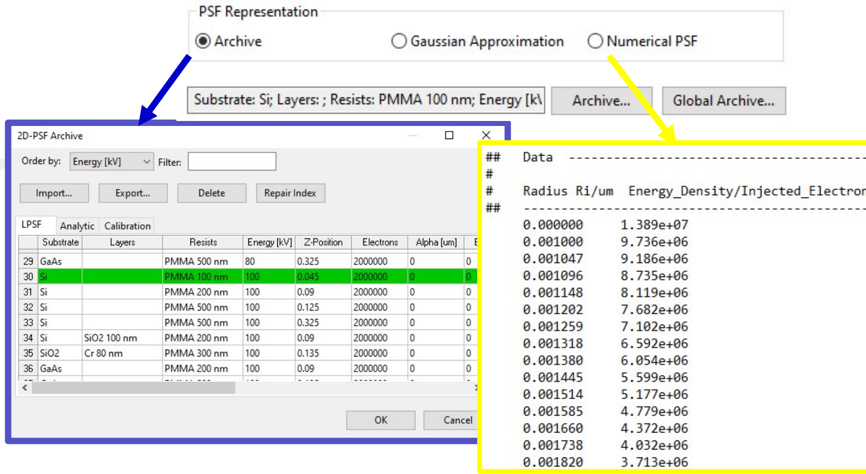


```
1 Pick [um] X: 918.2494, Y: 979.3003,
Bbox [um] LL (918.0950, 979.1100), w 0.5300, h 0.3200
//PRIM_CELL:
Rect (L:49(0), E:1.6446, Area: 0.1696 [um2], CoG: 918.3600, 979.2700)
Bbox [um] LL (918.1600, 979.1900), w 0.2450, h 0.2200
//PRIM_CELL:
Rect (L:49(0), E:1.6283, Area: 0.0539 [um2], CoG: 918.2820, 979.3000)
```

```
1 Pick [um] X: 918.1634, Y: 979.3324,
Bbox [um] LL (918.0950, 979.2450), w 0.5300, h 0.4300
//PRIM_CELL:
Rect (L:1(0), E:1.7809, Area: 0.2279 [um2], CoG: 918.3600, 979.4600)
```

PSF Definition

- From Monte Carlo Simulation
  - BEAMER Archive comes with PSF for major stack and acceleration voltage
  - TRACER for additional PSF
  - Numerical PSF from other MC simulator or experimental in txt format
- PEC algorithm is using table defined PSF
  - Not converted to Gaussians
  - PSF is split to Short- and Long-Range to be used in correction algorithm



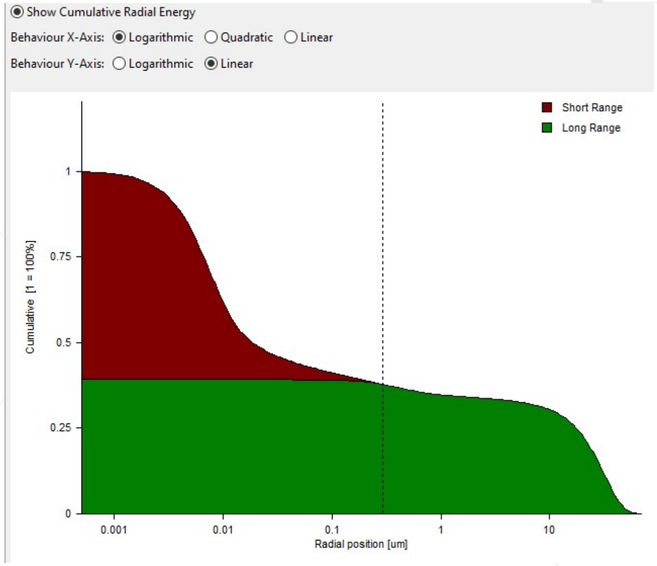
PSF Representation

● Archive ○ Gaussian Approximation ○ Numerical PSF

Substrate: Si; Layers: ; Resists: PMMA 100 nm; Energy [k\

	Substrate	Layers	Resists	Energy [kV]	Z-Position	Electrons	Alpha [um]	E
29	GaAs		PMMA 500 nm	80	0.325	2000000	0	0
30	Si		PMMA 100 nm	100	0.045	2000000	0	0
31	Si		PMMA 200 nm	100	0.09	2000000	0	0
32	Si		PMMA 500 nm	100	0.125	2000000	0	0
33	Si		PMMA 500 nm	100	0.325	2000000	0	0
34	Si	SiO2 100 nm	PMMA 200 nm	100	0.09	2000000	0	0
35	SiO2	Cr 80 nm	PMMA 300 nm	100	0.135	2000000	0	0
36	GaAs		PMMA 200 nm	100	0.09	2000000	0	0

```
##   Data  -----------------------------------
#
#    Radius Ri/um  Energy_Density/Injected_Electron
##   --------------------------------------------
     0.000000     1.389e+07
     0.001000     9.736e+06
     0.001047     9.186e+06
     0.001096     8.735e+06
     0.001148     8.119e+06
     0.001202     7.682e+06
     0.001259     7.102e+06
     0.001318     6.592e+06
     0.001380     6.054e+06
     0.001445     5.599e+06
     0.001514     5.177e+06
     0.001585     4.779e+06
     0.001660     4.372e+06
     0.001738     4.032e+06
     0.001820     3.713e+06
```



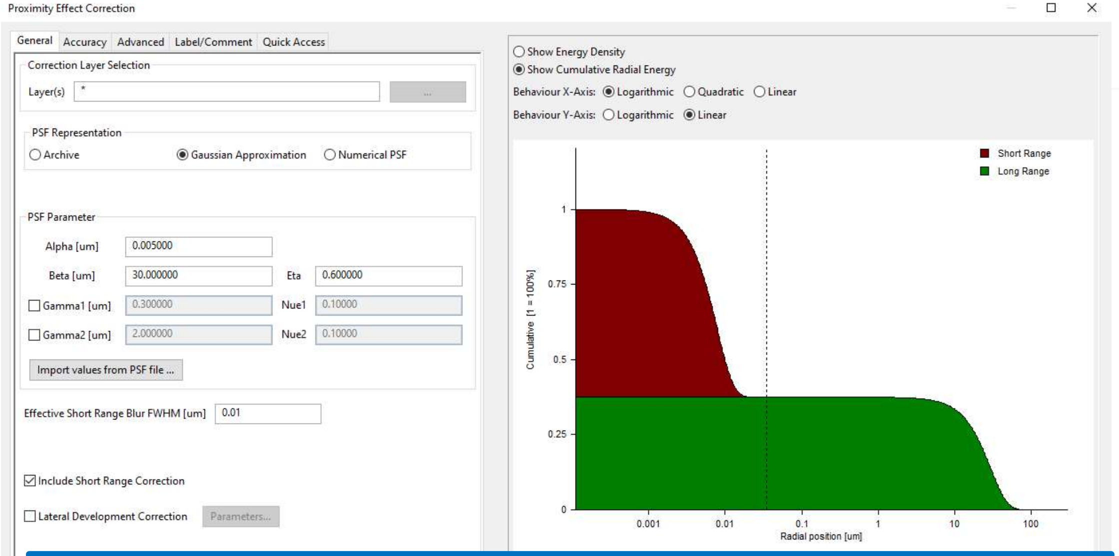
● Show Cumulative Radial Energy

Behaviour X-Axis: ● Logarithmic ○ Quadratic ○ Linear

Behaviour Y-Axis: ○ Logarithmic ● Linear

PSF With Gaussian

- “Traditional” Gaussian Definition
  - Allows using literature data
  - Easier “fit” PSF to experiments with only few parameter
  - No advantage with regards to PEC time
  - TRACER can fit MC simulated PSF to (multi) Gaussian



Proximity Effect Correction

General | Accuracy | Advanced | Label/Comment | Quick Access

Correction Layer Selection
Layer(s): *

PSF Representation
○ Archive ● Gaussian Approximation ○ Numerical PSF

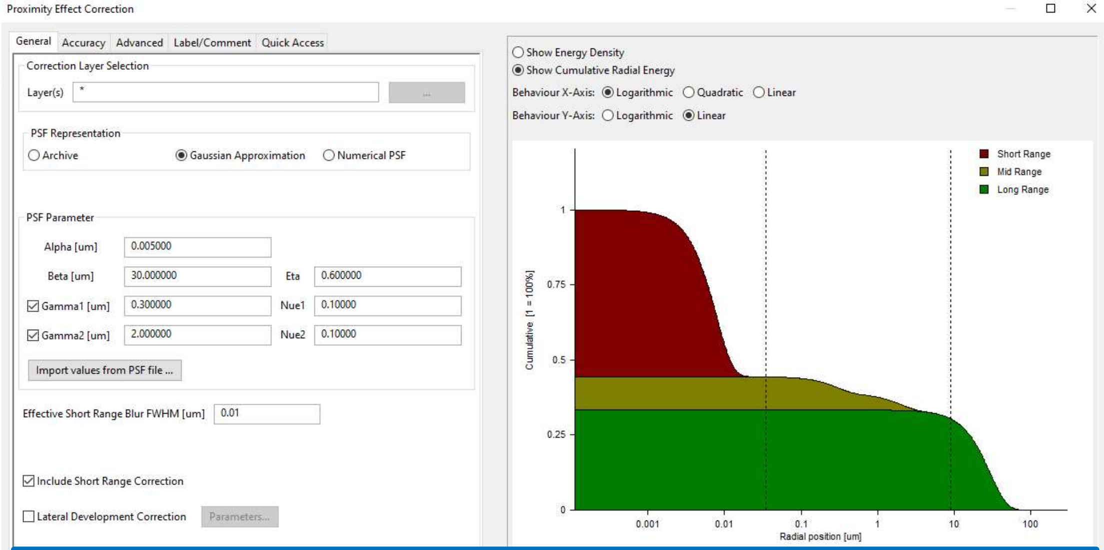
PSF Parameter
Alpha [um]: 0.005000
Beta [um]: 30.000000 Eta: 0.600000
☐ Gamma1 [um]: 0.300000 Nue1: 0.10000
☐ Gamma2 [um]: 2.000000 Nue2: 0.10000

Effective Short Range Blur FWHM [um]: 0.01

☑ Include Short Range Correction
☐ Lateral Development Correction

○ Show Energy Density
● Show Cumulative Radial Energy
Behaviour X-Axis: ● Logarithmic ○ Quadratic ○ Linear
Behaviour Y-Axis: ○ Logarithmic ● Linear

Double Gaussian



Proximity Effect Correction

General | Accuracy | Advanced | Label/Comment | Quick Access

Correction Layer Selection
Layer(s): *

PSF Representation
○ Archive ● Gaussian Approximation ○ Numerical PSF

PSF Parameter
Alpha [um]: 0.005000
Beta [um]: 30.000000 Eta: 0.600000
☑ Gamma1 [um]: 0.300000 Nue1: 0.10000
☑ Gamma2 [um]: 2.000000 Nue2: 0.10000

Effective Short Range Blur FWHM [um]: 0.01

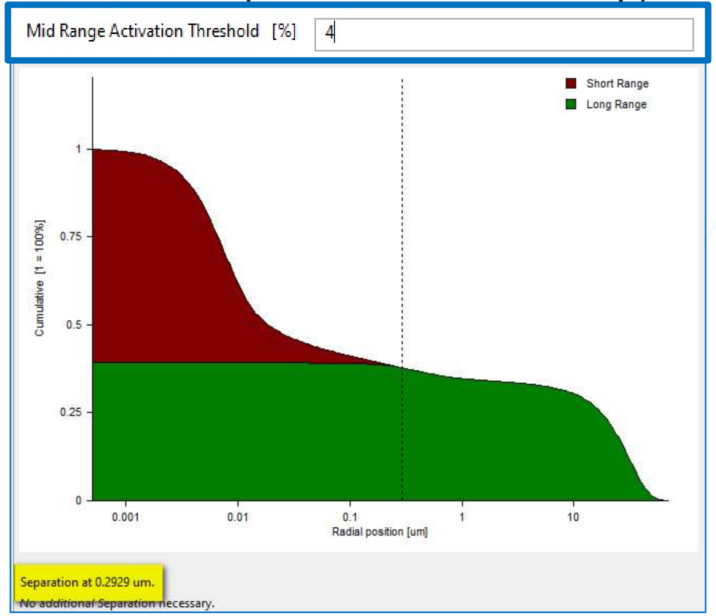
☑ Include Short Range Correction
☐ Lateral Development Correction

○ Show Energy Density
● Show Cumulative Radial Energy
Behaviour X-Axis: ● Logarithmic ○ Quadratic ○ Linear
Behaviour Y-Axis: ○ Logarithmic ● Linear

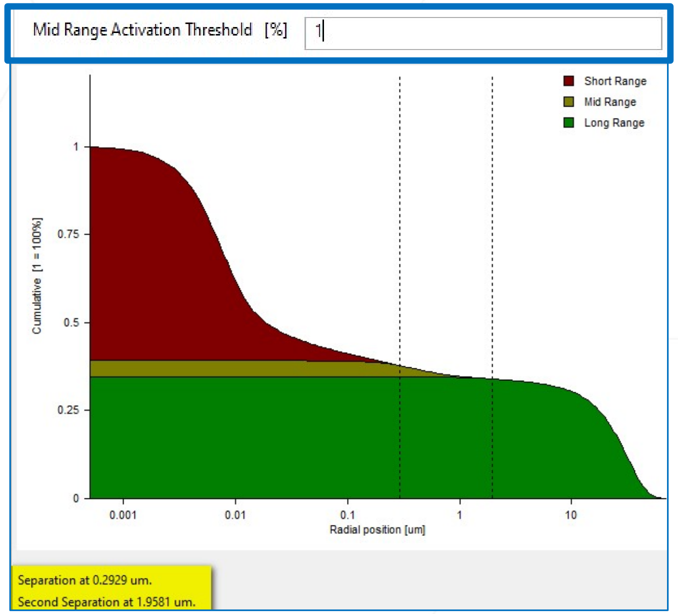
Four Gaussian

Short- & Mid-Range

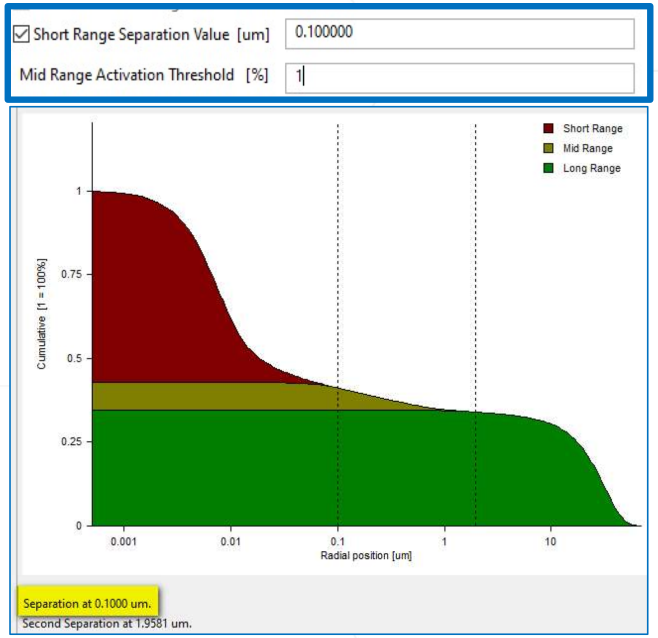
- Control of Mid-Range Energy
  - Triggered by % energy in mid-range relative to LR (Advanced tab)
  - For efficiency, include in LR correction (recommended 4-5% midrange energy)
- Short Range Separation point
  - Controls the amount of energy in short range (automatic as default compromising speed & accuracy)


Mid Range Activation Threshold [%] 4

Separation at 0.2929 um.
No additional Separation necessary.


Mid Range Activation Threshold [%] 1

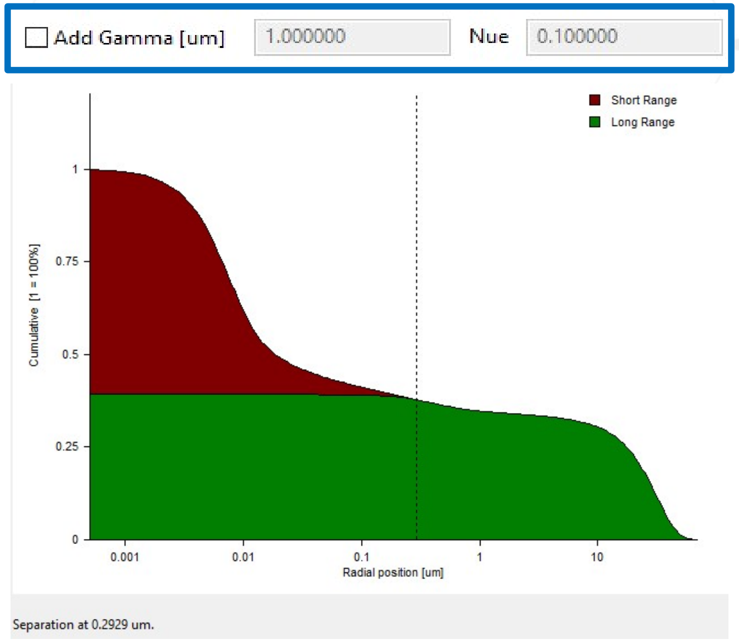
Separation at 0.2929 um.
Second Separation at 1.9581 um.


☑ Short Range Separation Value [um] 0.100000
Mid Range Activation Threshold [%] 1

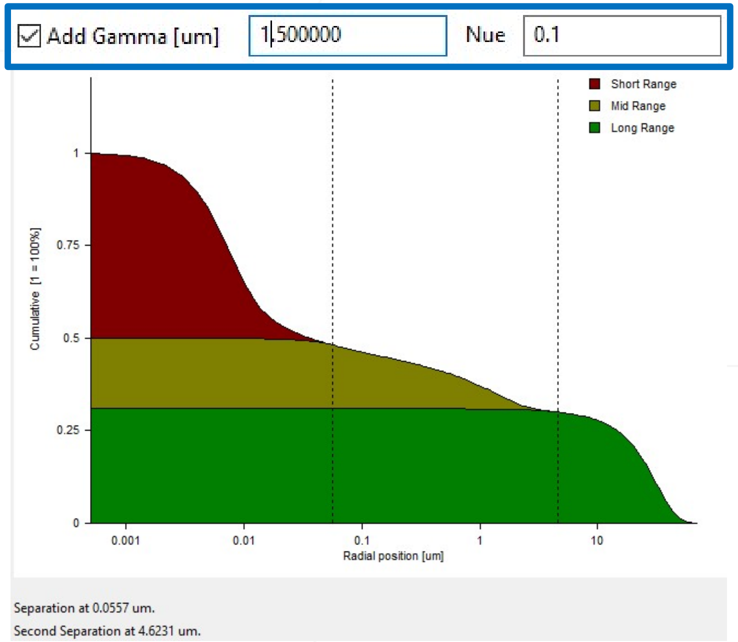
Separation at 0.1000 um.
Second Separation at 1.9581 um.

Additional „Gamma“ Term

- Some processes contribute an additional strong mid-range effect
  - Effects in addition to electron scattering modelled in MC
  - Resist and etching processes have additional “diffusion” type effects
  - HSQ is a popular candidate for mid-range effect
  - TRACER process calibration is considering that effect


☐ Add Gamma [um] 1.000000 Nue 0.100000

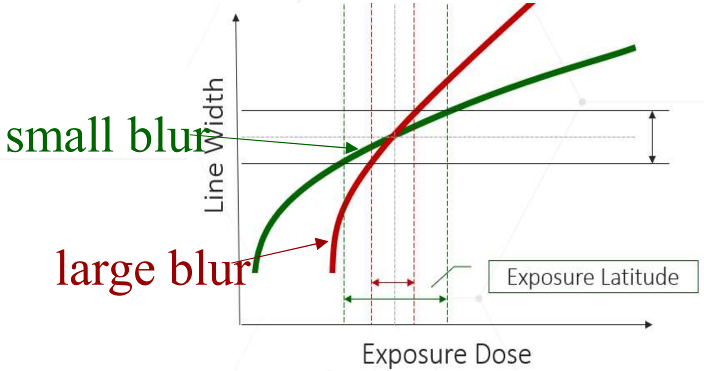
Separation at 0.2929 um.


☑ Add Gamma [um] 1.500000 Nue 0.1

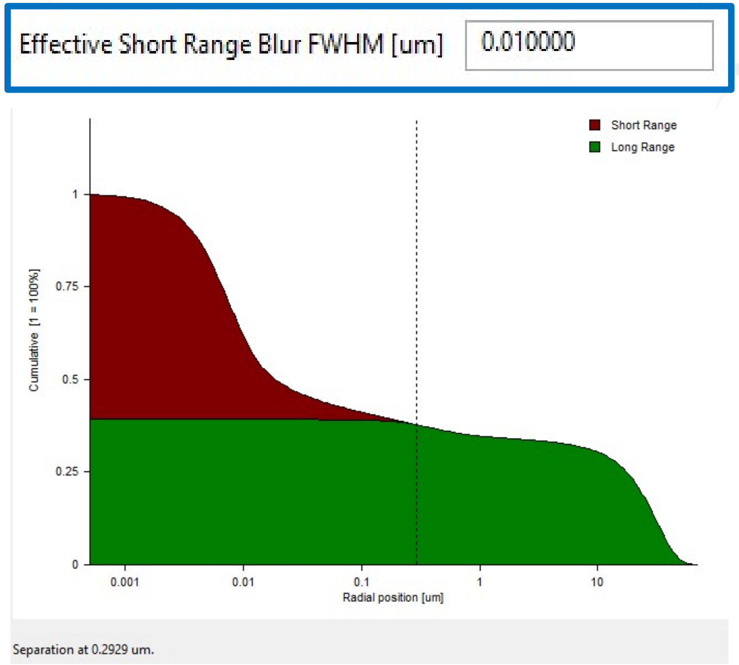
Separation at 0.0557 um.
Second Separation at 4.6231 um.

Effective Short Range Blur

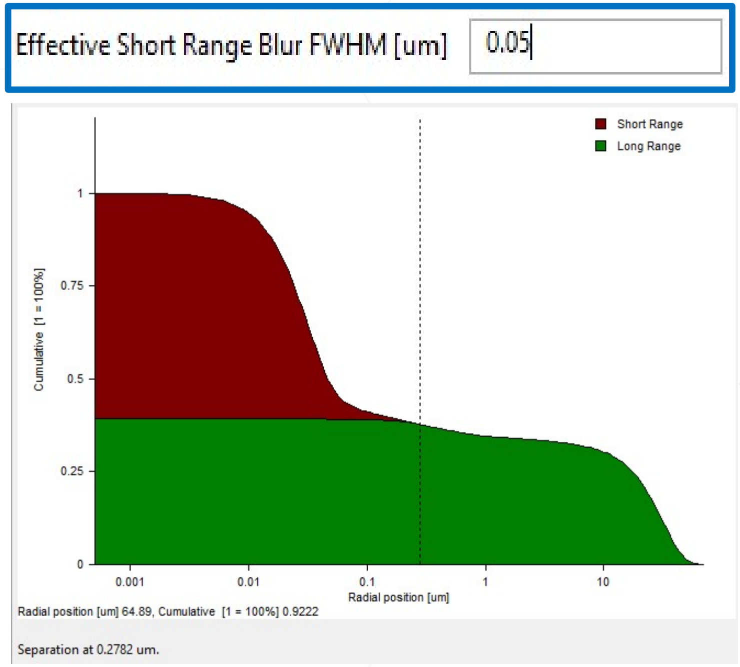
- Effective Short Range Blur combines
  - Beam blur (before entering resist)
  - Forward scattering within the resist
  - Resist development & etching process blur
  - Calibrated by TRACER or estimation from dose test



1st order estimate:
$FWHM = 0.76 * \Delta CD / \Delta\%dose$ 1)


Effective Short Range Blur FWHM [um] 0.010000

Separation at 0.2929 um.


Effective Short Range Blur FWHM [um] 0.05

Radial position [um] 64.89, Cumulative [1 = 100%] 0.9222

Separation at 0.2782 um.

Typical values:
100keV, low current (~ 1nA), high contrast thin (100nm) PMMA: ~ 15nm

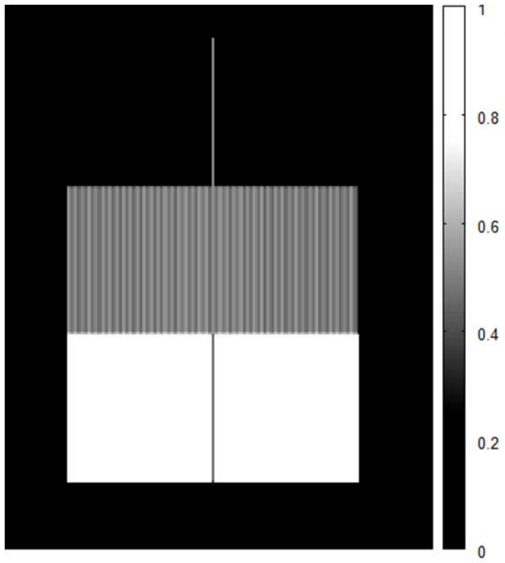
100keV, high current (~20nA), low contrast thick PMMA: ~ 30nm

50keV, high current (~50nA), low contrast thick PMMA: ~ 50nm

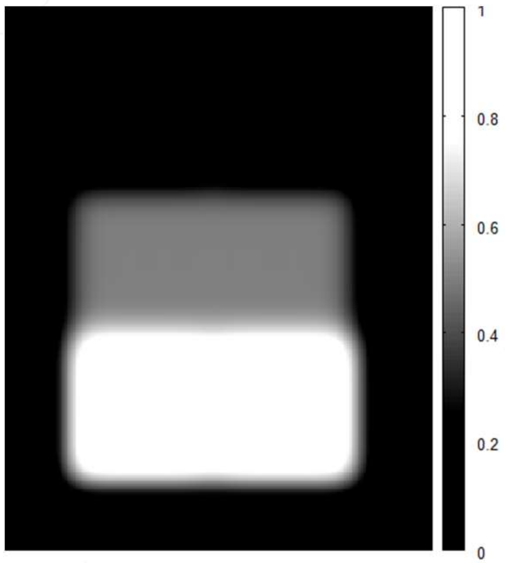
Outline

- Part 2 Summary: PEC Principle & Algorithm
- General Dose PEC Parameter
- Accuracy Control Parameter
  - Dose Assignment
  - Fracturing
- Advanced Model Parameter
- Summary
- Q&A

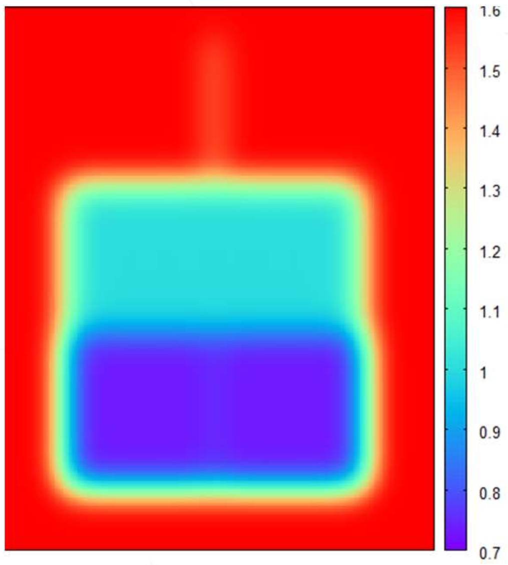
Dose Class Definition



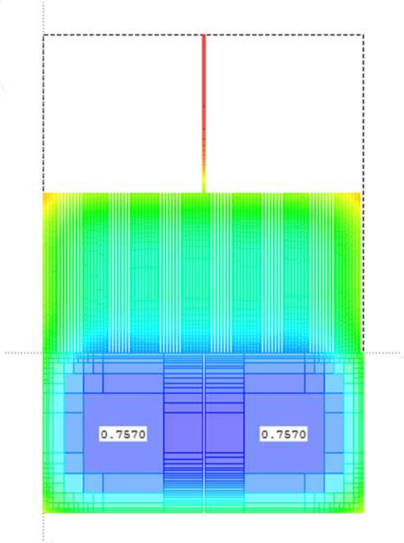
A. Original Layout as bitmap



B. Convolved pattern density



C. Correction dose map



D. Dose transfer to polygonal data including physical fracturing

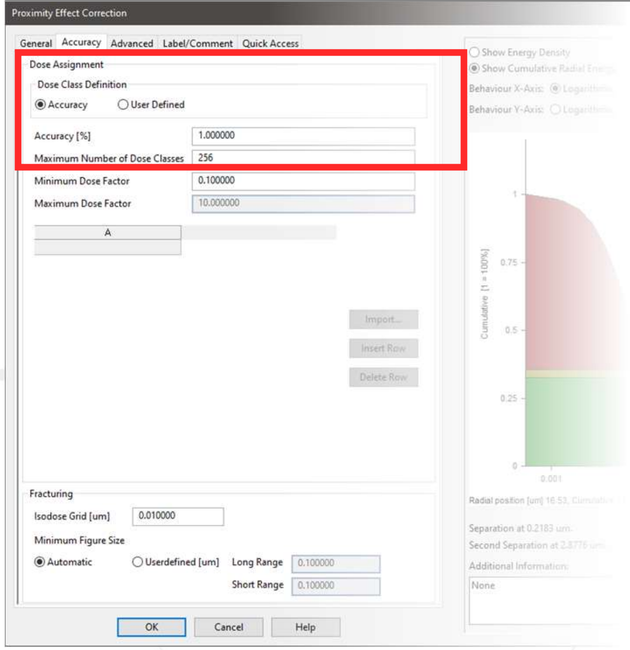
- BEAMER computes a continuous dose spectrum for the correction. For practical reasons these need to be discretized into dose classes. The control parameter for this is the DOSE CLASS DEFINITION

Accuracy

- PEC dose class accuracy is selected on the Accuracy tab
- Smaller values represent a higher accuracy
- The dose range in the correction is discretized:

PEC 10% Accuracy				
🟦 0.8264 (0)		0.83		1.10^{-2}
🟦 0.9091 (1)		0.91		1.10^{-1}
🟦 1.0000 (2)	=	1.00	=	1.10^{0}
🟩 1.1000 (3)		1.10		1.10^{1}
🟩 1.2100 (4)		1.21		1.10^{2}
🟨 1.3310 (5)		1.33		1.10^{3}
🟥 1.4641 (6)		1.46		1.10^{4}

PEC – Accuracy tab



Dose Assignment

Dose Class Definition

● Accuracy ○ User Defined

Accuracy [%]: 1.000000

Maximum Number of Dose Classes: 256

Minimum Dose Factor: 0.100000

Maximum Dose Factor: 10.000000

Fracturing

Isodose Grid [um]: 0.010000

Minimum Figure Size

● Automatic ○ Userdefined [um] Long Range: 0.100000

Short Range: 0.100000

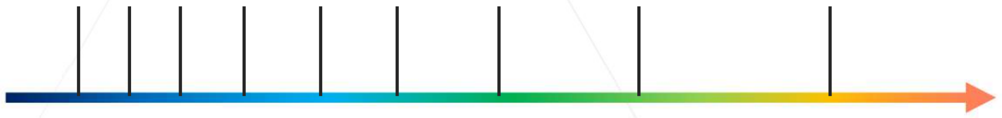
Radial position [um] 16.53, Cumulative

Separation at 0.2183 um.

Second Separation at 2.8776 um.

Additional Information:

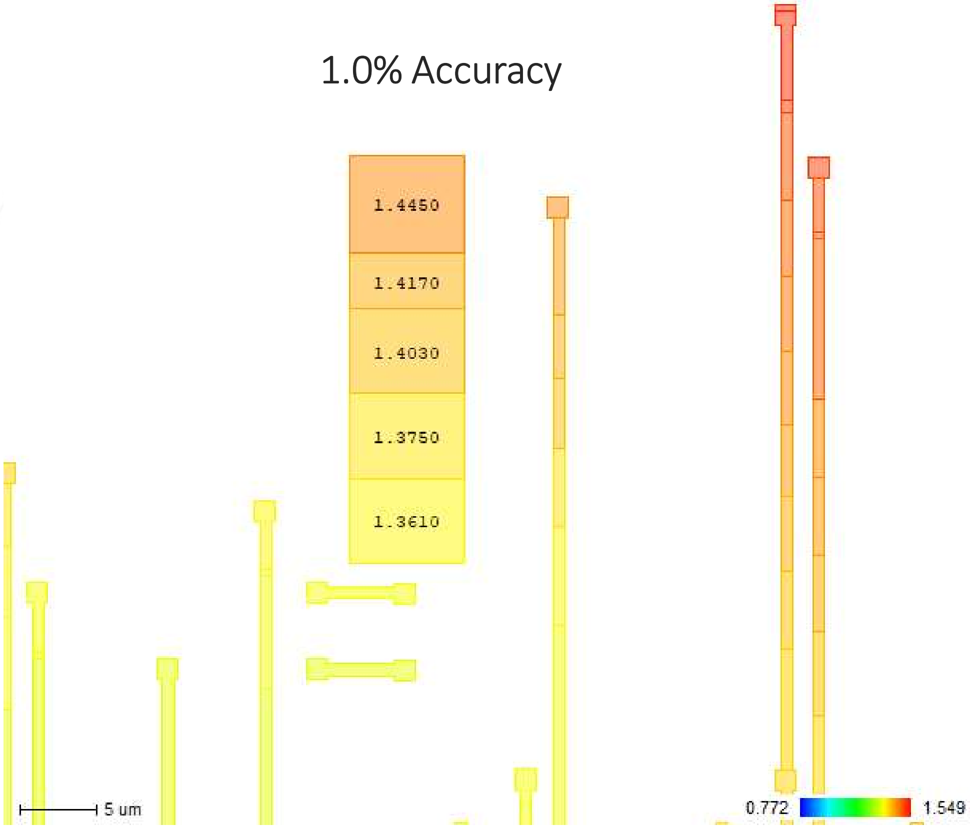
None



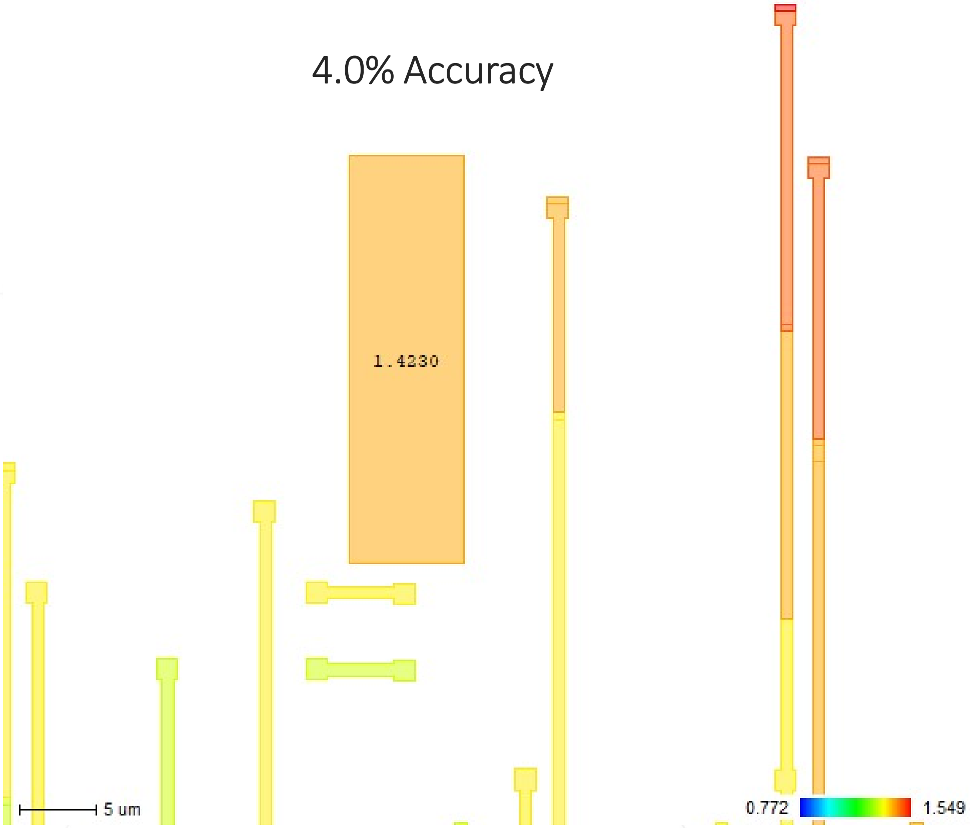
Accuracy

Larger accuracy value reduces shape count at cost of internal dose variation

1.0% Accuracy

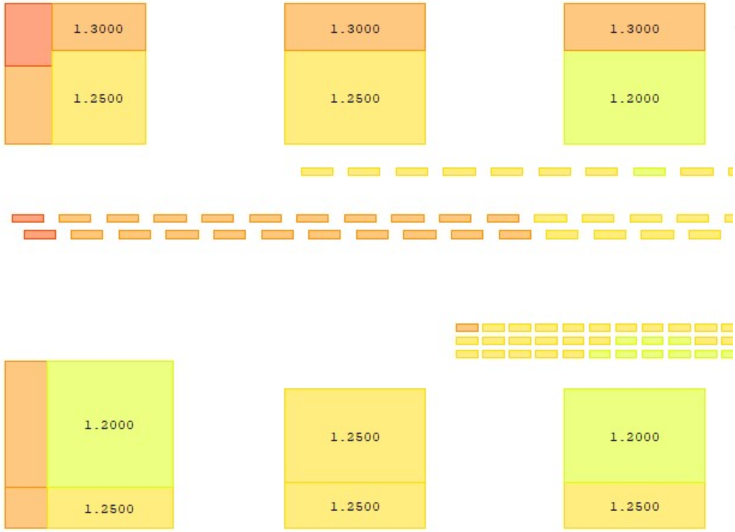


4.0% Accuracy

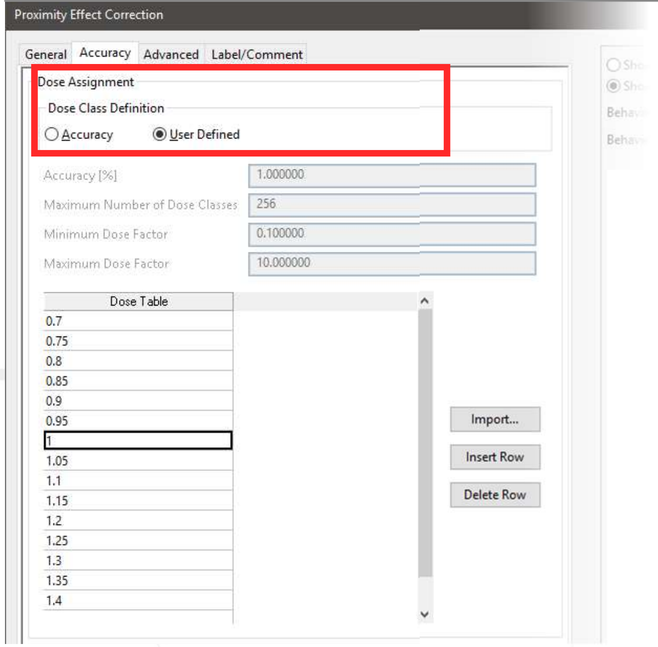


User Defined Dose Table

- Alternative option by user defined dose table
- Manually type in values or import generated values
- All shapes will be assigned doses from the table



PEC – Accuracy tab



Dose Assignment

Dose Class Definition

○ Accuracy ● User Defined

Accuracy [%] 1.000000
Maximum Number of Dose Classes 256
Minimum Dose Factor 0.100000
Maximum Dose Factor 10.000000

Dose Table
0.7
0.75
0.8
0.85
0.9
0.95
1
1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4

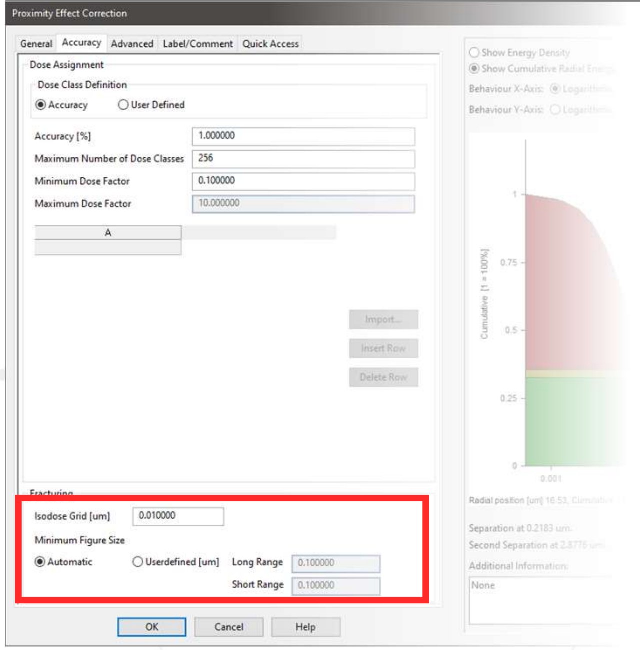
Isodose Grid & Minimum Figure Size

- Isodose Grid defines the "fracture grid" that PEC utilizes
- Interacts with the minimum figure size (MFS)

- The value should equal a multiple of the Beam Step Size

- Automatic mode determines the MFS based on the PSF.

PEC – Accuracy tab



Dose Assignment

Dose Class Definition

● Accuracy ○ User Defined

Accuracy [%]: 1.000000

Maximum Number of Dose Classes: 256

Minimum Dose Factor: 0.100000

Maximum Dose Factor: 10.000000

A

Fracturing

Isodose Grid [um]: 0.010000

Minimum Figure Size

● Automatic ○ Userdefined [um] Long Range: 0.100000

Short Range: 0.100000

Radial position [um] 16.53,

Separation at 0.2183 um

Second Separation at 2.8776 um

Additional Information:

None

Isodose Grid

MFS = 100 nm

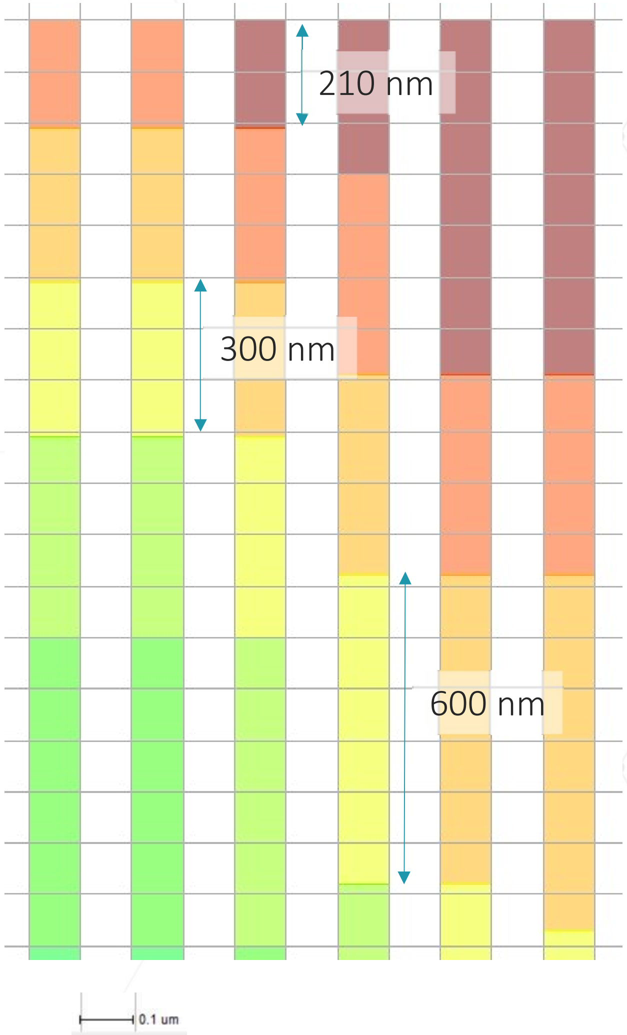
Isodose grid = 200 nm

All fractured shapes at least 200 nm

Shapes are fractured in 200 nm increments

200 nm, 400 nm, 600 nm…

Scale of Grid overlay is 100 nm



MFS = 100 nm

Isodose grid = 30 nm

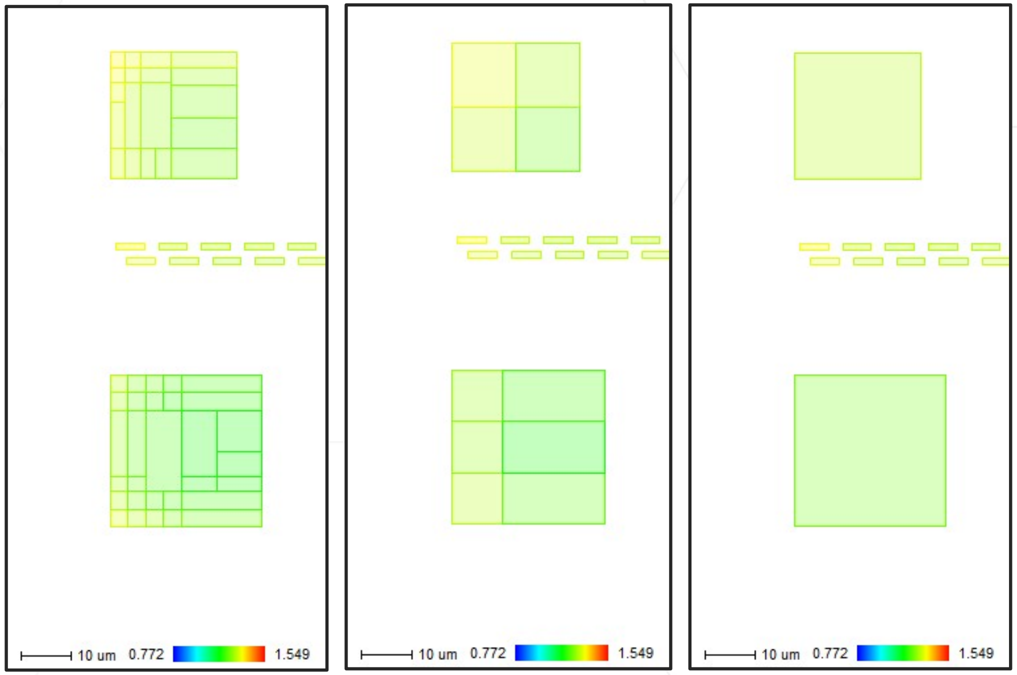
All fractured shapes at least 120 nm

Shapes are fractured in 30 nm increments

120 nm, 150 nm, 180 nm, 210 nm…

Minimum Figure Size

- Minimum figure size is editable on the PEC accuracy tab
  - Default: automatically calculated based on the chosen PSF
- Defines the smallest allowable size of PEC fractured shapes
  - Shapes larger than the MFS will not be fractured
- Manually increasing this value can reduce the total shape count



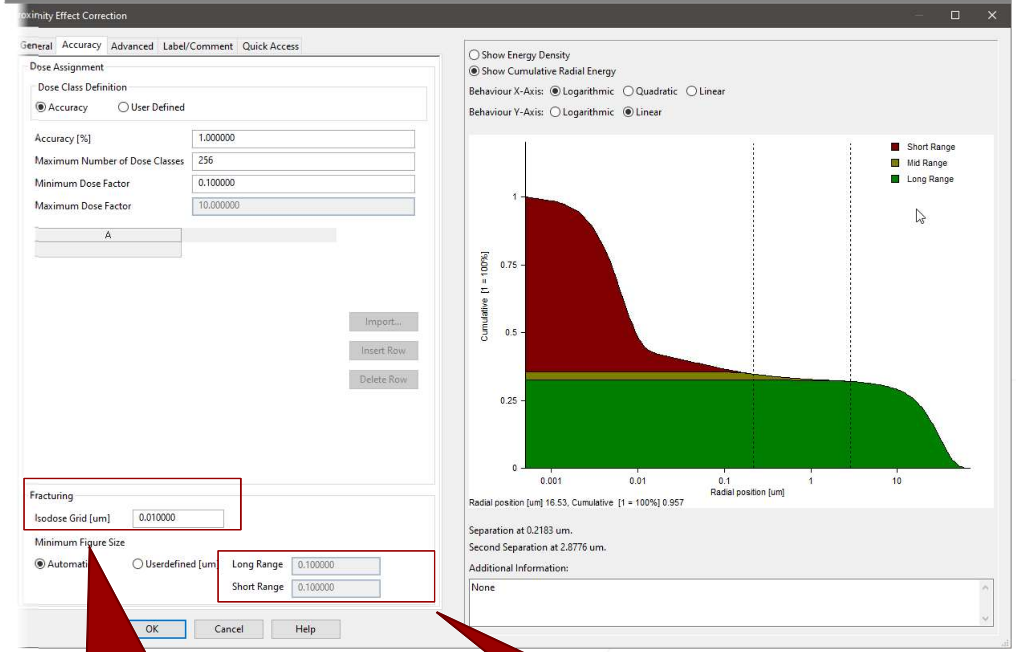
1 µm MFS
59 shapes

10 µm MFS
20 shapes

25 µm MFS
12 shapes

SR & LR Fracturing

PEC – Accuracy tab



Dose Assignment

Dose Class Definition

● Accuracy ○ User Defined

Accuracy [%] 1.000000

Maximum Number of Dose Classes 256

Minimum Dose Factor 0.100000

Maximum Dose Factor 10.000000

Fracturing

Isodose Grid [um] 0.010000

Minimum Figure Size

● Automati ○ Userdefined [um]

Long Range 0.100000

Short Range 0.100000

○ Show Energy Density

● Show Cumulative Radial Energy

Behaviour X-Axis: ● Logarithmic ○ Quadratic ○ Linear

Behaviour Y-Axis: ○ Logarithmic ● Linear

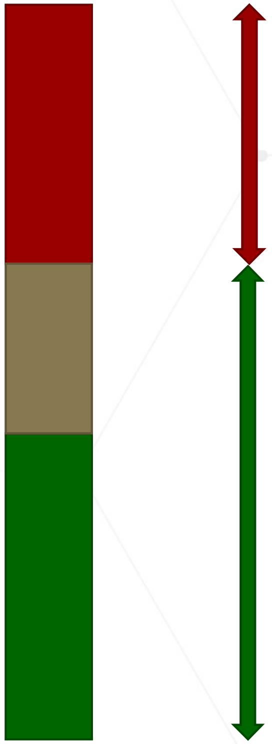
Radial position [um] 16.53, Cumulative [1 = 100%] 0.957

Separation at 0.2183 um.

Second Separation at 2.8776 um.

Additional Information:

None



Dedicated shape fracturing for short range effects

Global fracturing based on the long range correction

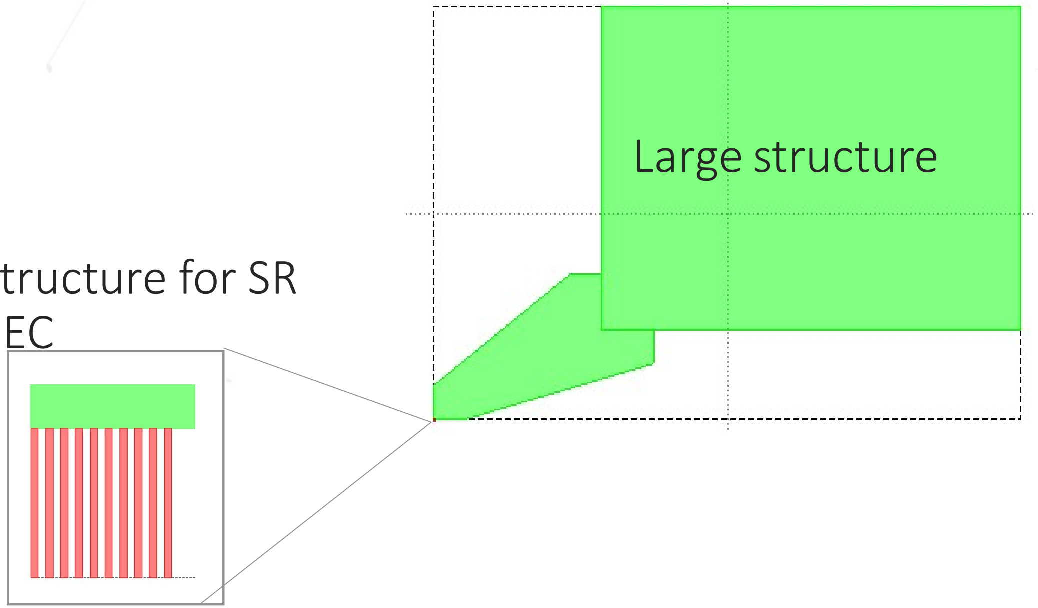
Resolution of the fractures

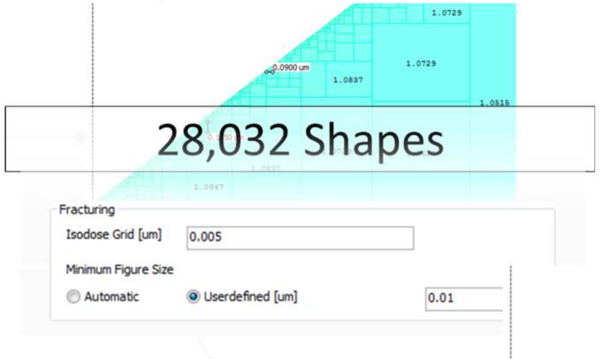
Minimum size for the algorithm

Fine fractures by SR PEC

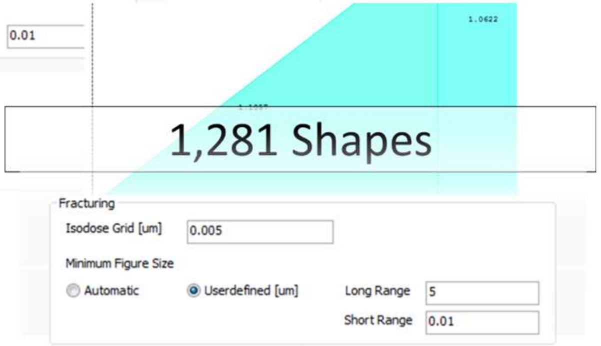
- SR PEC requires a small minimum figure size
  - Enables dose modulation at high resolution
- One MFS parameter would increase the shape count for LR pattern elements

Structure for SR PEC




28,032 Shapes

Fracturing
Isodose Grid [um] 0.005
Minimum Figure Size
○ Automatic ● Userdefined [um] 0.01


1,281 Shapes

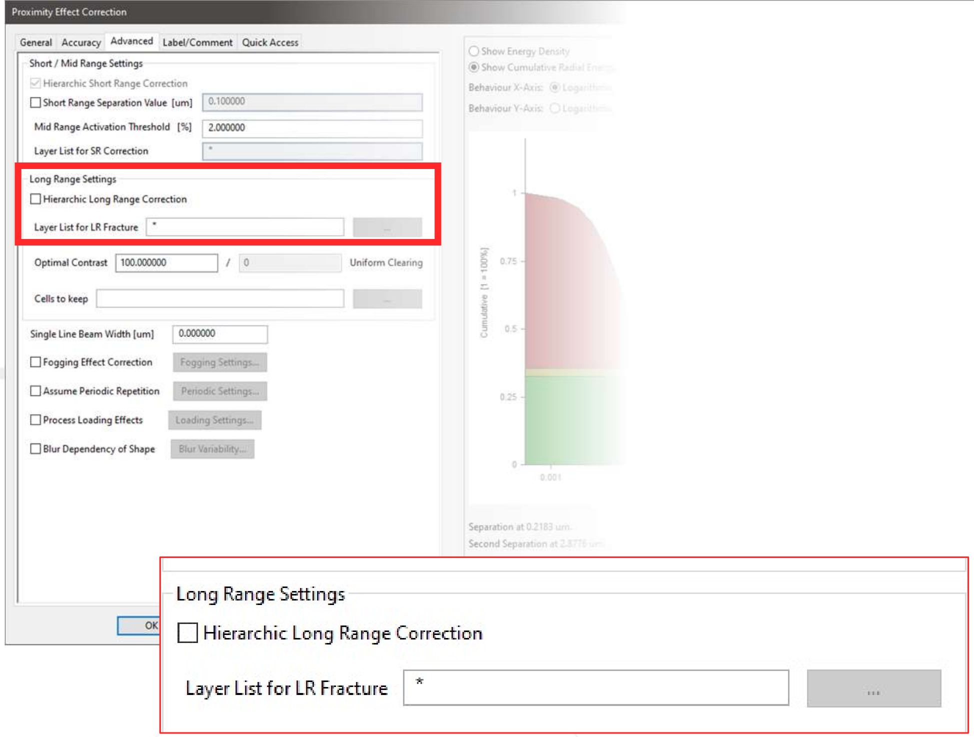
Fracturing
Isodose Grid [um] 0.005
Minimum Figure Size
○ Automatic ● Userdefined [um]
Long Range 5
Short Range 0.01

Layer Specific LR fracturing

Layer Specific correction allows:

- Dedicated control where LR fracturing is applied
- Ensures that layers are taken into account for proximity correction but don’t get additional fractures
- Works together with Correction Layer Selection on General tab to omit layers and controlled fractures / dose assignments

PEC – Advanced tab



Short / Mid Range Settings

☑ Hierarchic Short Range Correction

☐ Short Range Separation Value [um] 0.100000

Mid Range Activation Threshold [%] 2.000000

Layer List for SR Correction *

Long Range Settings

☐ Hierarchic Long Range Correction

Layer List for LR Fracture *

Optimal Contrast 100.000000 / 0 Uniform Clearing

Cells to keep

Single Line Beam Width [um] 0.000000

☐ Fogging Effect Correction — Fogging Settings...

☐ Assume Periodic Repetition — Periodic Settings...

☐ Process Loading Effects — Loading Settings...

☐ Blur Dependency of Shape — Blur Variability...

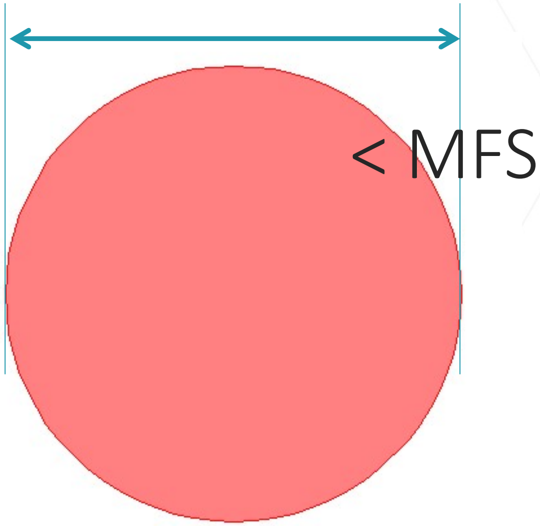
Long Range Settings

☐ Hierarchic Long Range Correction

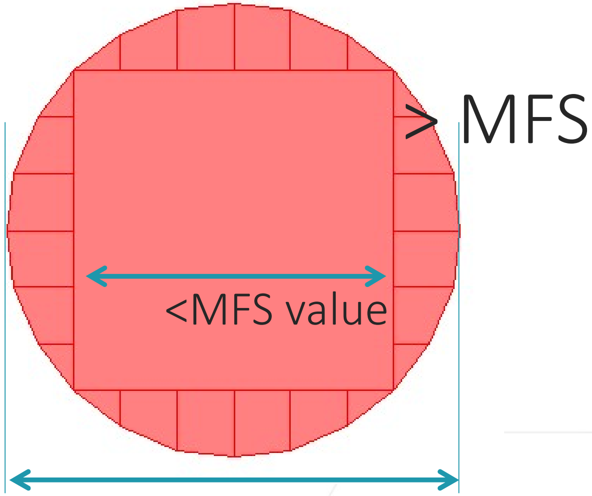
Layer List for LR Fracture *

Avoid fractures & Pre-Fracturing

For pattern elements below the Minimum Figure Size the parameter can be used to skip fractures.



The element gets one dose only



For larger then MFS elements the FRACTURE module can pre-fracture and give control on the fracturing of elements.
Additionally set the MFS large enough to avoid sub-fractures. Individual dose assignments are possible.

GenISys
Advancing the Standard

Outline

- Part 2 Summary: PEC Principle & Algorithm
- General Dose PEC Parameter
- Accuracy Control Parameter
- Advanced Model Parameter
    - Uniform Cleaning / Optimum Contrast
    - Lateral Development Correction
- Summary
- Q&A

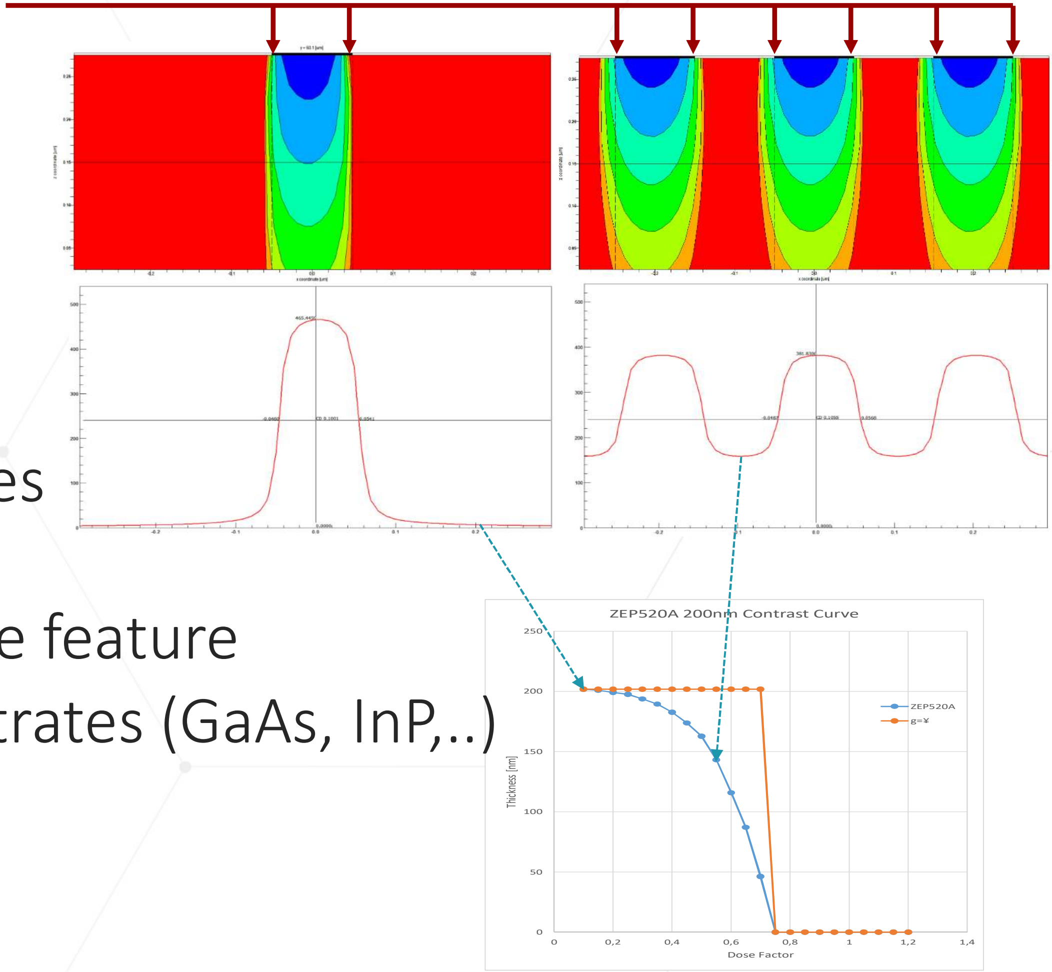
Lateral Development

Edge energies are equal:

- Dose to clear at feature edge
- Ideal for high contrast (thin) resists

Thick resist application

- Lower contrast resist development does not stop at feature edge
- Develops dependent on energy outside feature
- Effect is stronger for high density substrates (GaAs, InP,..)
- Results in density dependent bias



Lateral Development Correction

Lateral Development Bias can be corrected at PEC

- Density dependent Bias table
- Experimentally measured
- TRACER process calibration

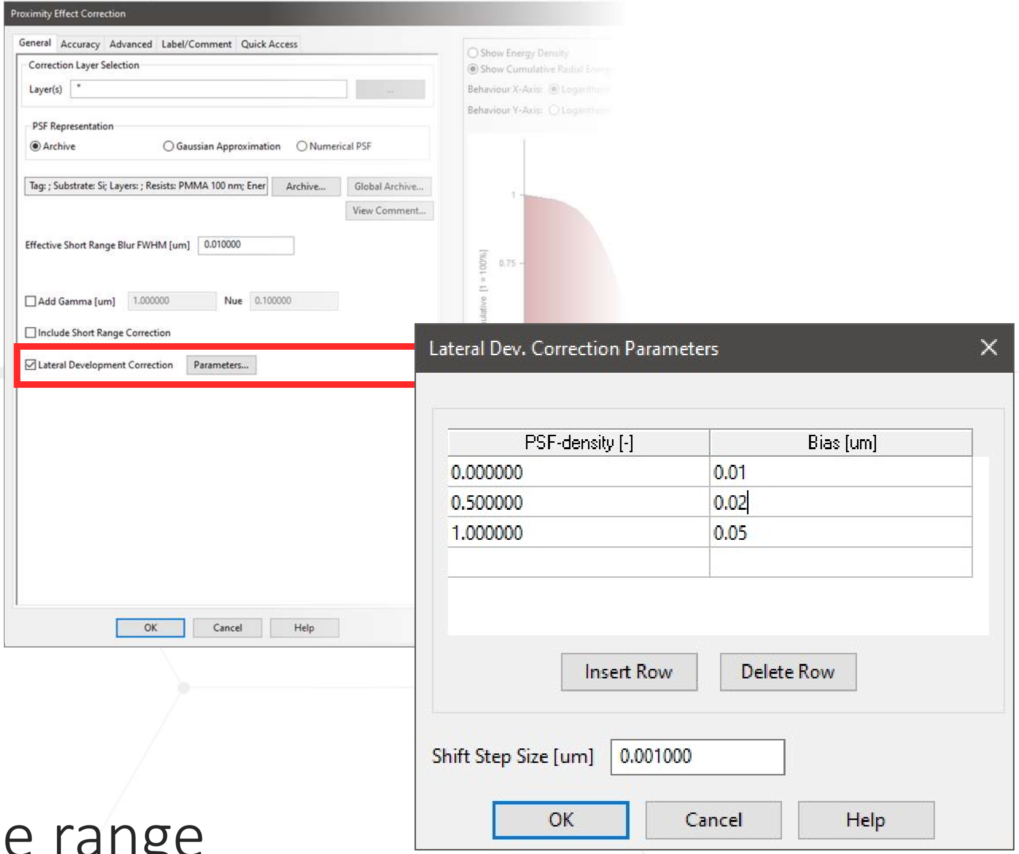
Correction:

- Moving feature edge dependent on PSF-density
- Assigning dose factor

PSF-Density:

- Local layout density within PSF influence range

PEC – General tab



Layer(s) *

● Archive ○ Gaussian Approximation ○ Numerical PSF

Tag: ; Substrate: Si; Layers: ; Resists: PMMA 100 nm; Ener

Effective Short Range Blur FWHM [um] 0.010000

☐ Add Gamma [um] 1.000000 Nue 0.100000

☐ Include Short Range Correction

☑ Lateral Development Correction

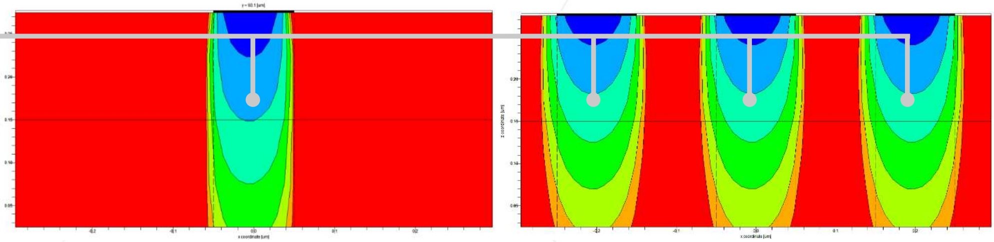
PSF-density [-]	Bias [um]
0.000000	0.01
0.500000	0.02
1.000000	0.05

Shift Step Size [um] 0.001000

Weakness: Non-uniform clearing

Bulk energies are not equal

- Bulk energy of iso is higher, dense lower
- Development rate of iso / dense is different
- Iso is clearing first followed by dense

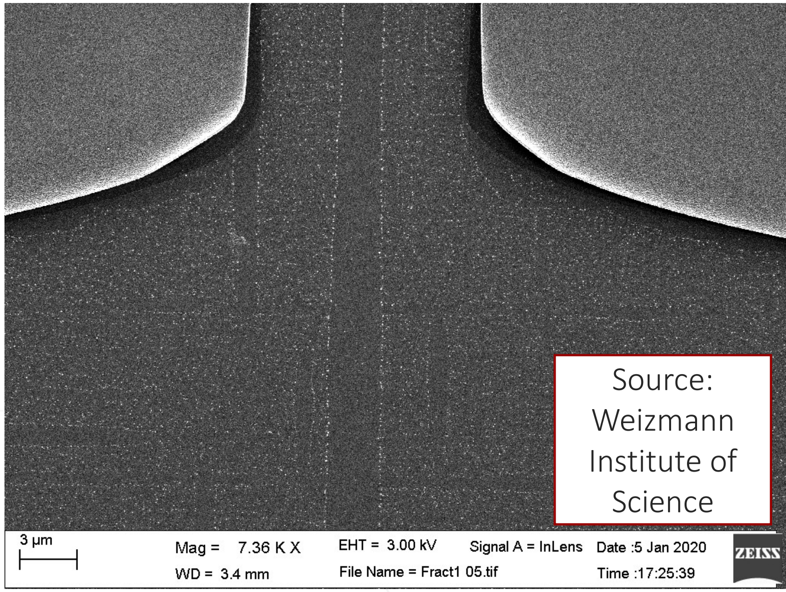


Large pads clear last

- Edge equalization is dropping dose of large pads for optimum contrast
- Stronger for high density substrates (GaAs, InP,...)
- Results in residues in large pads

Increasing Base Dose to clear residues

- large oversizing (lateral development) of critical feature



Source: Weizmann Institute of Science

Surface Equalization

Target of correction:

- Adjust all feature areas to the same absorbed energy:

Inside the feature E(x) = 1:

- Resist will be cleared (Positive)

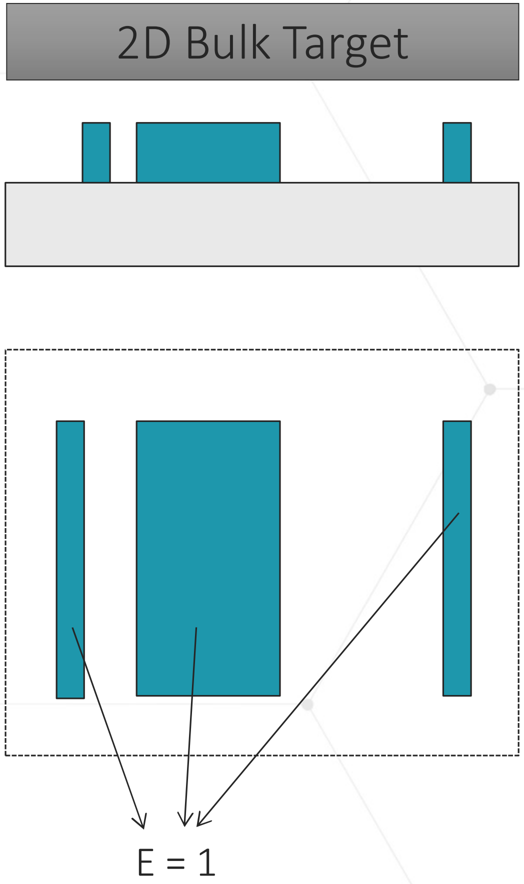
Outside the feature E(x) < D2C:

- Resist will remain (Positive)

Correction Equation:

- E(bulk) = 1 = D(x) ⊗ PSF

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



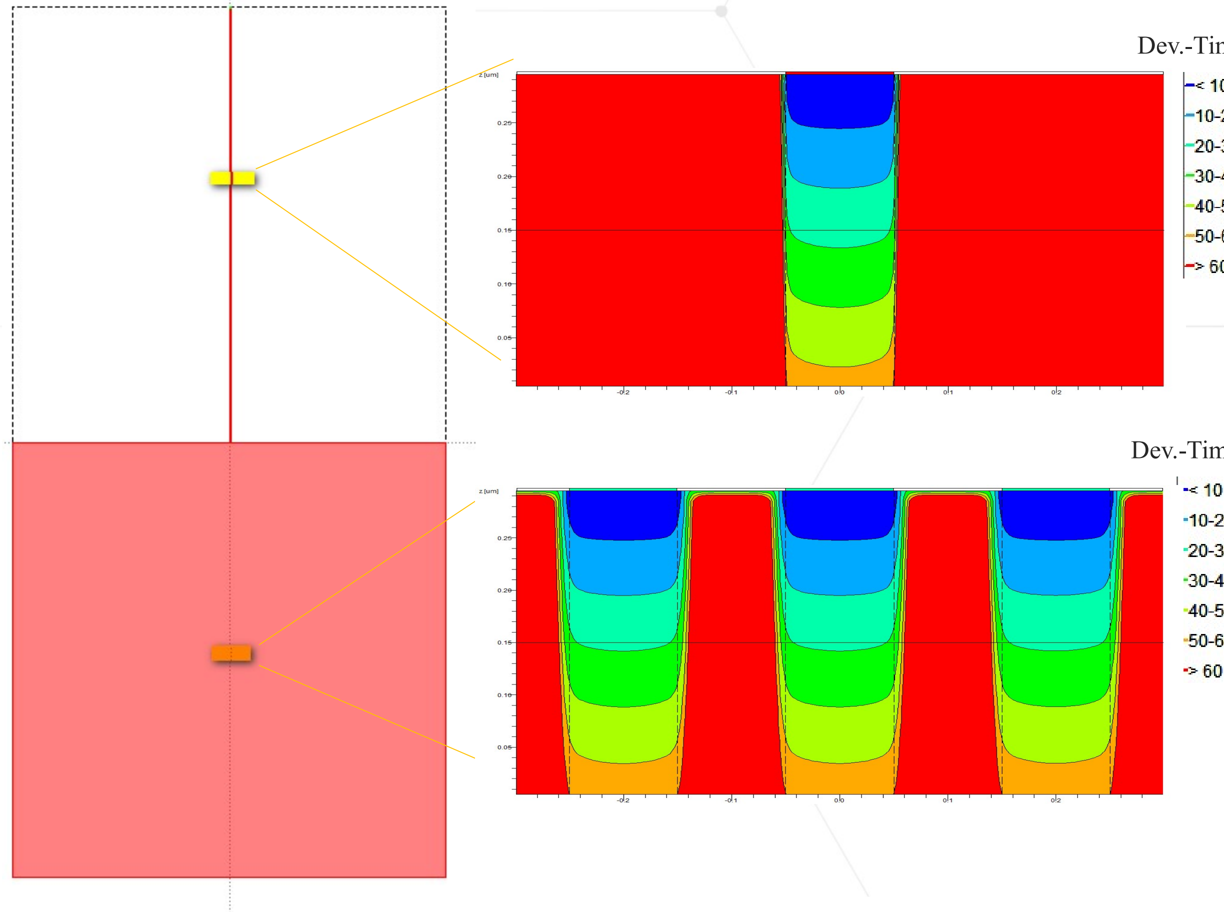
Pro & Con of Uniform Clearing

Bulk energy is equal

- Large /small, iso/dense clearing at same time

Edge energy is not equal

- Smaller process latitude

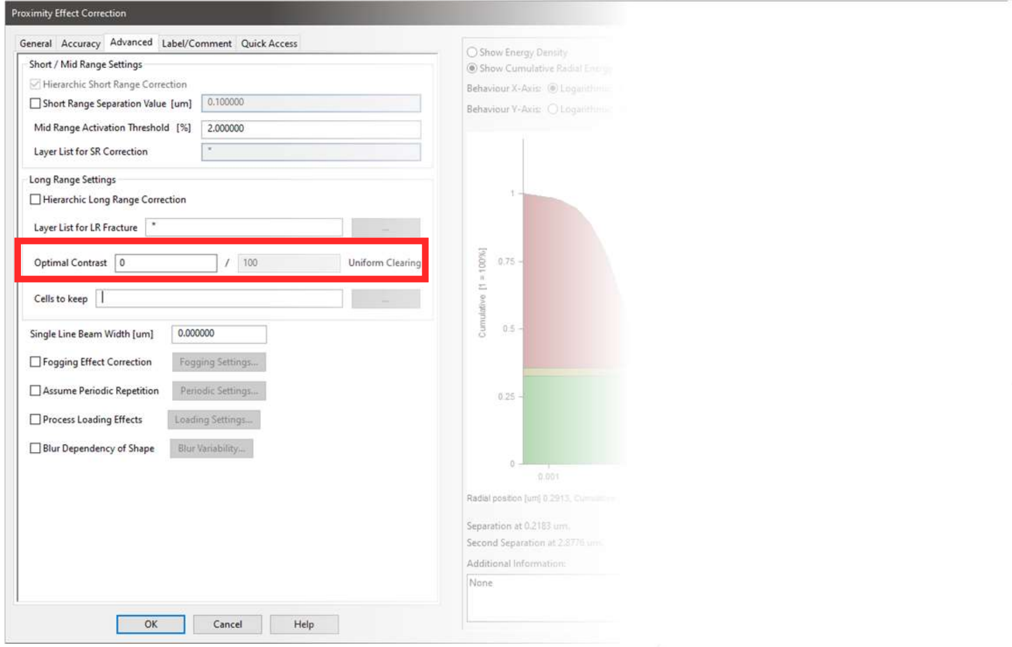


BEAMER allows „mixed mode“

- TRACER optimizes mixed factor

PEC – Uniform Clearing

PEC – Advanced tab



Proximity Effect Correction

Short / Mid Range Settings

☑ Hierarchic Short Range Correction

☐ Short Range Separation Value [um]: 0.100000

Mid Range Activation Threshold [%]: 2.000000

Layer List for SR Correction: *

Long Range Settings

☐ Hierarchic Long Range Correction

Layer List for LR Fracture: *

Optimal Contrast: 0 / 100 Uniform Clearing

Cells to keep:

Single Line Beam Width [um]: 0.000000

☐ Fogging Effect Correction

☐ Assume Periodic Repetition

☐ Process Loading Effects

☐ Blur Dependency of Shape

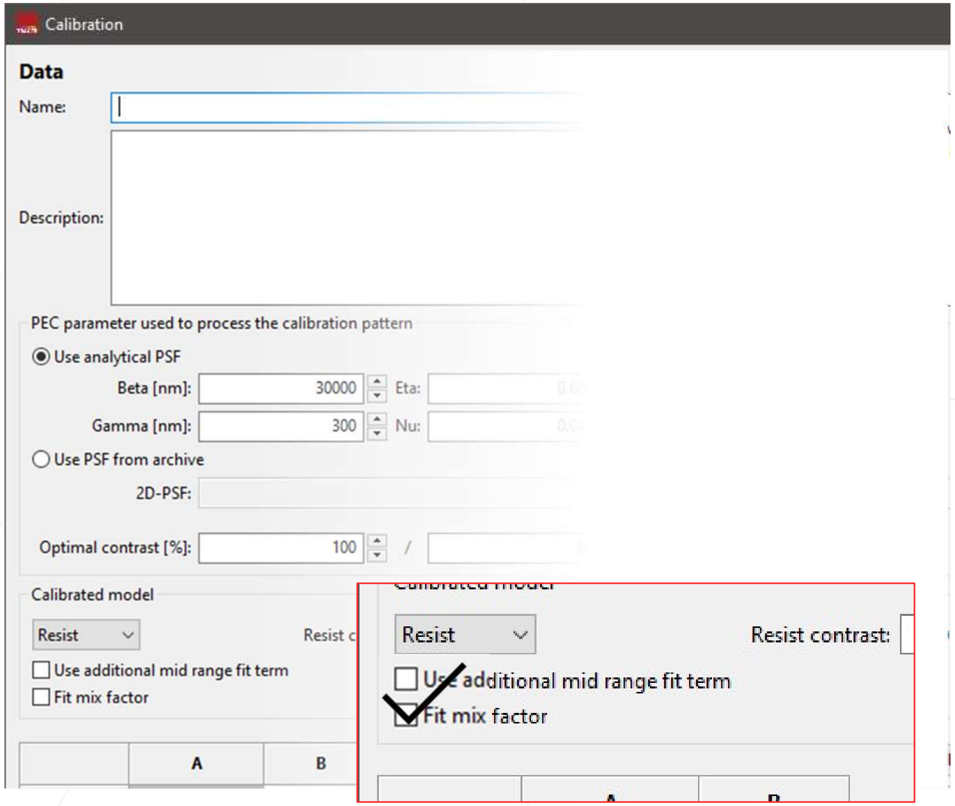
Radial position [um] 0.2913

Separation at 0.2183 um.

Second Separation at 2.8776 um.

Additional Information: None

Optimal Contrast: 0 / 100 Uniform Clearing



Calibration

Data

Name:

Description:

PEC parameter used to process the calibration pattern

● Use analytical PSF

Beta [nm]: 30000

Gamma [nm]: 300

○ Use PSF from archive

2D-PSF:

Optimal contrast [%]: 100 /

Calibrated model

Resist

Resist contrast:

☐ Use additional mid range fit term

☑ Fit mix factor

Outline

- Part 2 Summary: PEC Principle & Algorithm
- General Dose PEC Parameter
- Accuracy Control Parameter
- Advanced Model Parameter
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Summary

- Layout
  - All (and only) pattern which will be exposed into the resist should be included
  - PEC is maintaining layer (e.g. for bulk-sleeve, writing order control)

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

- PEC Accuracy Parameter
  - Dose classes are automatically generated by defining needed dose accuracy (or manually defined)
  - Minimum fracture size control and pre-fracturing allow to optimize number of shapes vs. accuracy
- Advanced Correction Parameter
  - Lateral development correction by PSF-density dependent Biases (calibrated by TRACER)
  - Low contrast resist on high density material may require correction for more “uniform clearing” (Mix factor OC/UC can be calibrated with TRACER)