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Nikola Belic, Ulrich Hofmann
October 14th, 2020

Proximity Effect in E-Beam Lithography

Overview and Agenda

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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…

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Part 2: Dose PEC Algorithm and Parameter

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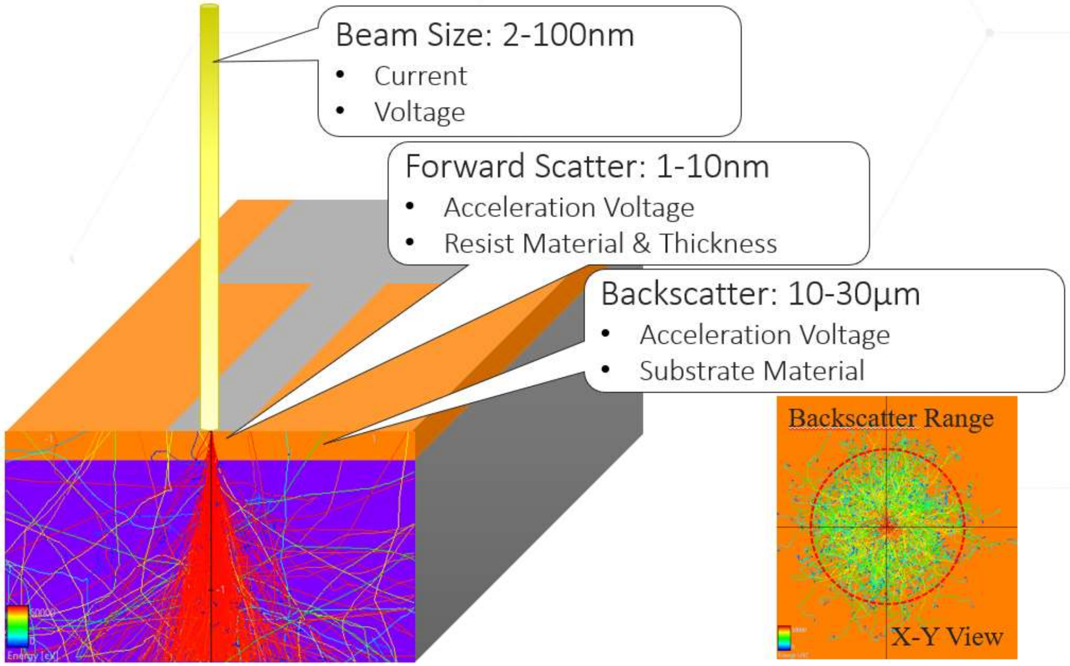
Outline

- Part 1 Summary: Electron Scattering & Proximity Effect
- Proximity Effect Correction Principle
- PEC Algorithm
- Main PEC parameter
- Summary + Q&A

Exposure → Scattering → Printed Feature

- Proximity Effect has major influence on e-beam lithography
  - Electron scattering in the material (resist, layers, substrate) spreads the energy
    - Strength and influence ranges depend on material and acceleration voltage



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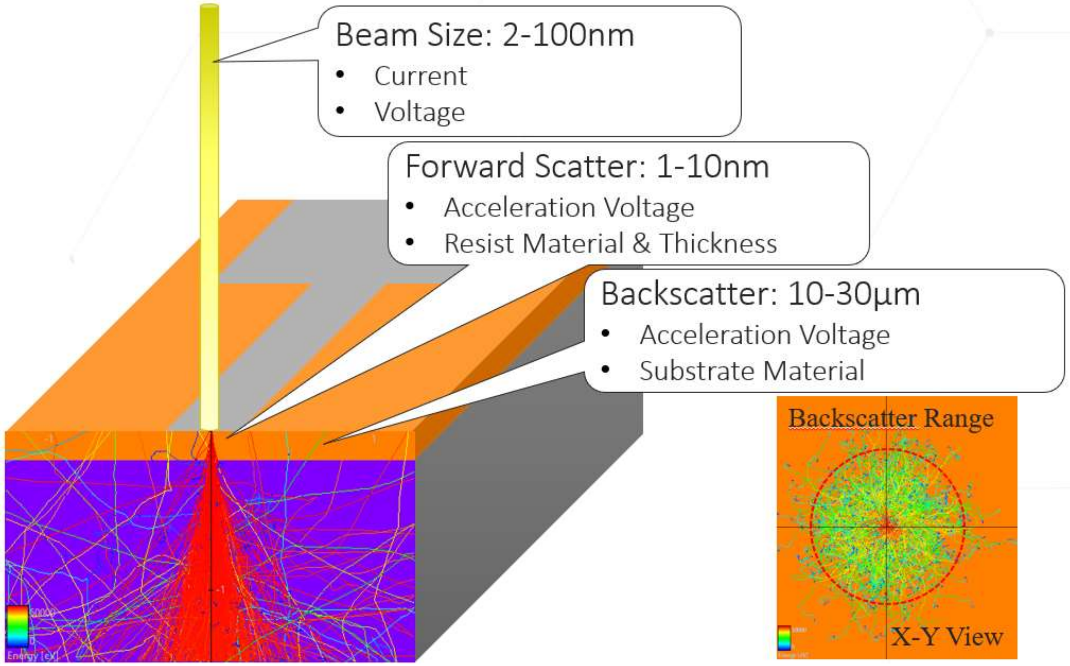
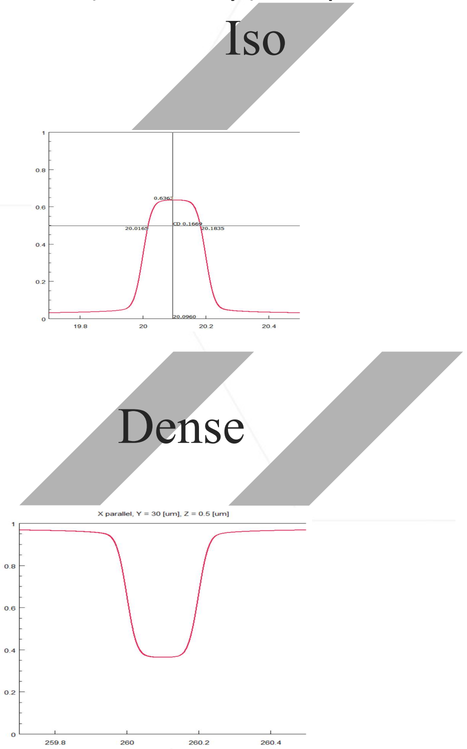
  - Adjacent features interact, leading to a layout (density) dependent absorbed energy





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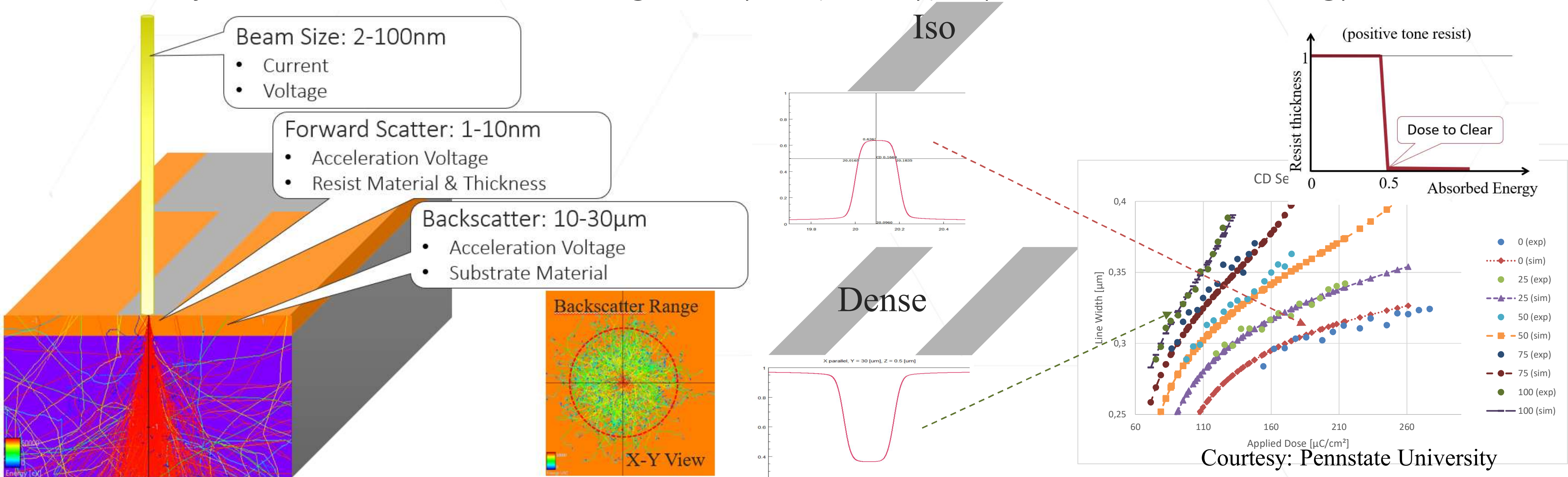

Courtesy: Pennstate University

Scattering → Absorbed Energy → Printed Feature

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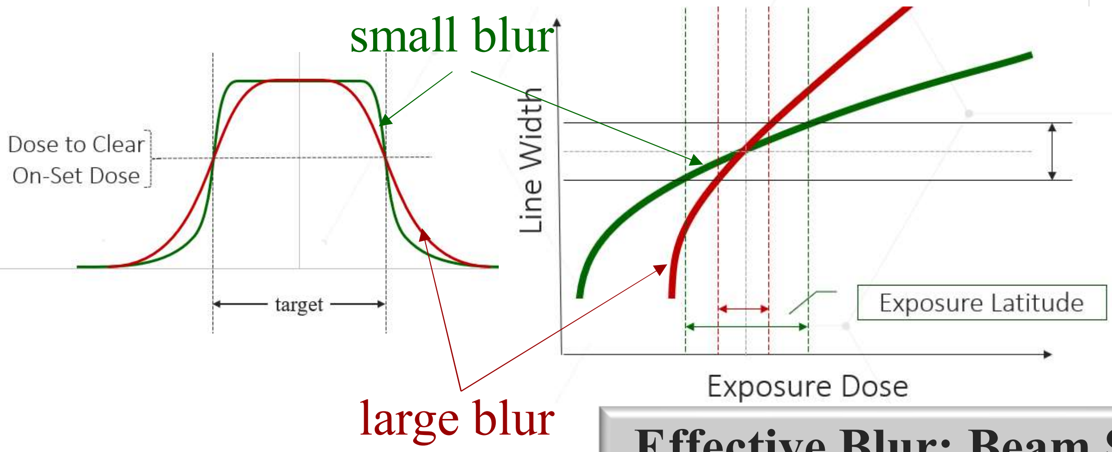
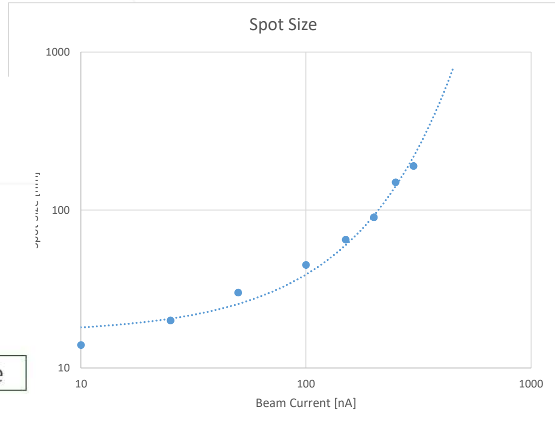
Blur couples Dose to CD

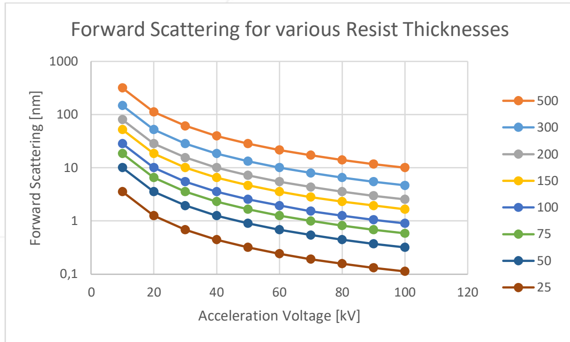
- Impact of proximity effect on lithography result depends on tool + process parameters
  - The effective short range blur transfers absorbed energy variation to CD variation
  - The effective beam size depends on e-beam tool parameters
    - beam current, apperture, focus (variation), noise
    - Reasonable exposure time and exposure quality ask for higher beam curent
  - The process (specifically resist) is another contributor to effective short range blur

Absorbed Energy

CD Sensitivity to Dose







Effective Blur: Beam Size + Scattering + Process

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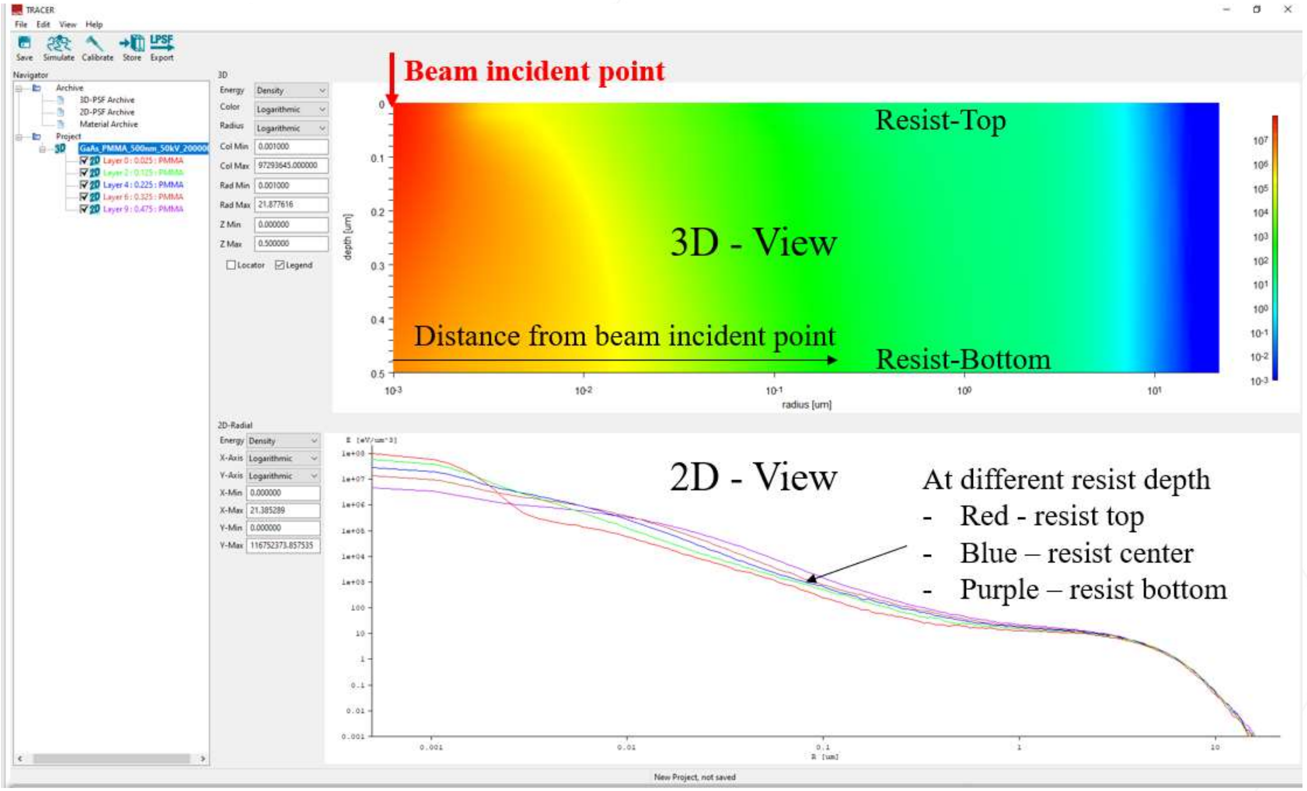
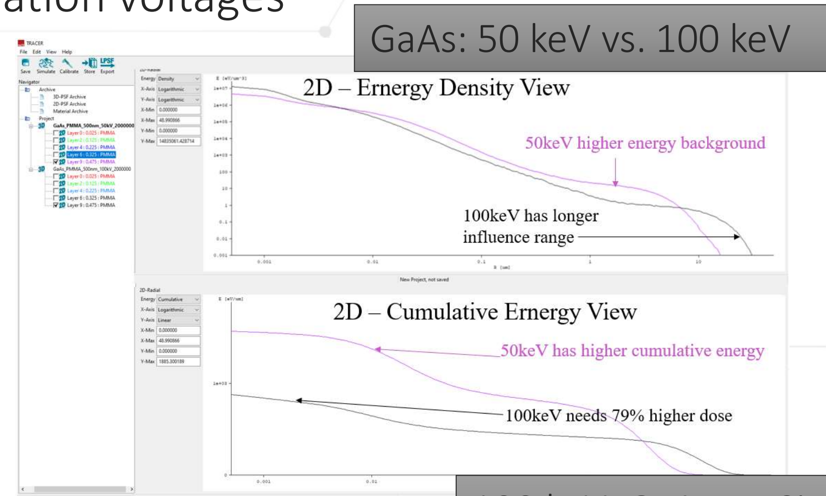
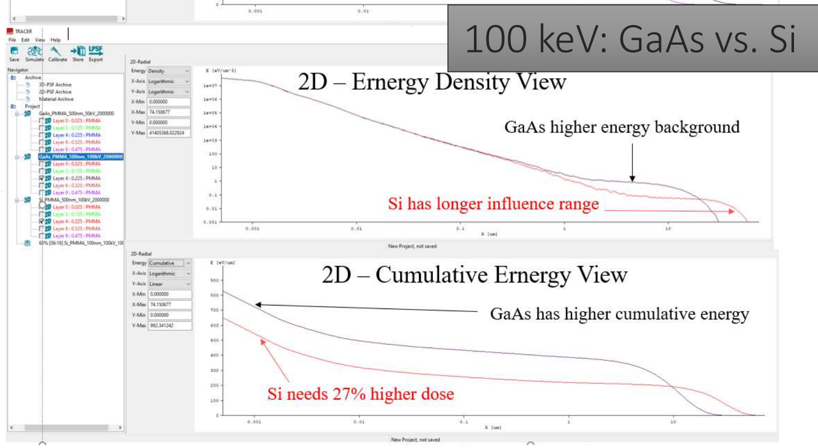
Electron Solid Interactions (Scattering)

- Monte-Carlo Simulation is an excellent technique to model electron scattering
  - Point Spread Function (PSF) for different stacks and acceleration voltages

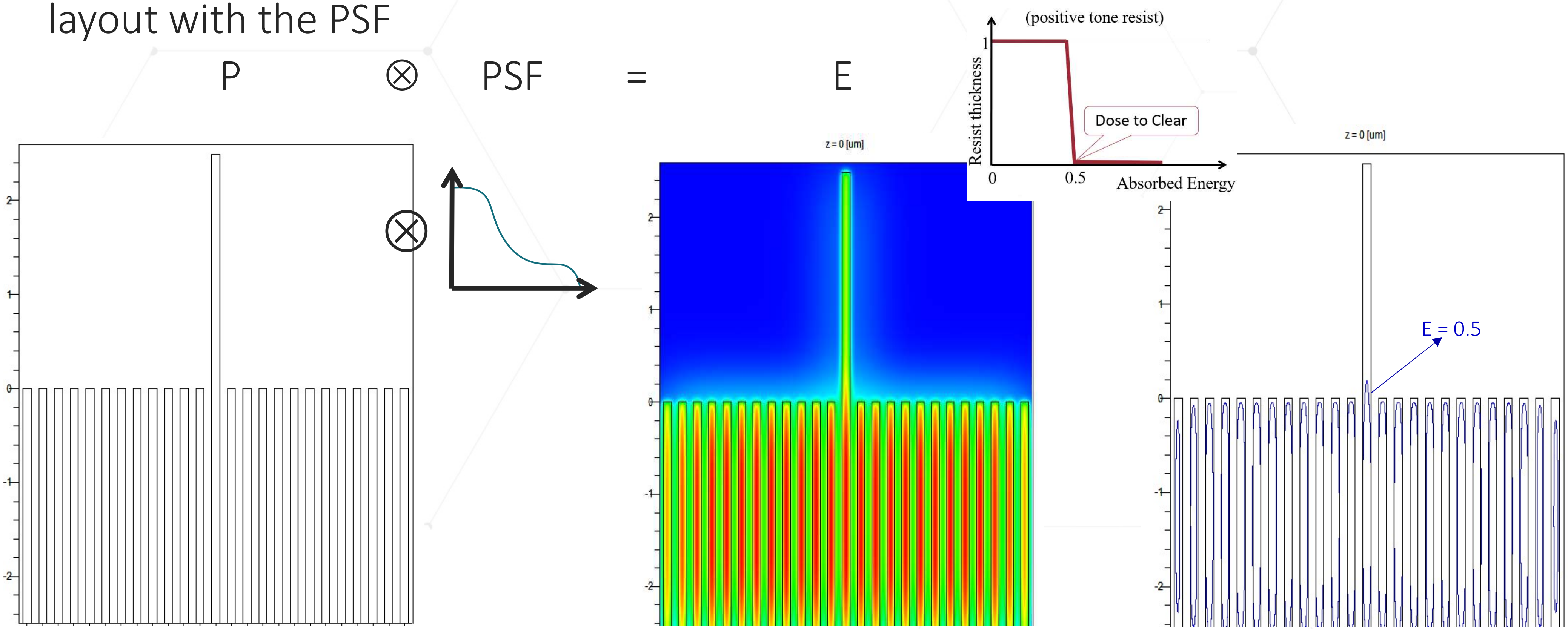






Baseline Simulation Mechanism

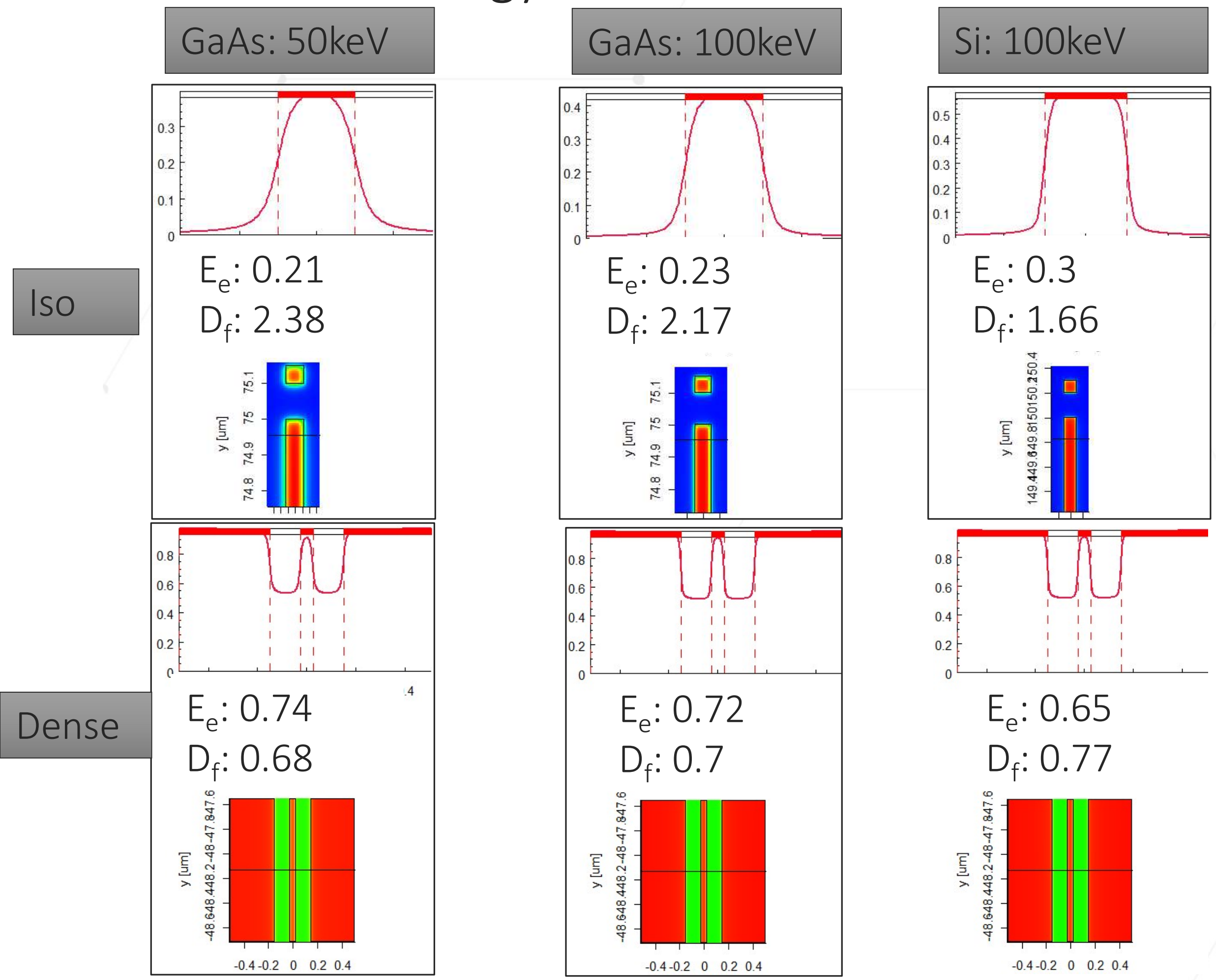
- Absorbed energy and resist contour at D2C can be simulated by convolution of the layout with the PSF



Threshold already provides 1st order indication of printed feature

Simulation Extended

- Absorbed energy at Iso & Dense for different stacks end acceleration voltage



- Absorbed energy at the layout edge (E_e) is varying depending on layout density (iso and dense), leading to layout dependent CD
- Consequently layout density dependent dose factor will be needed to adjust all feature edges to the same absorbed energy (dose to clear)
- The dose factors depend on acceleration voltage and stack (mainly substrate material density)

How to get these Dose Factors

- One can
  - Determine iso / dense dose factors experimentally
  - Alternatively determine iso / dense dose factors by simulation
  - Manually apply these to the pattern (including fracturing of critical geometries)
  - Redo this process for each pattern / process change / V_{acc} change / stack change

- Or
  - Use an algorithm to do the job for you
    - and invest in a characterized base line process

- Makes your life so much easier

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Lithography

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  - Constraints
  - Edge Equalization
  - Benefits of PEC
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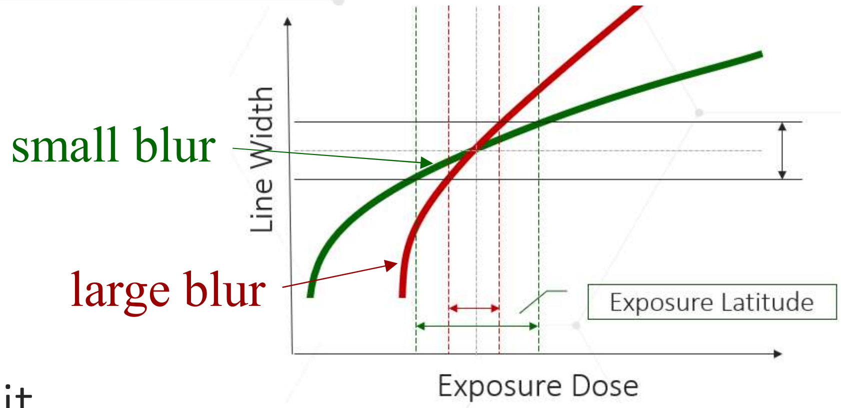
Correction Principles

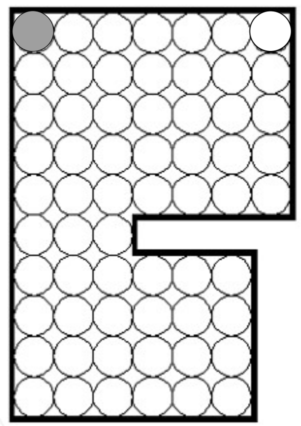
- e^--Scattering → Dose Errors → CD Errors (effective blur)
  - 1000's of paper discussed a multitude of aspects
- Degree of Freedom (what to modulate)
  - Shape, Dose, or a combination of both
- Correction Target (what to optimize for)
  - Algorithmic: Linear Operator, Area Equalization, Edge Equalization
  - Machine Learning
- Algorithms (how to compute this)
  - Iterative Inverses (e.g. Newton Inverse), Ghost (1st order Inverse)
  - Approximate Solutions
  - Linear Optimization

Each one would deserve its own tutorial

Dose vs. Shape

- „Best practice“
  - Dose errors should be corrected by dose modulation
  - Shape errors should be corrected by shape
- Rationale
  - Dose correction can be blur independent
    - Shape correction only works for ONE blur
  - Dose correction does not introduce resolution limit
    - Amount of Shape modulation limited by smallest feature / gap
  - Tools allow reasonable fine dose control (both GB and VSB)
    - Shape Modulation only in increments of Shot Pitch (Shape Fill)
  - Exception: Shape modulation can help in contrast limited scenarios
    - E.g. undersize / overdose…

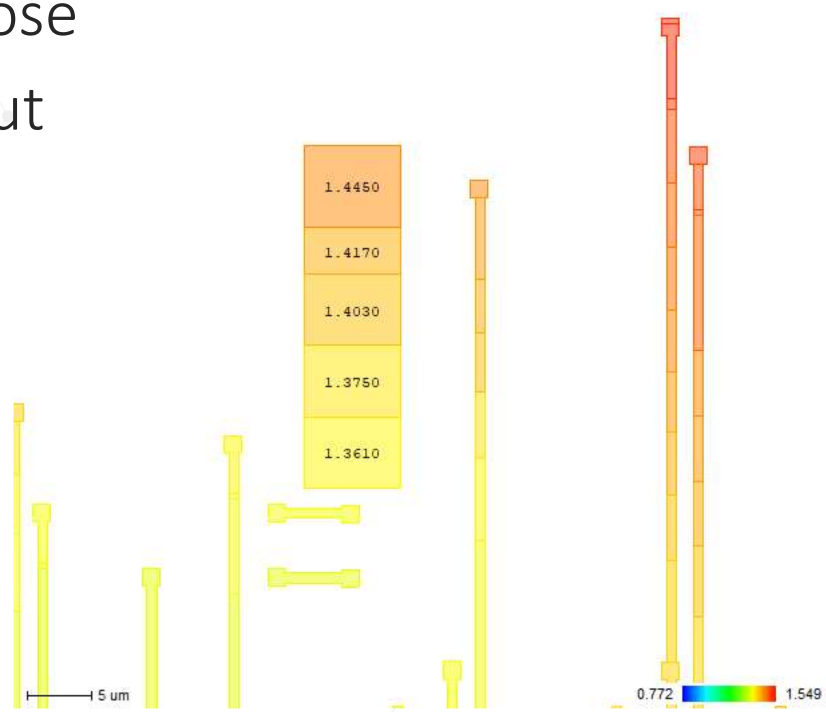




Standard e⁻-scattering PEC is best corrected via dose modulation

Side Note: PEC Fracturing

- Tools can expose one shape only with ONE dose
- Therefore, a dose PEC must fracture the layout in areas / shapes of equal dose
- Leads to another tradeoff
  - Fewer shapes: less overhead, coarse grain doses
  - More Shapes: more overhead, fine grain doses



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References

1. D. Kern, A novel approach to proximity effect correction, Proc. Symp. On Electron and Ion Beam Science and Technology, 9th Int. Conf., Vol. 80-6, pp. 326-339 (1980)
2. G. Owen and P. Rissman, Proximity effect correction in electron beam lithography by equalization of background dose, J. Appl. Phys., 54(6), 3573-3581 (1983)
3. R. Crandall et al, Contrast Limitations in Electron-Beam Lithography, EIPBN 1999
4. M. Parikh, Corrections to proximity effects in electron beam lithography, J.Appl.Phys., 50(6), 4371-4377 (1979)
5. H. Eisenmann et al, PROXECCO – Proximity Effect Correction by Convolution, J.Vac.Sci.Technol., B Vol.11, No.6, Nov/Dec 1993
6. J. Pavkovich, Proximity effect correction calculations by the integral equation approximate solution method, J. Vac.Sci. Technol., B, Vol.4, No.1, Jan/Feb 1986
7. T. Abe et al, Fast and Highly accurate Proximity Effect Correction for Mask Making, 3rd International Workshop on High Throughput Charged Particle Lithography, Hawaii, 1998

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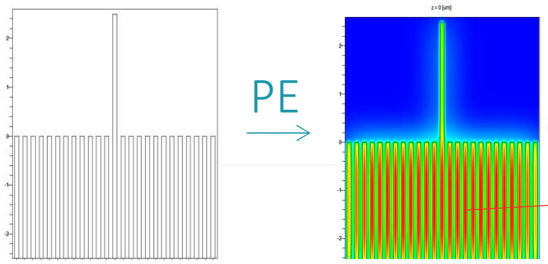
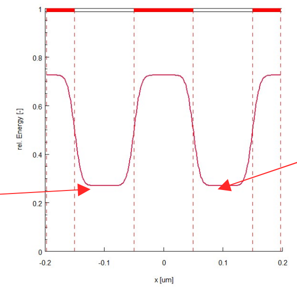
PEC Targets





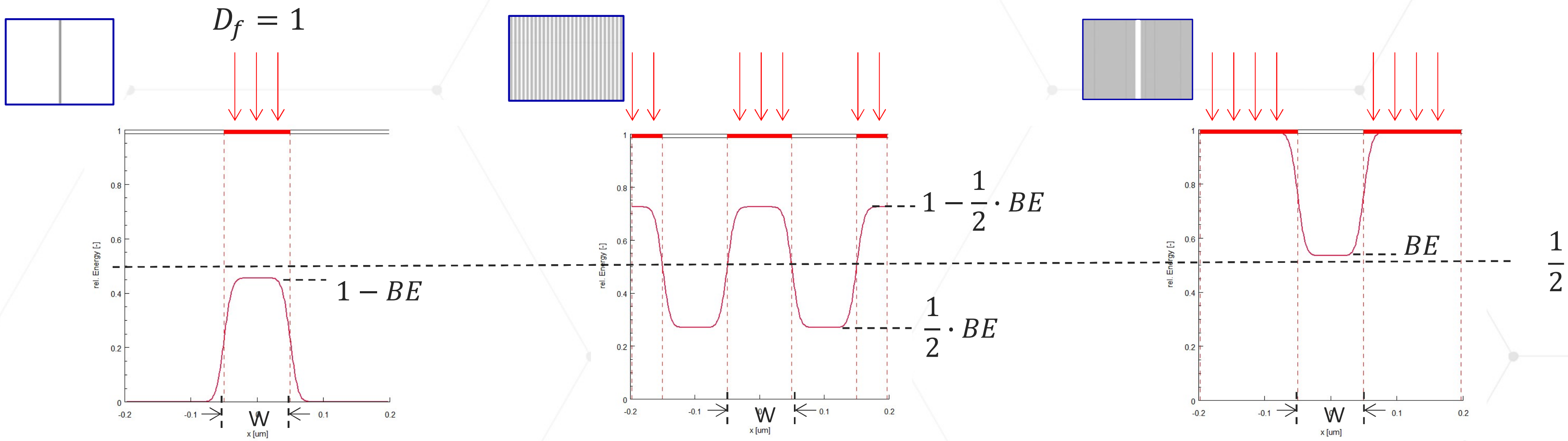
e^- in gaps cannot be „sucked out“

would require positrons…

- Proximity Effect (Blur) is like a diffusion.
- Due to “information loss” the process can not be inverted!

- Prior linear (convolution based) PEC approaches, e.g. Ghost, deconvolution had shortcomings.
- So the more generic goal of PEC becomes the equalization of dose discrepancies across the layout.
- The correction result strongly depends on a thoroughly chosen target definition.
- Subsequently the (non-linear) <u>edge equalization</u> target PEC is discussed.

Three limiting cases illustrating the proximity effect



Case 1. Narrow line (w << β) Case 2. Lines & Spaces (50%) Case 3. Narrow gap (w << β)

Fig. Three limiting cases illustrating the proximity effect. Pavkovic, j: Vac. Sci. Technol. B 4 (1), 86

- Glossary:
  - BE: Backscattered Energy
  - FE: Forwardscattered Energy
  - BE + FE ≔ 1
  - D_f : Applied Dose Factor

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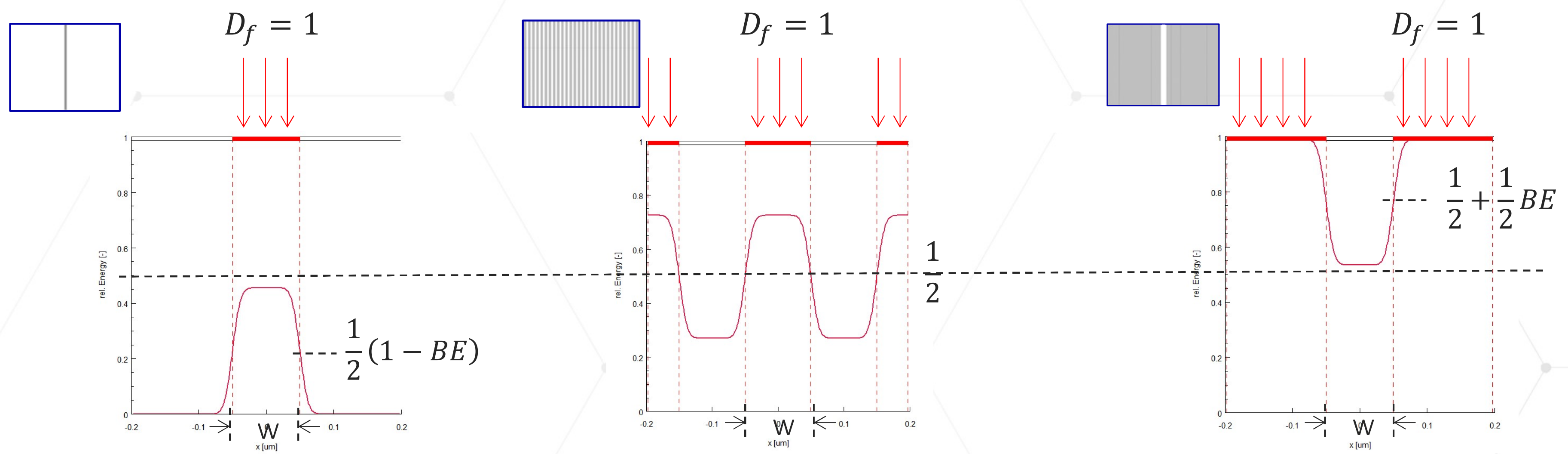
Three limiting cases illustrating the proximity effect



Case 1. Narrow line (w << β)   Case 2. Lines & Spaces (50%)   Case 3. Narrow gap (w << β)

- Glossary:
  - BE: Backscattered Energy
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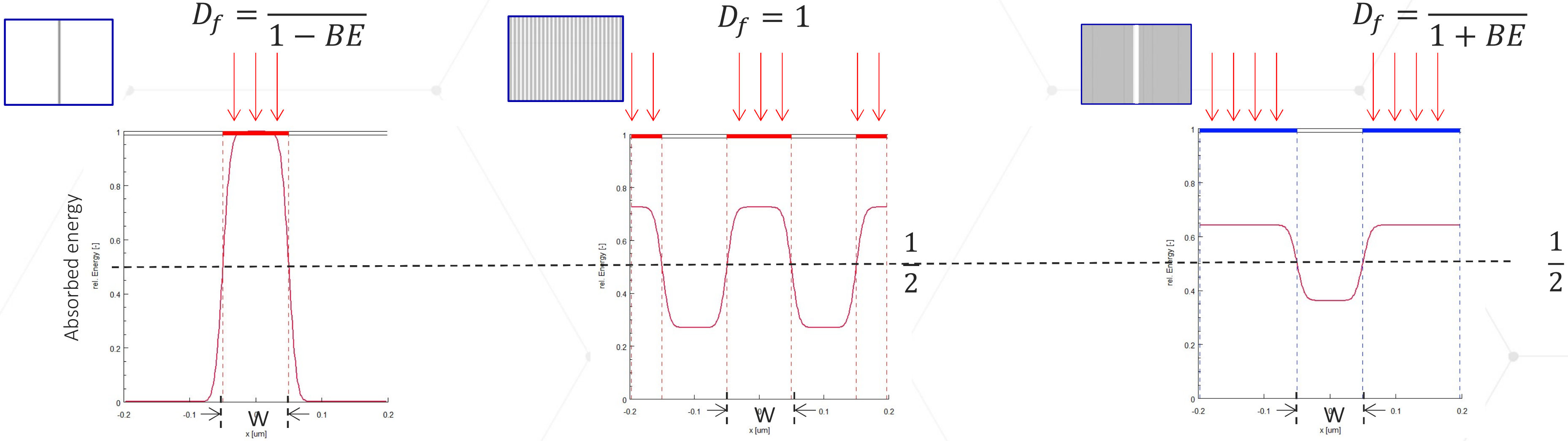
- **Edge Equalization** → Adjust the dose the way that :
  - Exposed area Dose > D2C (Dose to Clear)
  - Unexposed area Dose < D2C.
  - Target : D2C dose @ all edges

Edge Equalization is blur independent

$$D_f = \frac{1}{1 - BE} \qquad D_f = 1 \qquad D_f = \frac{1}{1 + BE}$$



Case 1. Narrow line (w << β)

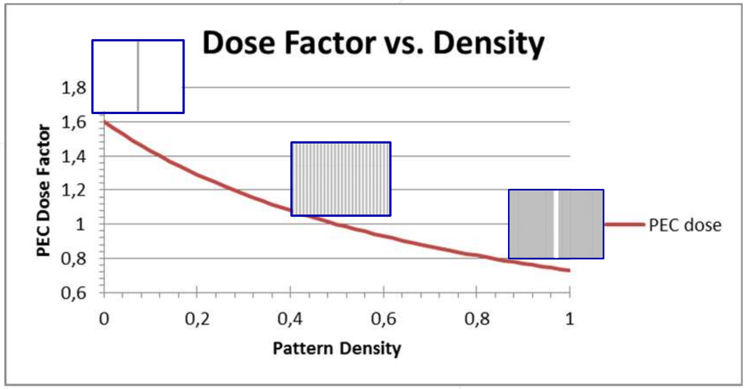
Case 2. Lines & Spaces (50%)

Case 3. Narrow gap (w << β)

NOTE: DTC @ Edge → Isofocal point!

$$D_f \cdot \left\{ \frac{1}{2} \cdot FE + \rho \cdot BE \right\} = \frac{1}{2} \quad \rightarrow \quad D_f = \frac{1}{1 + BE(2\rho - 1)}$$

ρ: *long range pattern density*



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Mix Factor

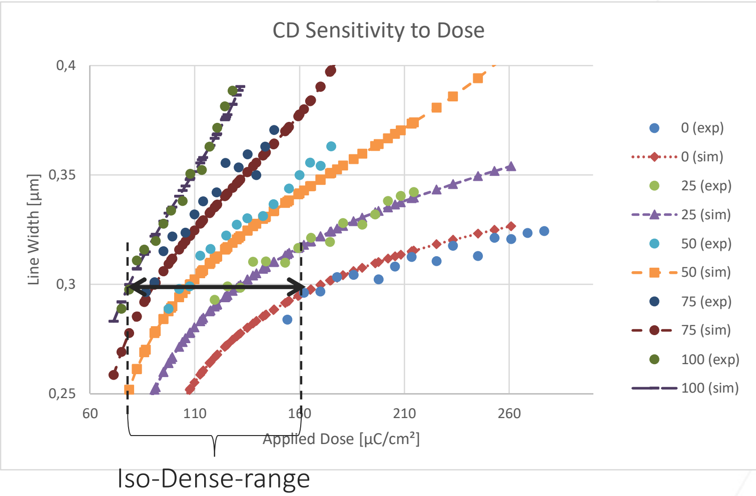
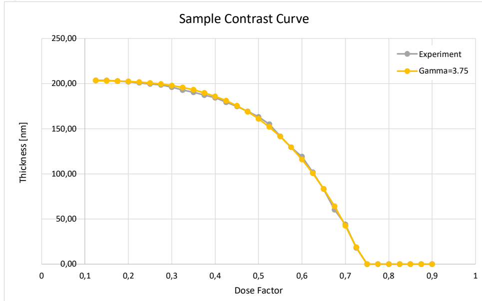


Fig. CD sensitivity to Dose. Showing the Iso to Dense dose range; By courtesy of Pennstate Univ.

- Edge equalization (iso-focal) works well for high-contrast resists
- Low contrast resists ($\gamma \leq 3$) add additional effects
  - E.g., lateral development changes CD
    - As a result, required doses change
- PEC can take into account lateral Biases
  - Alternatively, adopt dose range to process



$$\theta = \theta_0 * \left(1 - \left(\frac{D}{D_0}\right)^{\gamma}\right)$$

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

In order to make the dose range tunable the mix factor **mf** [0:1] is introduced.
0: uniform clearing
1: optimal contrast ≙ edge equalization (default)

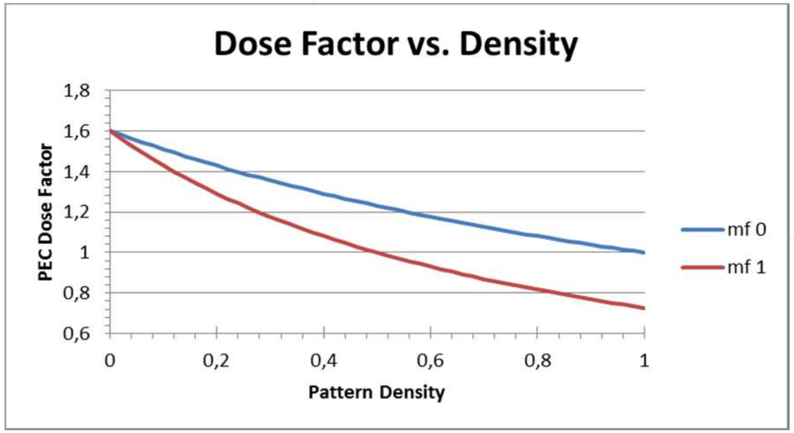


Fig. Dose factor vs. density for the limiting mix factors. (BE = 0.375)

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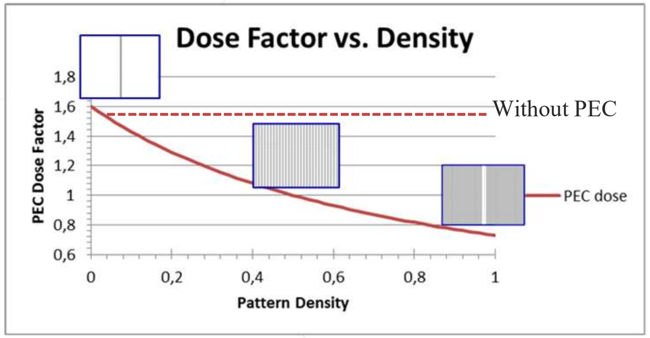
Benefits of PEC

- Process portability
  - No dose matrices for setup
  - Takes out pattern dependence
  - Easily transferable to other stacks / voltages
- CD linearity (also density dependent)
- Opens / enlarges process window
- Dose Latitude (Contrast) enhancement for sparse features
- Pixel time reduction



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  - Principle algorithm
  - Long-, Mid-, Short-Range
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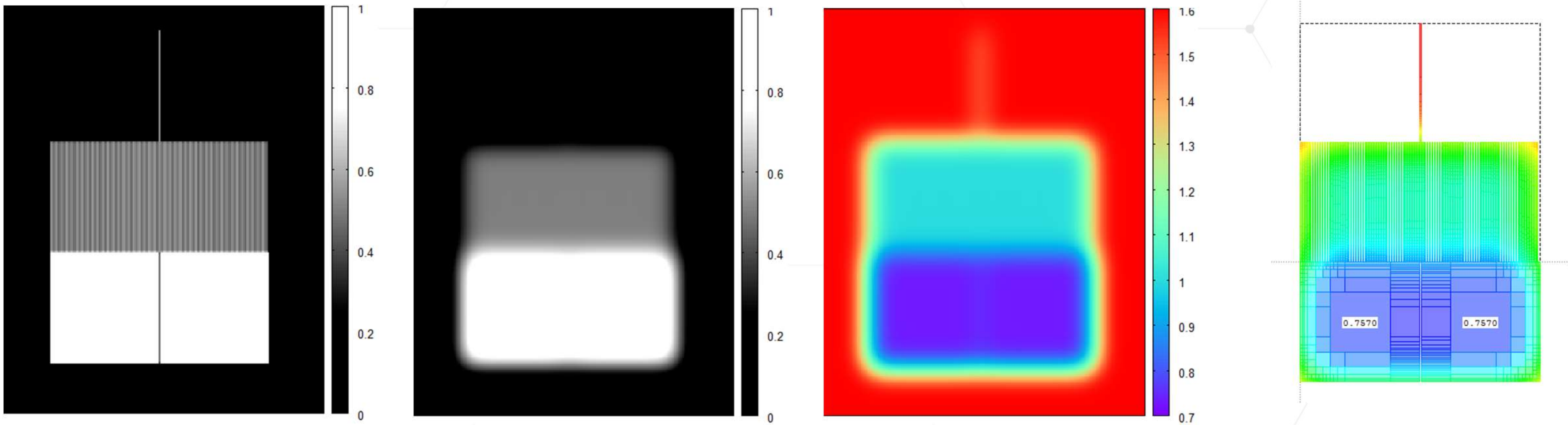
Back-Scatter PEC: Pixel Based



A. Original Layout as bitmap

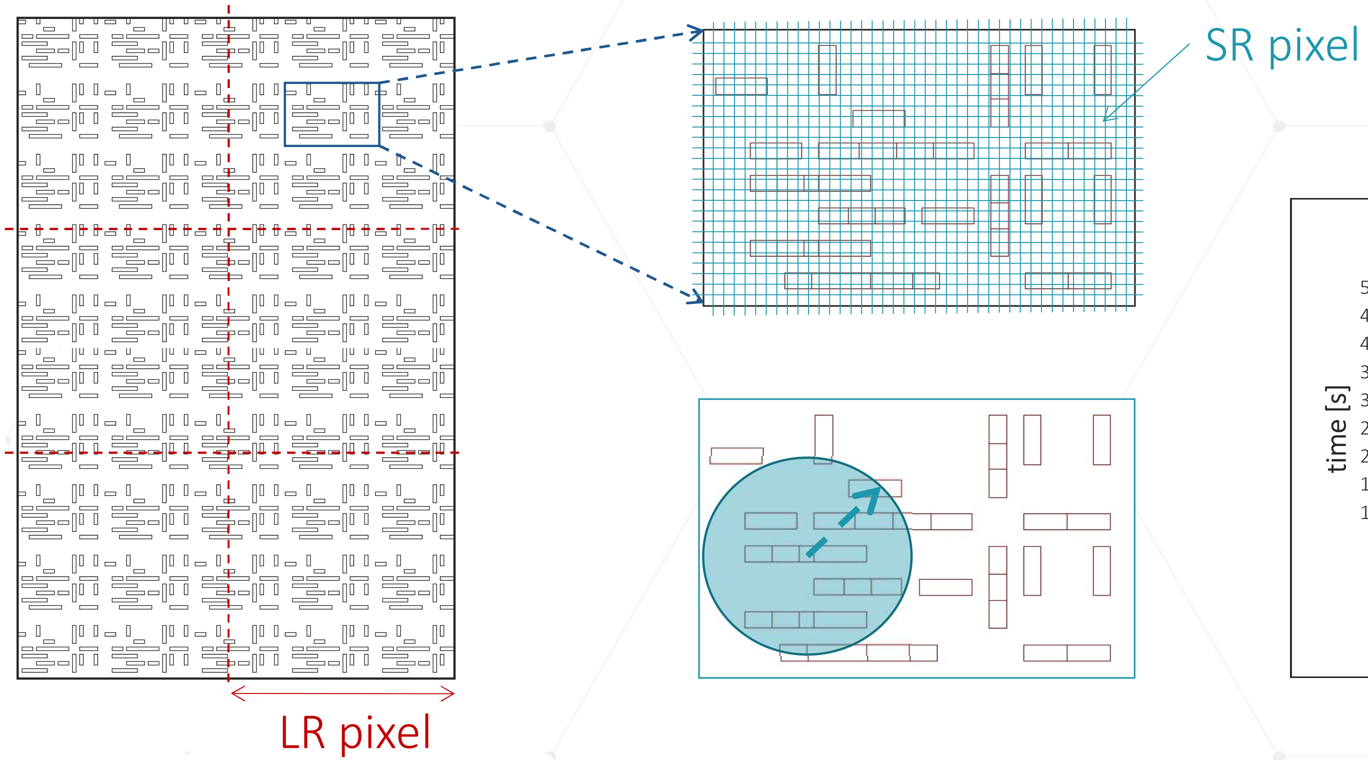
B. Convolved pattern density

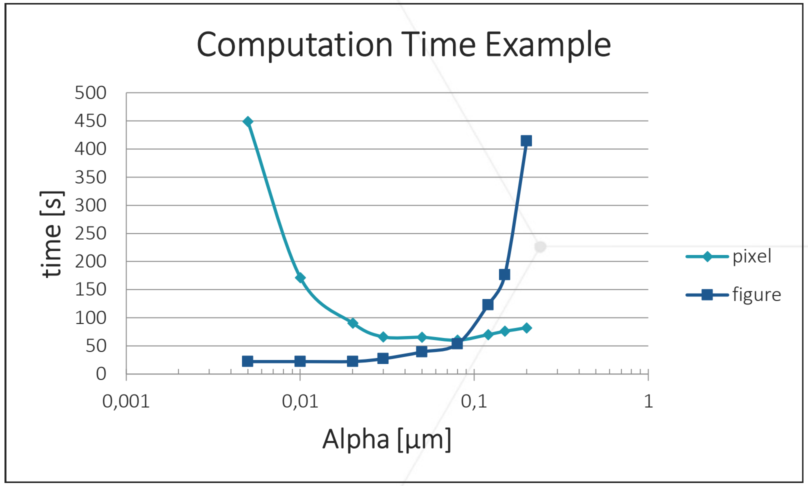
C. Correction dose map

C. Dose transfer to polygonal data including physical fracturing

- Fast (applicable to large layouts in reasonable times) -> Pixel based -> FFT
- Stable and robust
- Physical Fracturing

Influence Range ⇔ Algorithm Choice





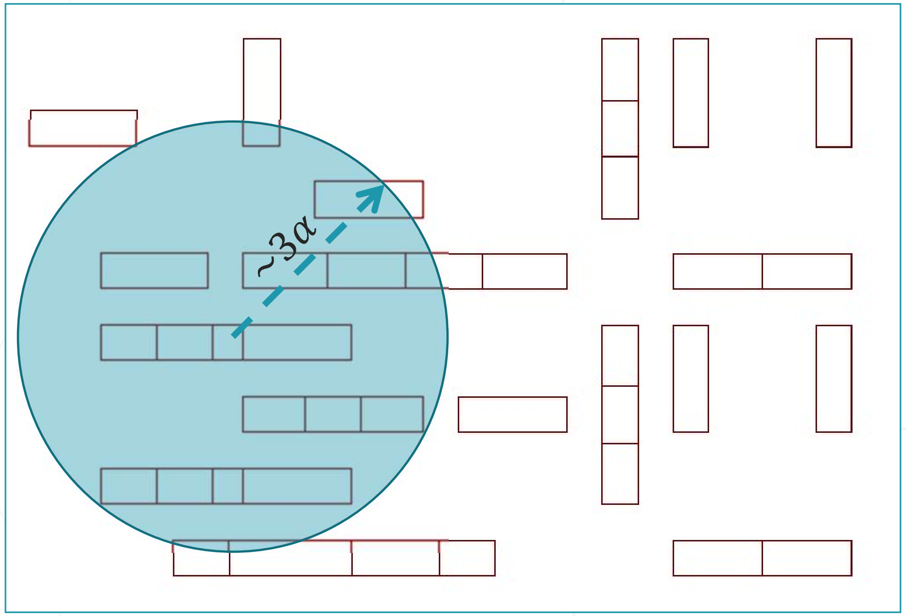
- Due to the range discrepancy the required SR pixel size would be ~1/1000 compared to LR!
- Complexity increase: 1000^2

- Conclusion: SR pixel based computations are feasible only for simulation of small samples but not for PEC.

Fig. PEC test runs, measured performance for pixel- and figure based algorithms.
Variable alpha parameter, beta = 30µm, eta = 0.6, Beam-blur 0.01µm.
Design: Array of 375000 squares of 0.024µm width.

Short Range PEC

- Using a self consistent method for the compensation of the short range effect is favorable as the complexity is proportional to the average neighbor count (ANC) which is per se small in a short range vicinity.
- Complexity: O(N * ANC(α))
- In order to boost performance a DRC is performed to identify SR PEC relevant areas.



- Mid Range (MR) PEC is the computationally most challenging.
  - If feasible it is included either in SR or LR.
  - If not it is performed on a finer grid.

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  - PSF selection, Base Dose, Effective Blur
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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 [1)]
- 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

- Dose Error
  - Influence of a dose deviation on an edge position: extracted from the computed edge position shift.
  - According to the linear edge model the CD error can be approximated by:
  - ΔCD = (FWHM / 0.76) Δ%dose [1)]
    - Example: ΔCD = (50nm / 0.76) * 3% = 2nm
- Please note: reducing dose accuracy for 2D PEC might even improve results
  - CD change can be minimal (see formula)
  - Especially consider to avoid MR parts if the contribution is small

- Remark 1: the 0.76 factor is the same factor used for spot size measurements: 12% - 88% (the difference is 0.76)
  - Background: the 12-88% point of an Erf() function is the FWHM of the corresponding Gaussian

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Summary

- Always use PEC
  - No dose matrices needed, applicable for all patterns, ...
  - Opens/enlarges process window
- Edge equalization is an efficient and robust method
  - Iso-focal criteria provides best CD control also at field corners / edges
- PEC influence ranges
  - SR, LR and MR PSF parts treated differently (computational complexity)
- Basic parameters pretty simple: PSF, Effective Blur, Base Dose
- Low Contrast Resist processes may require adoption of dose range D_{iso}/D_{dense}
  - Mixed Mode: Optimal Contrast / Uniform Clearing