GenISys
Advancing the Standard

Ulrich Hofmann, Nezih Ünal

October 7th, 2020

Proximity Effect in E-Beam Lithography

Overview and Agenda

BEAMER LAB TRACER ProSEM MASKER

GenISys
Advancing the Standard

Webinar Outline

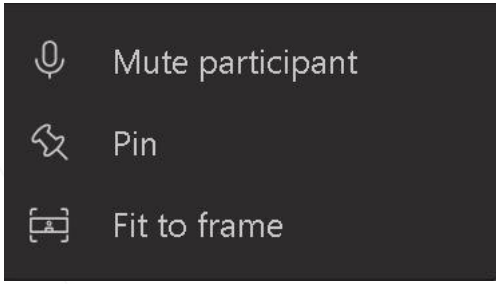
Part	Subject	Date
1	Electron Scattering and Proximity Effect	07-Oct-2020, 6:00pm CEST, 12:00pm EDT, 9:00am PDT
2	Dose PEC Algorithm and Parameter	14-Oct-2020, 6:00pm CEST, 12:00pm EDT, 9:00am PDT
3	Optimization of Dose PEC Parameter	21-Oct-2020, 6:00pm CEST, 12:00pm EDT, 9:00am PDT
4	Process Effect, 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…

GenISys
Advancing the Standard

Pre-Cursor

- IMPORTANT NOTICE: Please note that this session will be recorded. By joining these webinar sessions, you automatically consent to such recordings. If you do not consent to being recorded, do not join the session.
    - Q&A will not be recorded
- MS Teams essentials (App Users):
    - Right click on image, use „Pin“ to enlarge



- This webinar/session is an overview/introduction
    - It picks out essential ingredients
    - In case you want / need more depth -> let us know

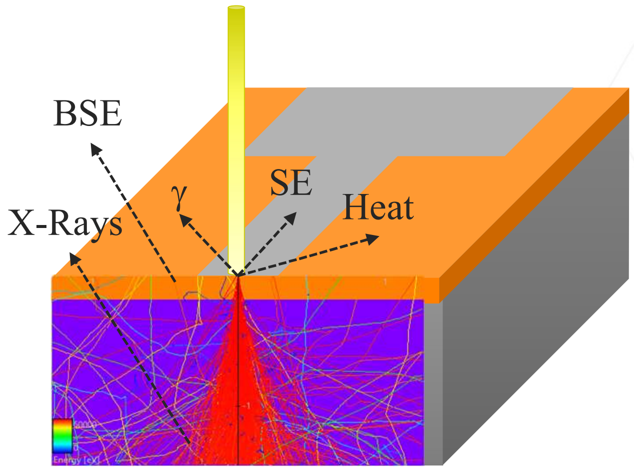
Ulrich Hofmann, Nezih Ünal
April 29th, 2020

Proximity Effect in E-Beam Lithography

Part 1: Electron Scattering & Proximity Effect

BEAMER LAB TRACER ProSEM MASKER

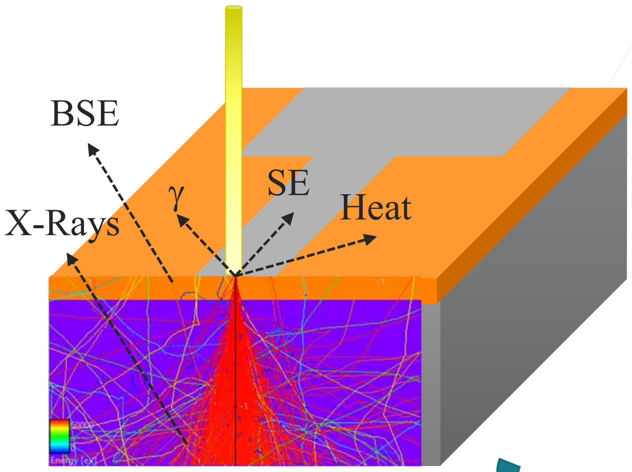
How an E-Beam transforms to structures

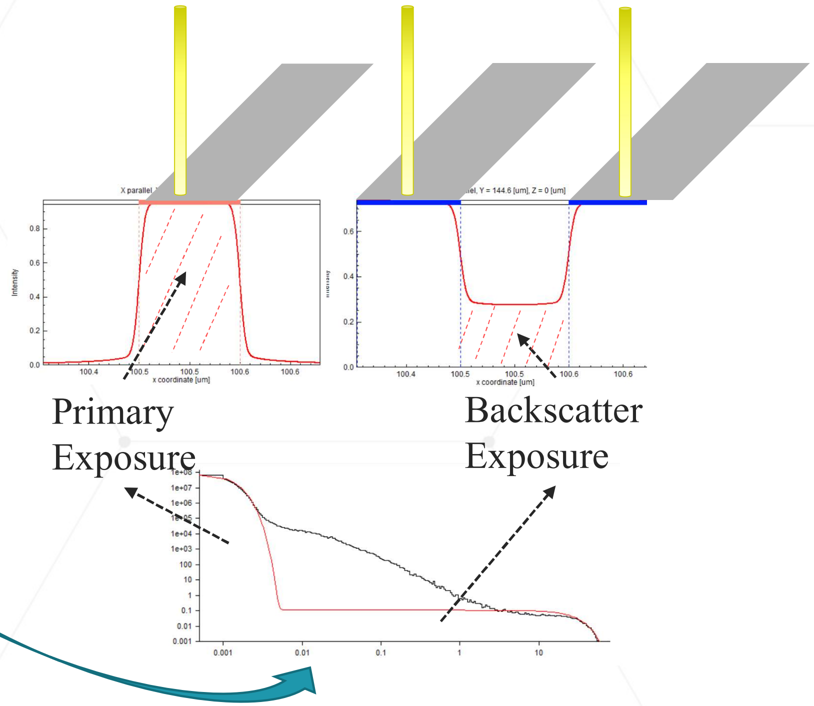


Electrons hit sample

- Exposure from primary electrons
- Exposure from backscattered electrons
- SE's, Heat, X-Rays, Photons, …
  - Elastic + inelastic scattering

How an E-Beam transforms to structures





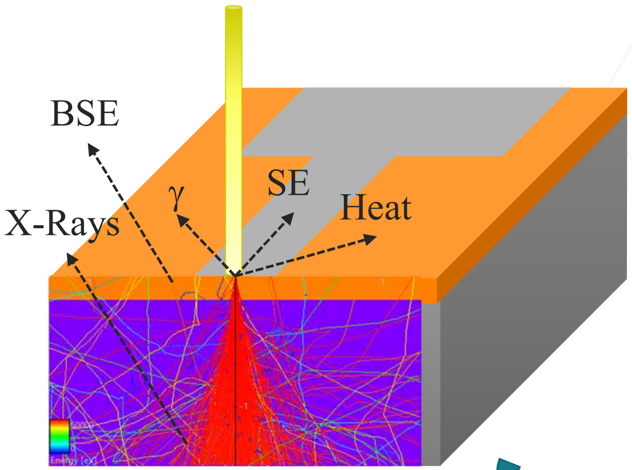
Electrons hit sample

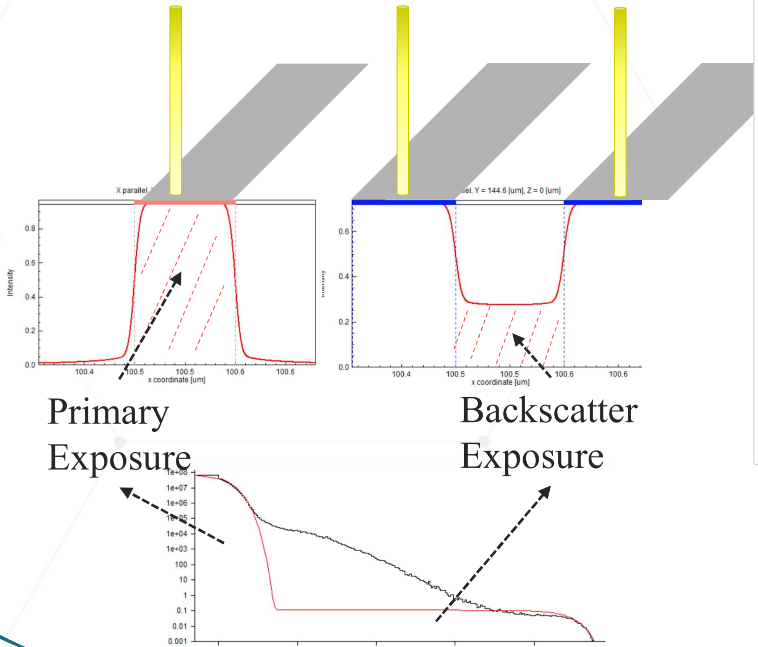
- Exposure from primary electrons
- Exposure from backscattered electrons
- SE's, Heat, X-Rays, Photons, …
  - Elastic + inelastic scattering

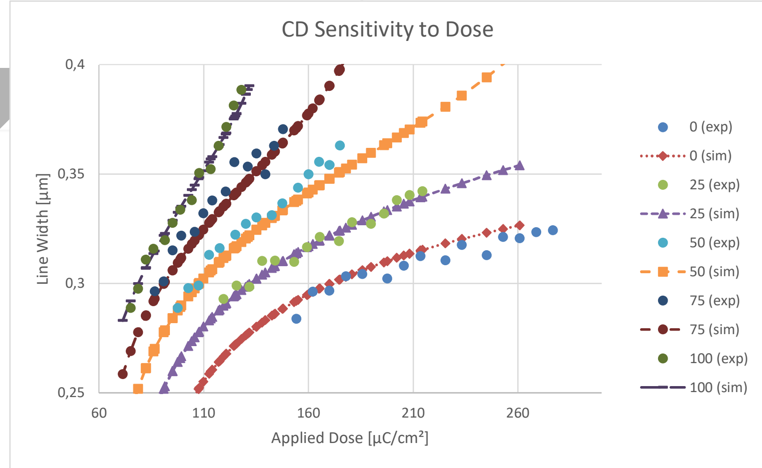
Energy deposition

- Local (primary exposure)
- Proximity (backscattering)

How an E-Beam transforms to structures







Courtesy Pennstate University[3]

Electrons hit sample

- Exposure from primary electrons
- Exposure from backscattered electrons
- SE's, Heat, X-Rays, Photons, …
  - Elastic + inelastic scattering

Energy deposition

- Local (primary exposure)
- Proximity (backscattering)

Printed Features

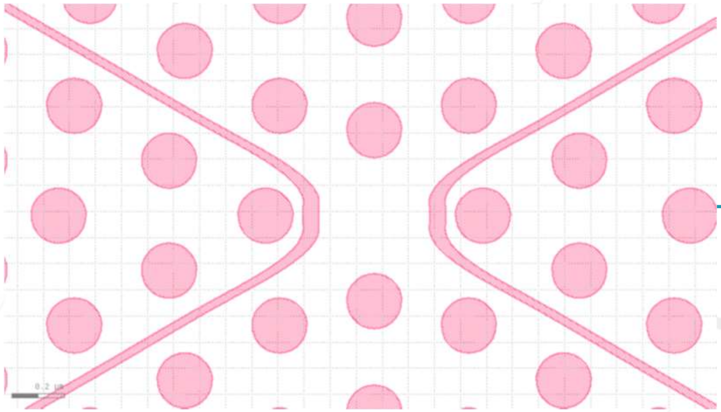
- CD = f(Dose, Density)
- Iso-features require more dose
- Dense features at degraded EL

Scattering → Energy Deposition → Printed Feature

GenISys
Advancing the Standard

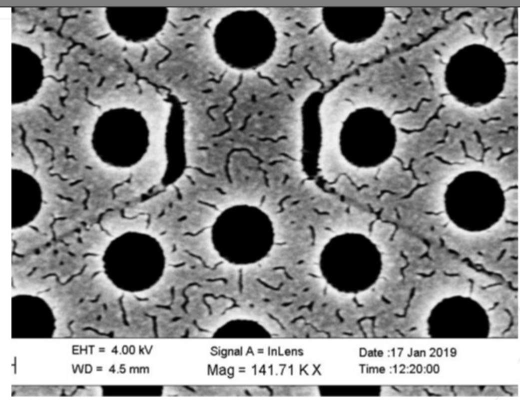
Problem Statement

What you want



E-Beam
Small Spot

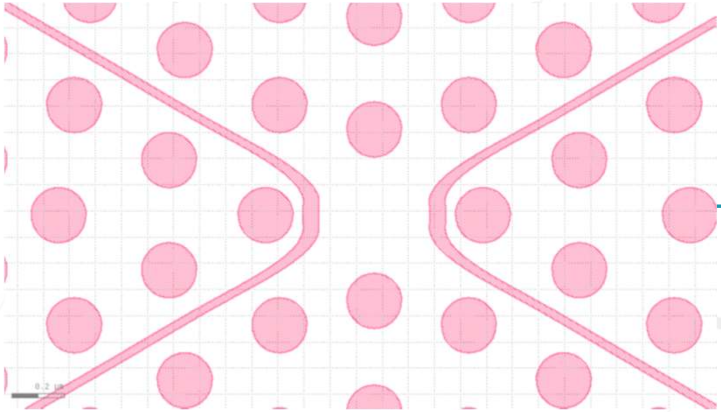
What you get



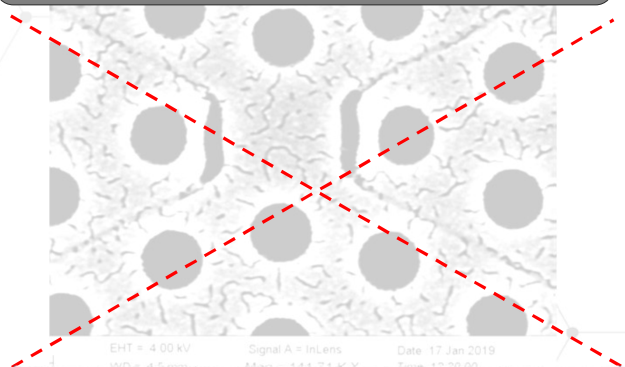
Courtesy University of British Columbia[2]

Problem Solved

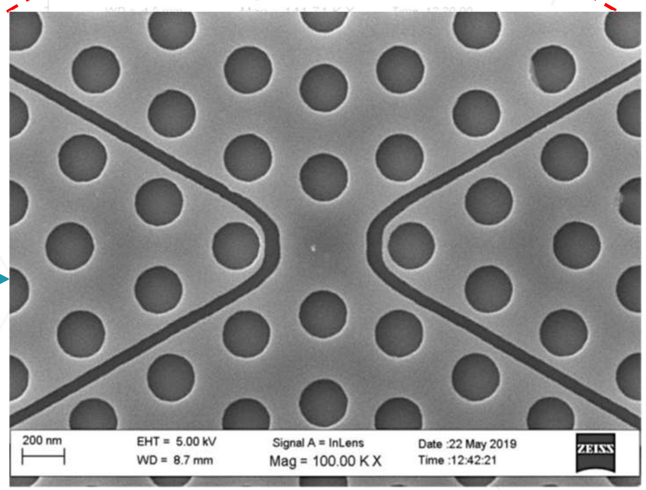
What you want



What you get



E-Beam
PEC



Courtesy University of British Columbia[2]

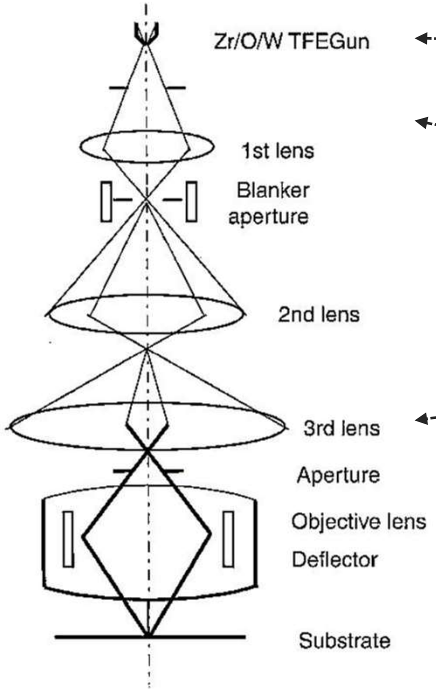
GenISys
Advancing the Standard

Outline

- E-Beam Lithography Primer
  - Beam Forming: Tool
  - Exposure: Electron Solid Interactions
  - Process: Resist Response
- Monte Carlo Simulation with TRACER
- Simulation of Proximity Effect
- Proximity Effect Correction
- Summary
- Q&A

Shaping Strategies

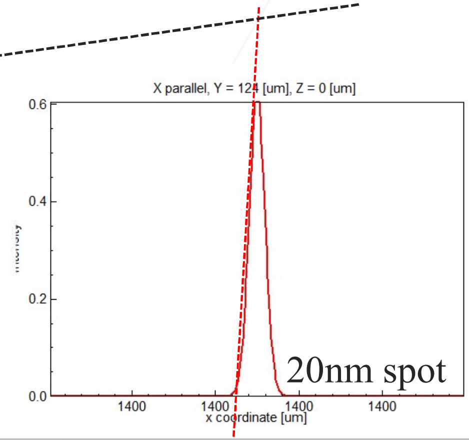
Gaussian (GB) e-beam writer | Variable-shaped (VSB) e-beam writer

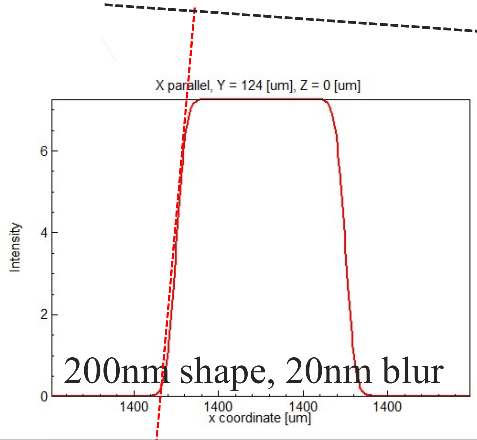


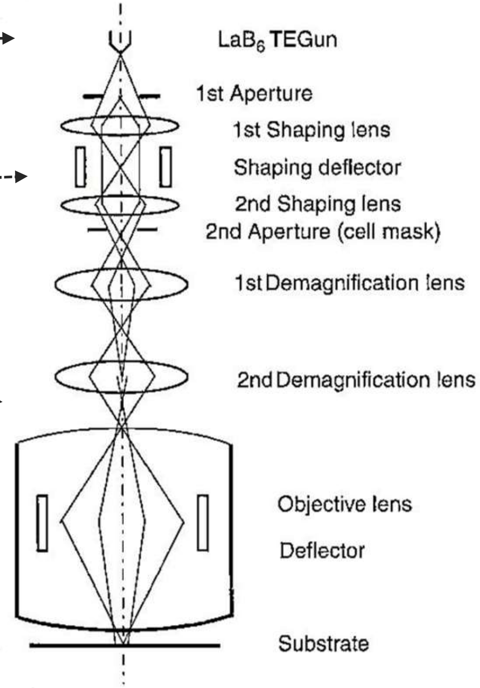
Source

Beam Shaping

Optics



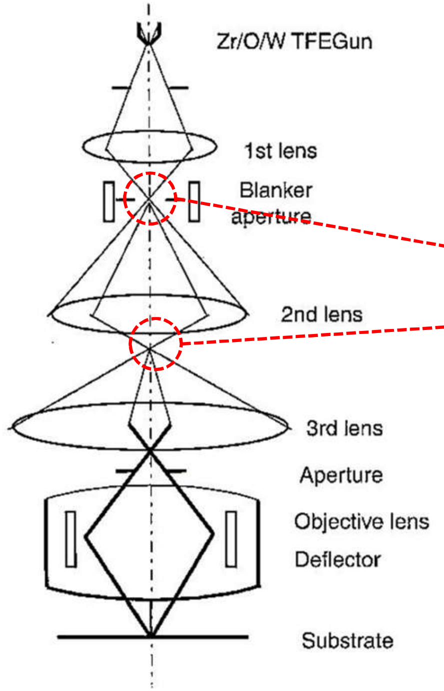




Spot Size / Blur have profound influence on lithography

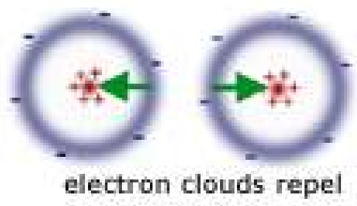
Spot Size / Blur Limitations

Gaussian (GB) e-beam writer

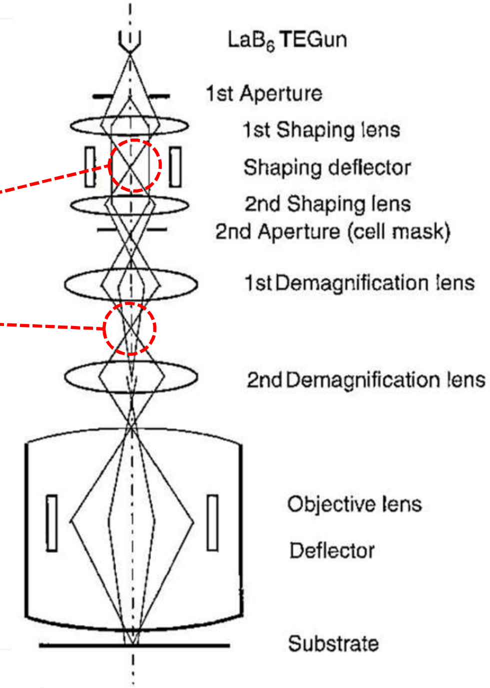


Fundamental issue:
cross-overs

Electrons repel
(more electrons
more repulsion)



Variable-shaped (VSB) e-beam writer

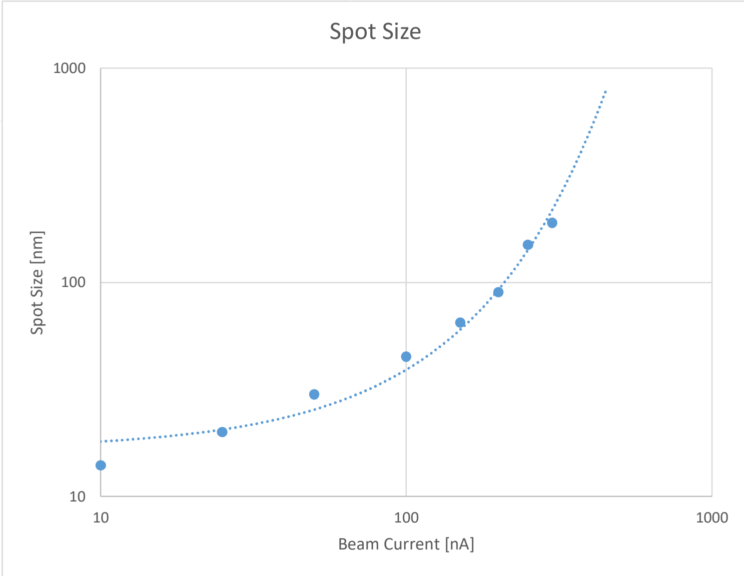


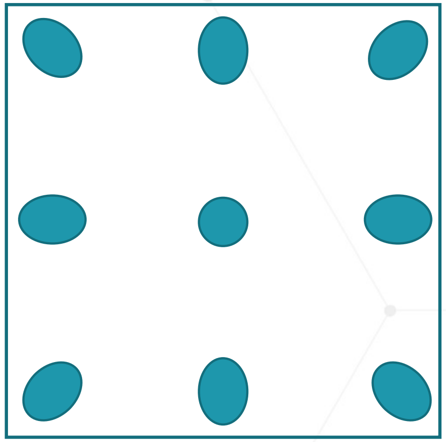
Higher current ⇒ larger blur / spotsize

Spot Size / Blur

- Best Spot Size (field center) depends on
  - Beam Current
  - Beam Forming Aperture
  - Acceleration voltage, Column Design

- Spot Size/Shape varies within field
  - Strongest without dynamic focus / stigmation

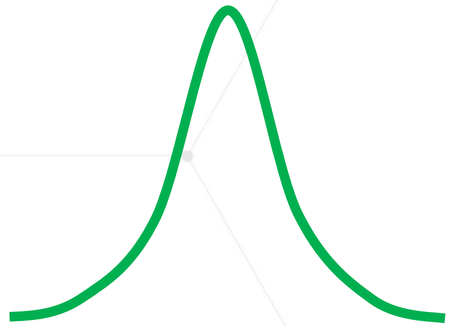




Spot grows with Beam Current and changes with position in field

Why is Spot Size / Blur So Important

- A Spot Beam has 3 degrees of freedom

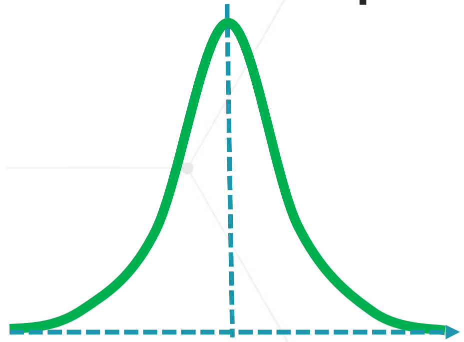


GenISys
Advancing the Standard

Why is Spot Size / Blur So Important

- A Spot Beam has 3 degrees of freedom

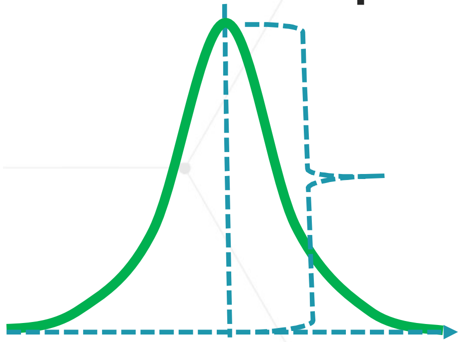
Positional /CD Errors
Settling Errors (DAC, eddy currents)
Vibration, Noise
Position Drift (Stitching)
Process Bias
Over/under-etch



Why is Spot Size / Blur So Important

- A Spot Beam has 3 degrees of freedom

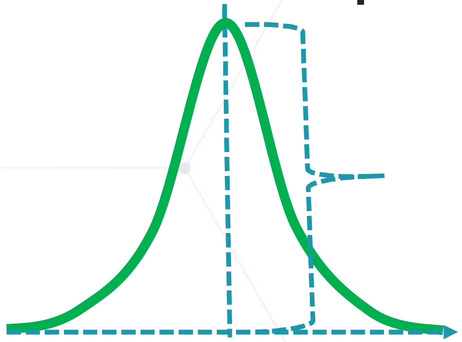
Positional /CD Errors	Dose Errors
Settling Errors (DAC, eddy currents)	Current drift
Vibration, Noise	Dwell time errors
Position Drift (Stitching)	
Process Bias	Electron scattering, fogging
Over/under-etch	Resist thickness variations



Why is Spot Size / Blur So Important

- A Spot Beam has 3 degrees of freedom

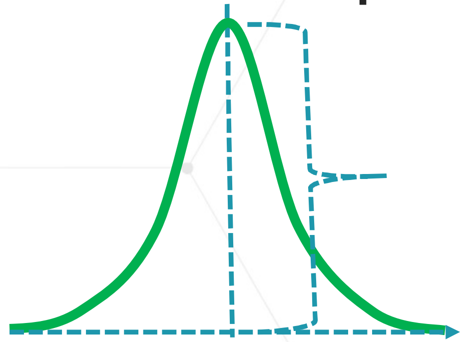
Positional /CD Errors	Dose Errors	Shape Errors
Settling Errors (DAC, eddy currents)	Current drift	Aberrations
Vibration, Noise	Dwell time errors	Distortions
Position Drift (Stitching)		Defocus
Process Bias	Electron scattering, fogging	
Over/under-etch	Resist thickness variations	



GenISys
Advancing the Standard

Why is Spot Size / Blur So Important

- A Spot Beam has 3 degrees of freedom



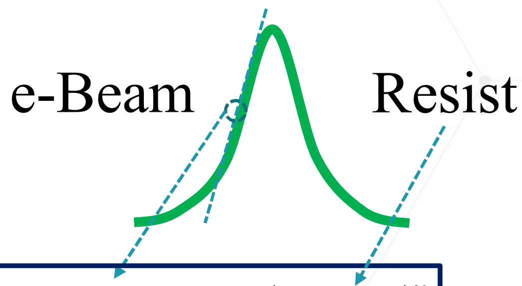
Positional /CD Errors	Dose Errors	Shape Errors
Settling Errors (DAC, eddy currents)	Current drift	Aberrations
Vibration, Noise	Dwell time errors	Distortions
Position Drift (Stitching)		Defocus
Process Bias	Electron scattering, fogging	
Over/under-etch	Resist thickness variations	

Dose / Shape Errors are coupled to CD errors

Larger Spot/Blur translates given Dose / Shape Errors into larger CD Errors

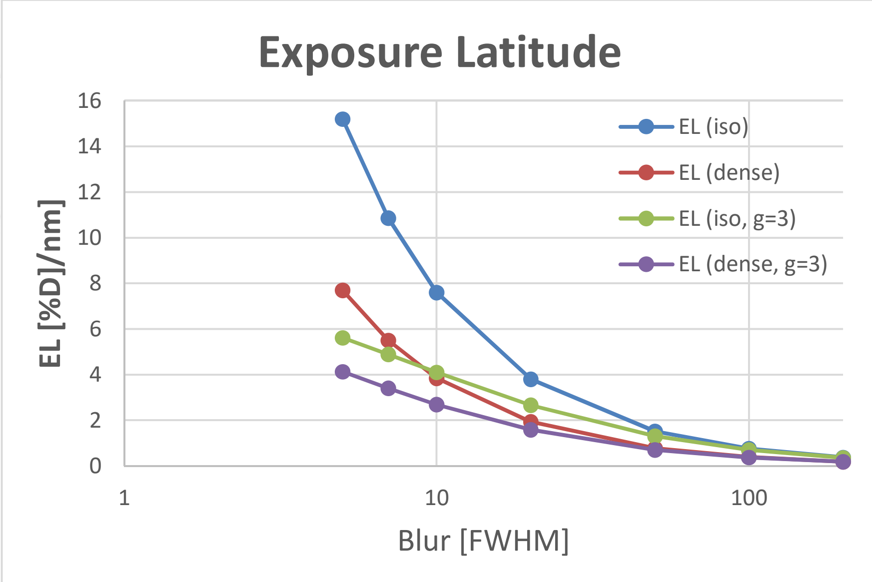
Reverse Thinking: Exposure Latitude

- Exposure Latitude is the allowed dose error for a given CD error (e.g. 10%)
  - Dose Errors from source stability (~ 1%), scattering, resist thickness fluctuations, …
  - To get 10% EL for ± 1nm CD variation, one needs a blur < 7nm for iso features
    - For lower-contrast resists (e.g. γ=3), one can only get 5% EL/nm



$$\frac{1}{EL} \approx \frac{2}{ILS} + 2\gamma\Theta \left| \frac{E_{edge}}{E_{center}} \right|^{\gamma}$$

C.Mack: LPM

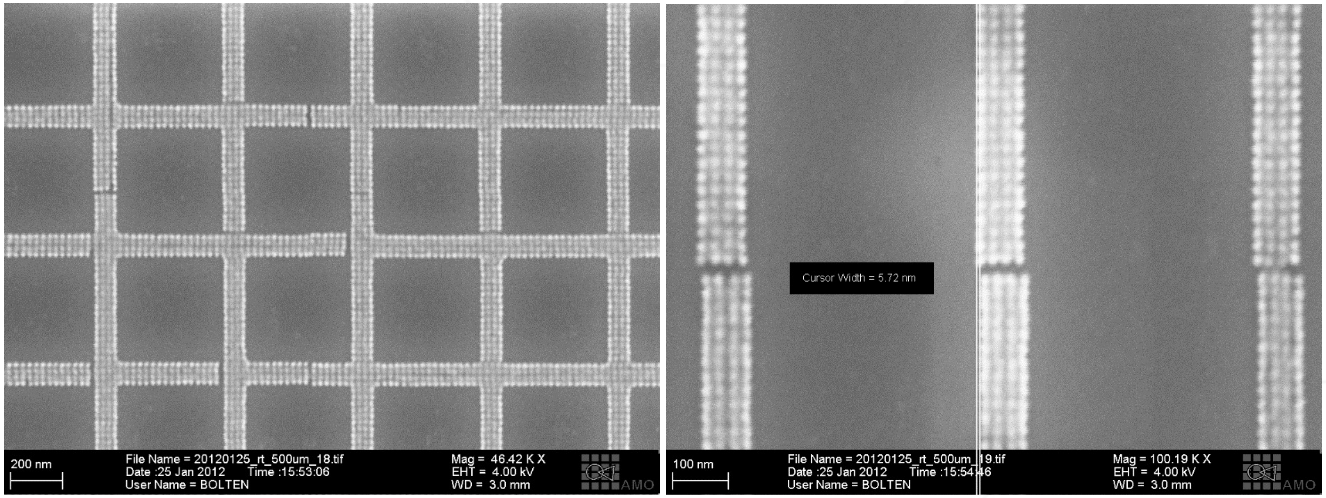


Note: this is why people think „a smaller spot is better“

Small Blur / Small Spot Drawbacks

- Throughput Hit
  - Exposure Time = Dose * Area / I
    - Exposing a 2.5 cm² waveguide at 1nA (200µC/cm² resist) would require 6 days…
    - Exposing a 2.5 cm² waveguide at 50nA (200µC/cm² resist) requires 3 hours

- Positional errors are (im-)printed directly



Courtesy AMO GmbH

Larger spots mitigate positional errors (blurring into adjacent structures)

Spot Size Tradeoffs

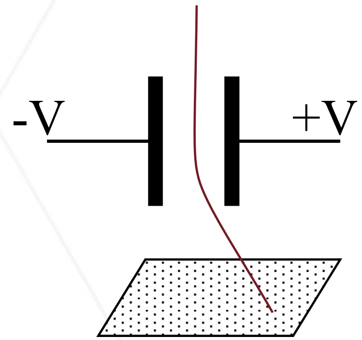
Quality Criteria	Smaller Blur / Spot Size	Larger Blur / Spot Size
Resolution	↑	↓
CD Control / Exposure Latitude	↑	→
LER, LWR	↓	↑
Positional Accuracy	↓	↑
Write Time	↓	↑

- Choice of spot size is application dependent
  - Small spot is better only if small features are required and resist resolution is adequate
    - A small spot does not imply an equally good exposure latitude
    - For low-γ resists, the incremental gain of smaller spots is small
  - Large photonic crystals are better when NOT using the smallest spot
    - Positional accuracy most important

Exposure Latitude at larger spots mitigated through corrections (PEC, …)

Beam Position / Beam Jitter

- Example: e-Beam electrostatic deflectors
  - A voltage V corresponds to a (desired) position
  - ~100 µV voltage difference between two adjacent positions
    - For practical reasons, the voltage swing is ~100V
    - 1nm positional accuracy within a 1mm field means 10^6 positions



  - Every metal is an antenna and picks up > 1mV...
    - Even in a perfectly shielded room, there is 50/60 Hz noise from power supplies, pumps, ...
  - In other words, the beam is **never** where it is intended to be...
- Similar arguments can be constructed for the other deflection options

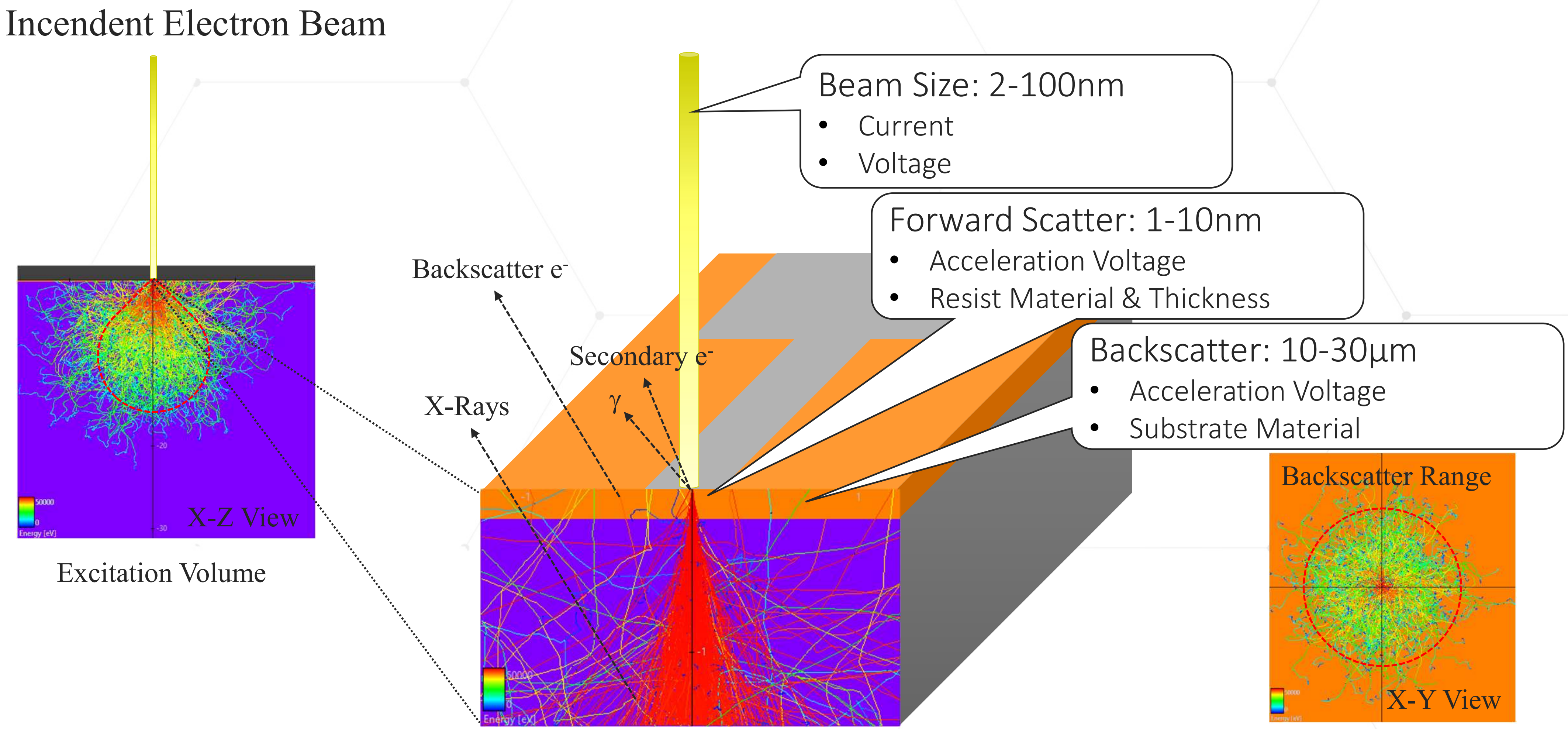
Noise creates Beam Jitter, effectively broadening the Beam

GenISys
Advancing the Standard

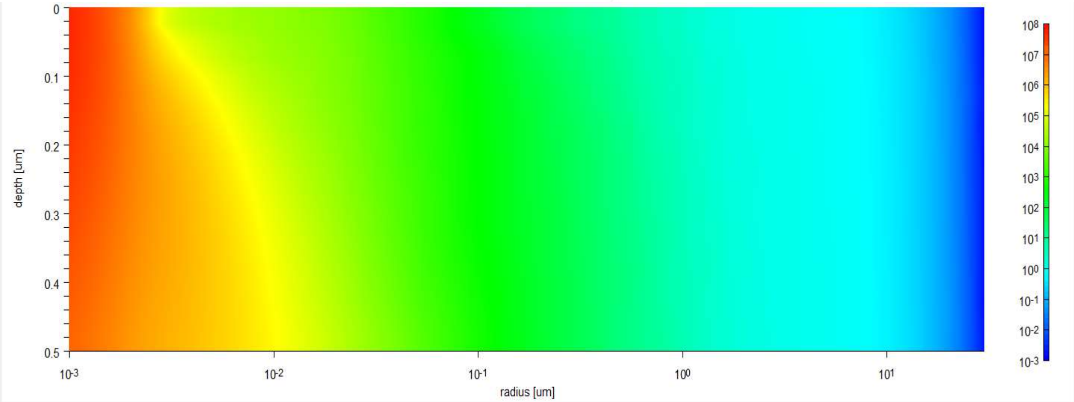
Outline

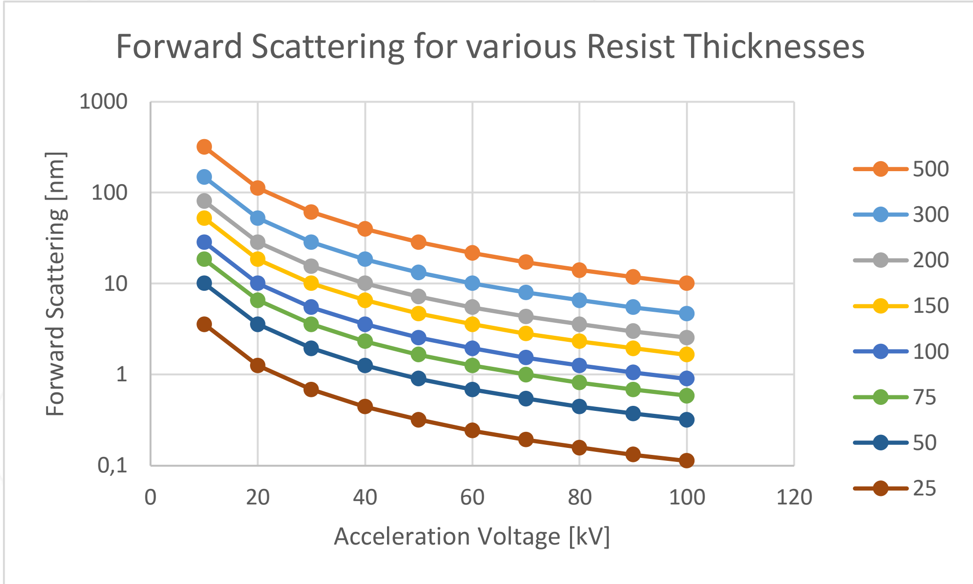
- E-Beam Lithography Primer
  - Beam Forming: Tool
  - Exposure: Electron Solid Interactions
  - Process: Resist Response
- Monte Carlo Simulation with TRACER
- Simulation of Proximity Effect
- Proximity Effect Correction
- Summary
- Q&A

Electron-Solid Interactions



Forward Scattering

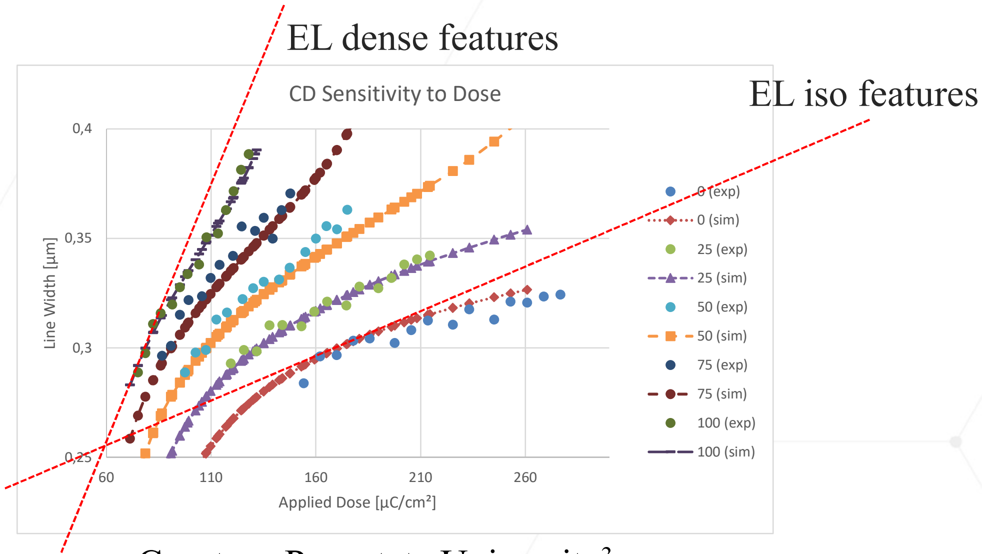




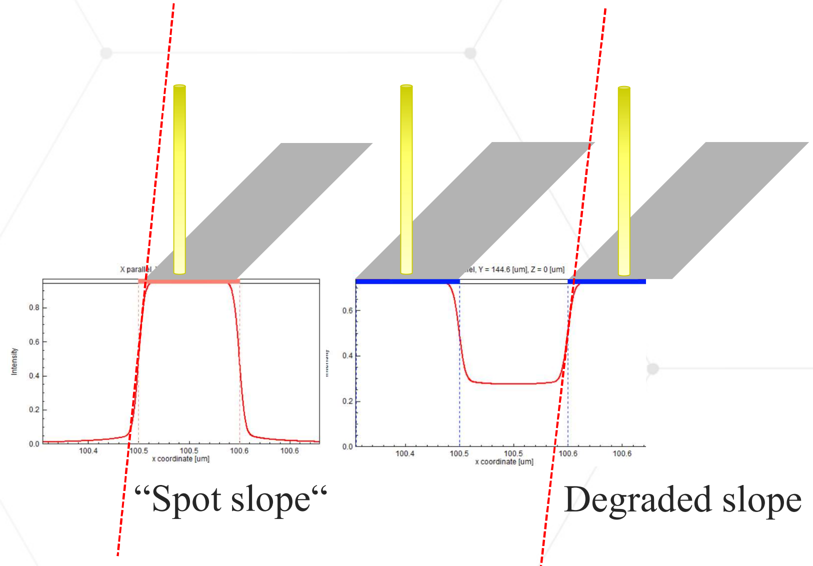
- Forward Scattering (~ $(\theta / V_{acc})^{1.5}$) blurs the beam further in z:
  - Stronger with thicker resists (θ: resist thickness)
  - Higher beam voltage V_{acc} reduces this somewhat

GenISys
Advancing the Standard

Backscattering



Courtesy Pennstate University[3]

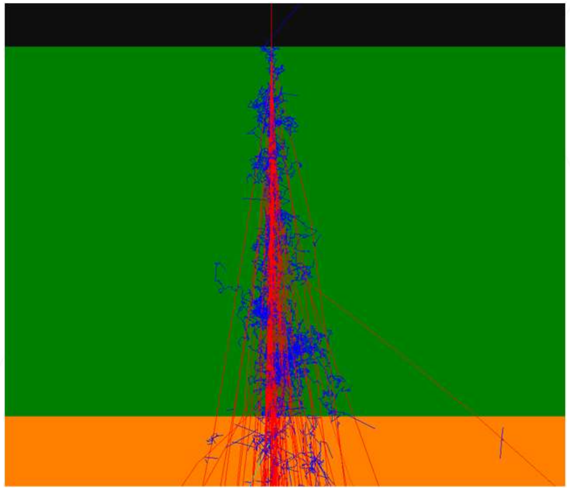


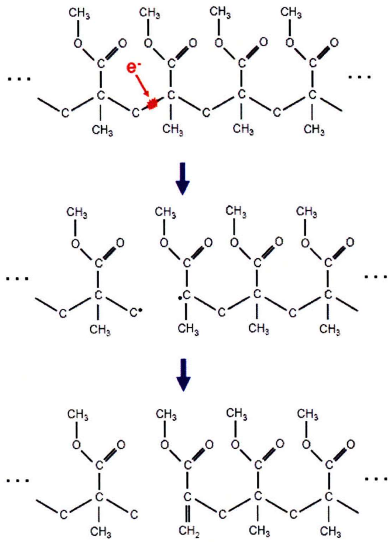
- Sounds surprising: backscattering also contributes to effective blur
  - The different Exposure Latitudes between iso- and dense features are indicative
  - Slopes in absorbed energy profile are different
    - (const background + spot) has different slope than (spot)

Outline

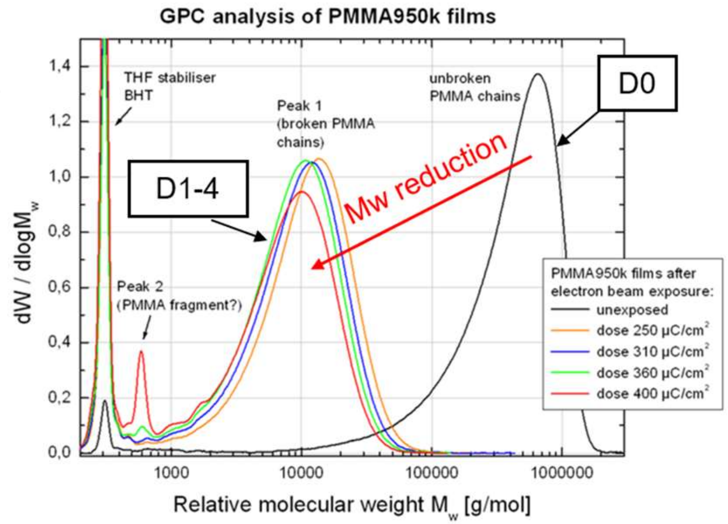
- E-Beam Lithography Primer
  - Beam Forming: Tool
  - Exposure: Electron Solid Interactions
  - Process: Resist Response
- Monte Carlo Simulation with TRACER
- Simulation of Proximity Effect
- Proximity Effect Correction
- Summary
- Q&A

Exposure Mechanisms





PMMA scission, Alexander et al.[5]



Courtesy of Paul Scherrer Institute[6]

- For positive resists, generated secondary electrons break bonds
  - Mean Free Path for 100eV electrons is ~nm; Total travel distance 1-5nm
  - This is why Monte Carlo Tracing of Primary Electrons is a good indicator
    - Side Note: material density is the only parameter required for accurate enough Monte Carlo

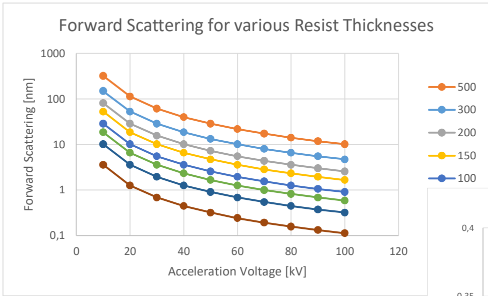
- Development then washes the shorter chains (more soluble) away

Total Effective Blur

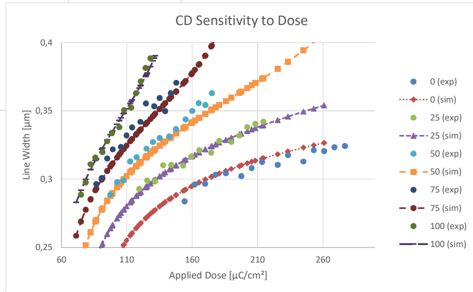
- $Spot_{eff} = Spot_{Beam}$ ← depends on current, 2-100nm

⊗ Jitter ← noise dominated

⊗ Forward Scattering ← 1-10nm



⊗ Back Scattering ← reduced EL for dense



⊗ Resist Effects ← diffusion, lateral development, …

Development, Scattering and Beam Jitter typically dominate over native Beam Size

References

1. McCord MA, Rooks M. Electron beam lithography. In: Rai-Choudury P, editor. Handbook of microlithography, micromachining and microfabrication, vol. 1. Bellingham: SPIE; 1997. ISBN 978-081-942-378-8.
2. Kashif Masud Awan and Gerald Lopez, Photonic Device Patterning Optimization, BEAMeeting at EIPBN 2019
3. Gerald G. Lopez, Glen De Villafranca, Mohsen Azadi, Meredith G. Metzler, Kevin Lister, Michael Labella, Chad Eichfeld, Nikola Belic, Ulrich Hofmann, On the trends and application of pattern density dependent isofocal dose of positive resists for 100 keV electron beam lithography, JOURNAL OF VACUUM SCIENCE & TECHNOLOGY B; NOV 2018, 36 6, 13p.
4. J. Bolten, C. Manecke, T. Wahlbrink, M. Waldow, and H. Kukz, ‘At low costs: Study on optical propagation losses of silicon waveguides fabricated by electron beam lithography’, Microelectronic Engineering, vol. 123, pp. 1–3, Jul. 2014
5. P.Alexander, R.M.Black, A.Charlesby, Proc.Royal Soc. (London) A320, 136 (1955)
6. Schleunitz, Arne & Guzenko, Vitaliy & Messerschmidt, Martin & Atasoy, Hakan & Kirchner, Robert & Schift, Helmut. (2014). Novel 3D micro- and nanofabrication method using thermally activated selective topography equilibration (TASTE) of polymers. Nano Convergence. 1. 7. 10.1186/s40580-014-0007-5.

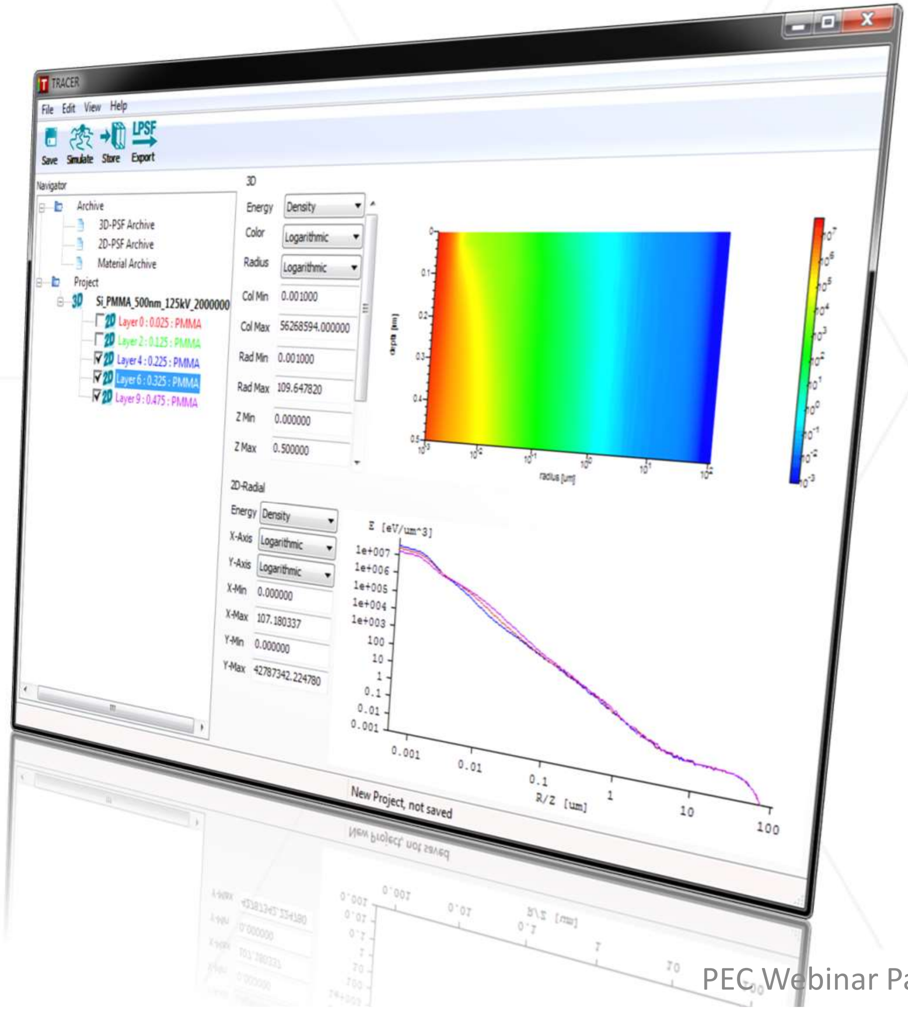
7. Raith GmbH, www.raith.com/products
8. Jeol Electron Beam Lithography, www.jeol.co.jp/en/products
9. Elionix, www.elionix.co.jp/english/products
10. Crestec, www.crestec8.co.jp/index_en/business_en/
11. Advantest, www.advantest.com/products/e-beam-lithography
12. Vistec electron beam GmbH, www.vistec-semi.com

Outline

- E-Beam Lithography Primer
- Monte Carlo Simulation with TRACER
  - Material Database
  - Stack Definition
  - Acceleration Voltage
  - Sensitivity Analysis
- Simulation of Proximity Effect
- Proximity Effect Correction
- Summary
- Q&A

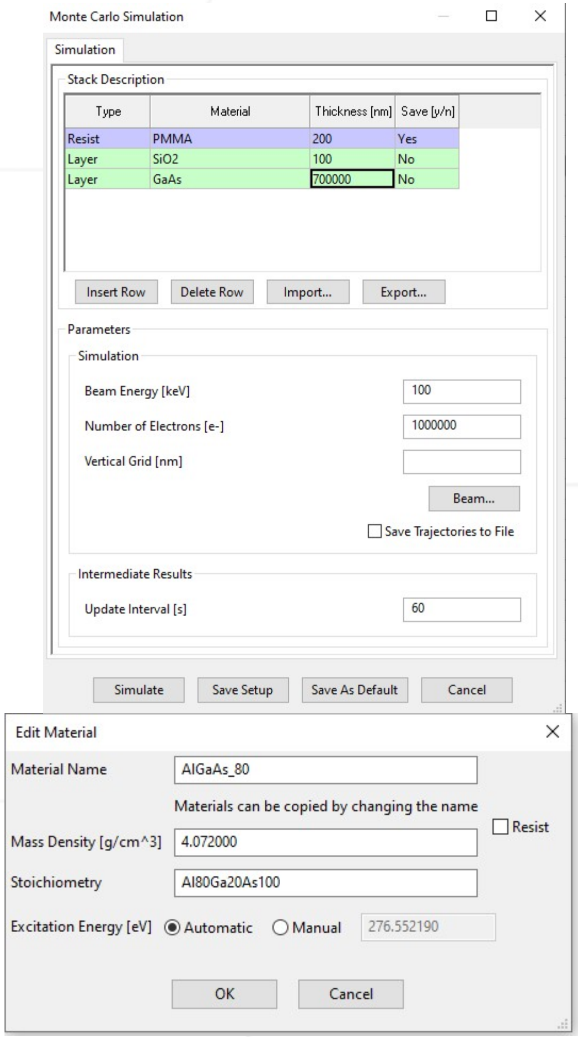
Live Demo

TRACER calculates the absorbed energy spread over resist thickness and distance.



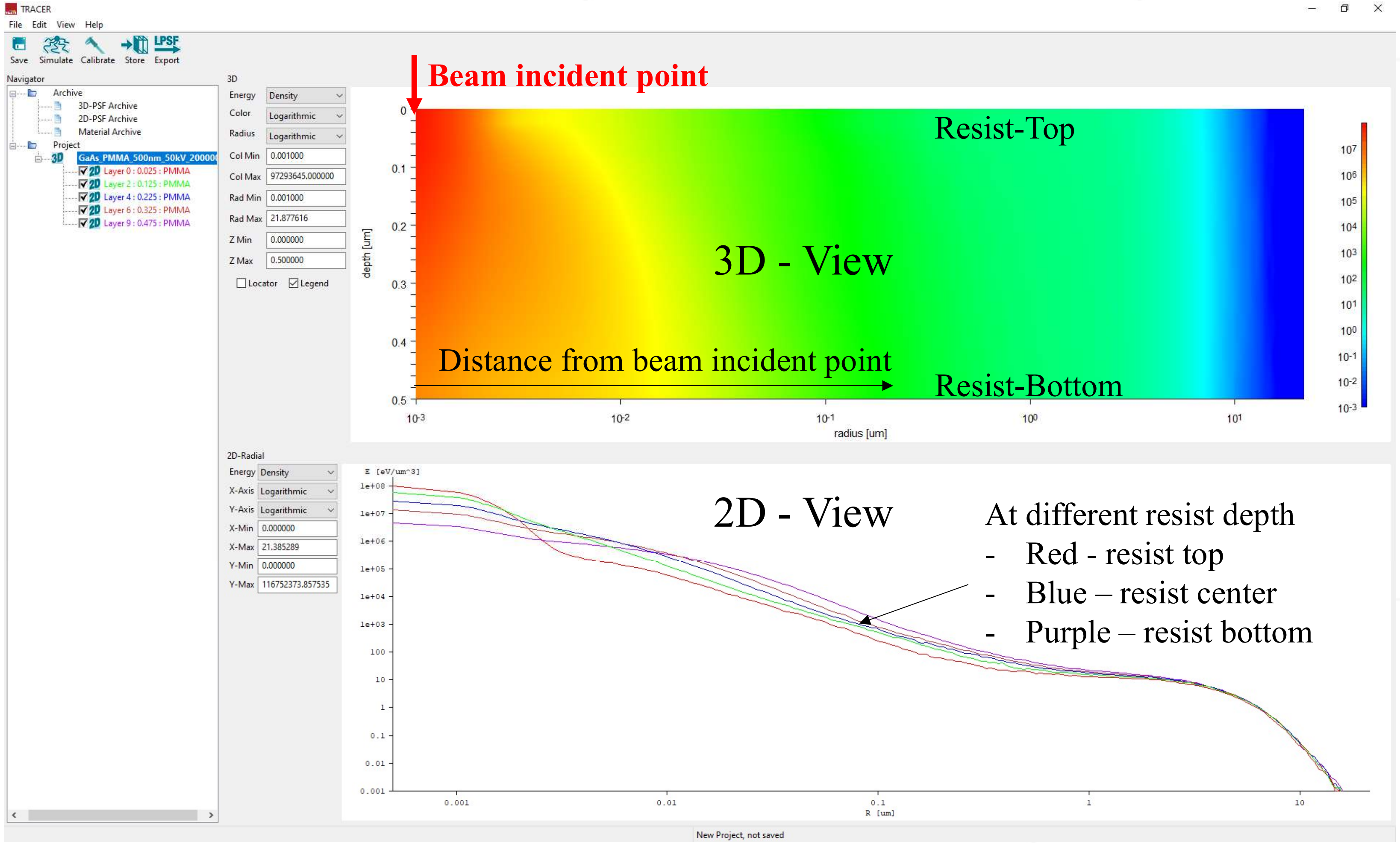
Running a Simulation

- Define the Stack
  - Start with subrate material, e.g. GaAs wafer
    - Material data are coming from database
    - Adding new (custome) material is easy
      - Define Stoichiometrie
      - Define mass density (from literature or measure)
      - Excitation Energy determined automatic by database, or entered manually
  - Add coating (layer) onto the substrate
  - Add the resist on top (special layer market Resist)
- Define Beam Energy, e.g. 100keV
- Define number of electron, e.g. 1 million
  - More electron give better statistics (quality for PSF)
  - 1-5 million are recommended for good quality
- Save Trajectories, only for a nice presentation plot
- Hit Simulate, wait a couple minutes



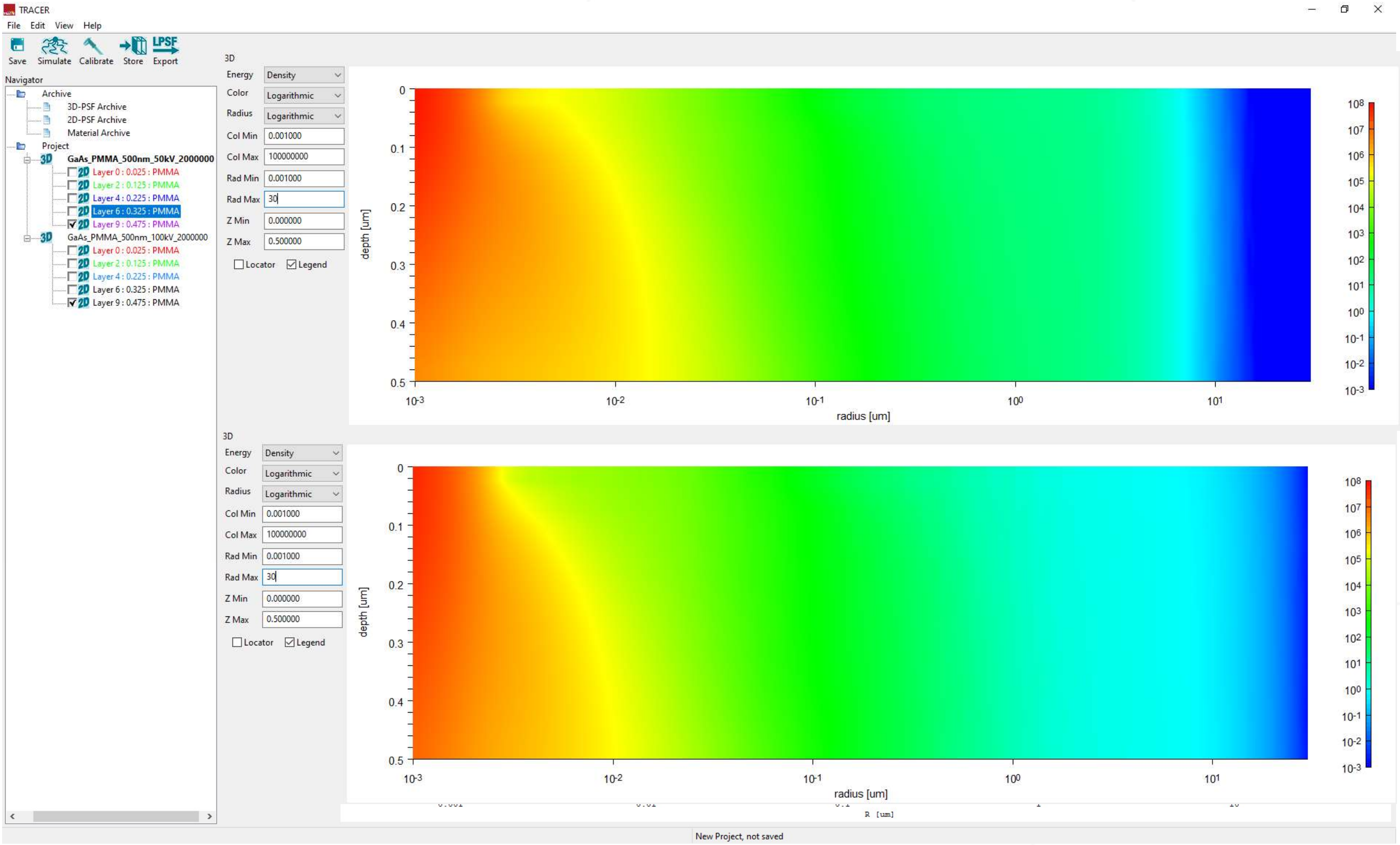
Simulation Result

• Simulation Result for GaAs wafer with 500nm PMMA resist exposed at 50keV



Impact of Acceration Voltage

- GaAs wafer with 500nm PMMA at 50keV vs 100keV

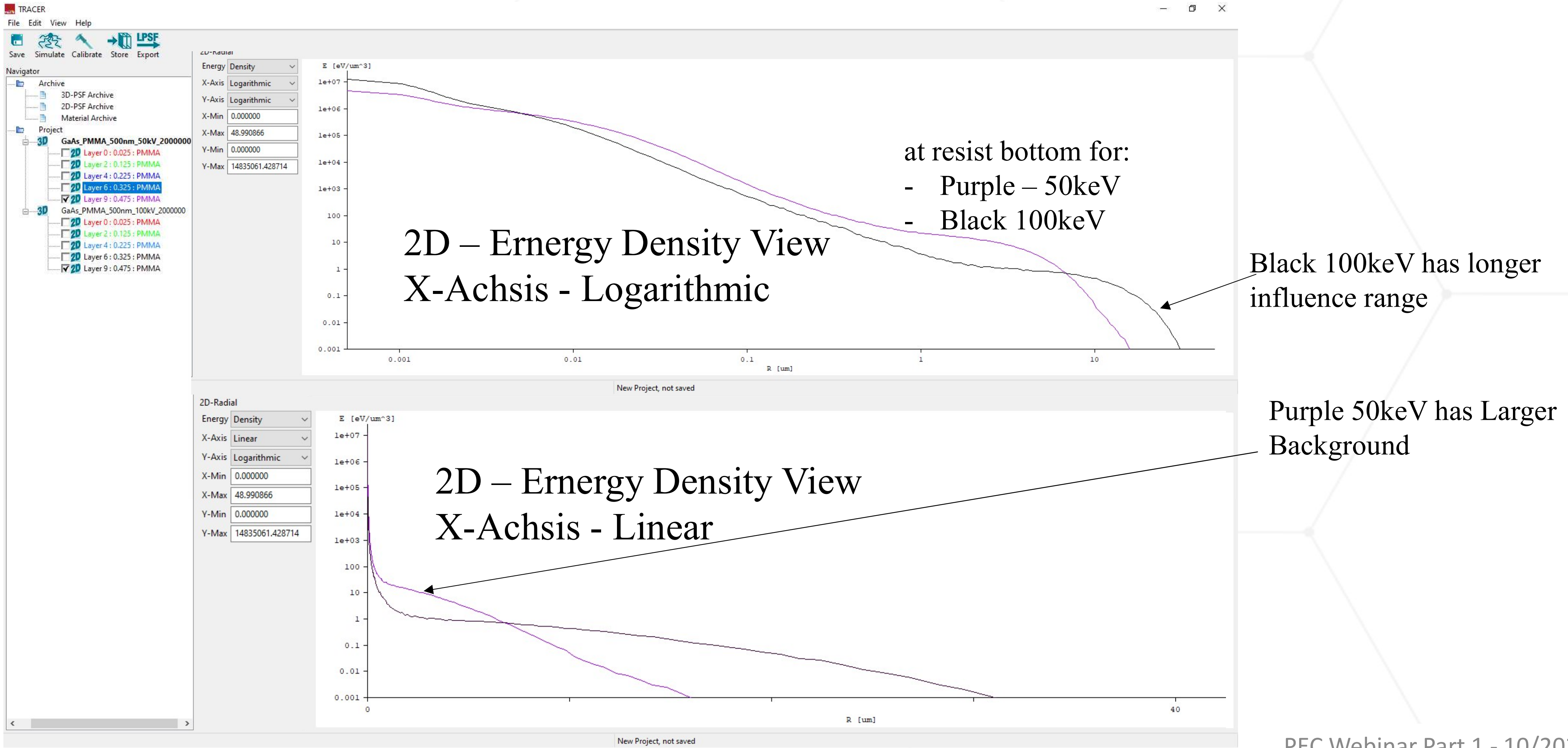


50keV
- Larger short range blur
- Shorter influence range

100keV
- Less short range blur
- Longer influence range

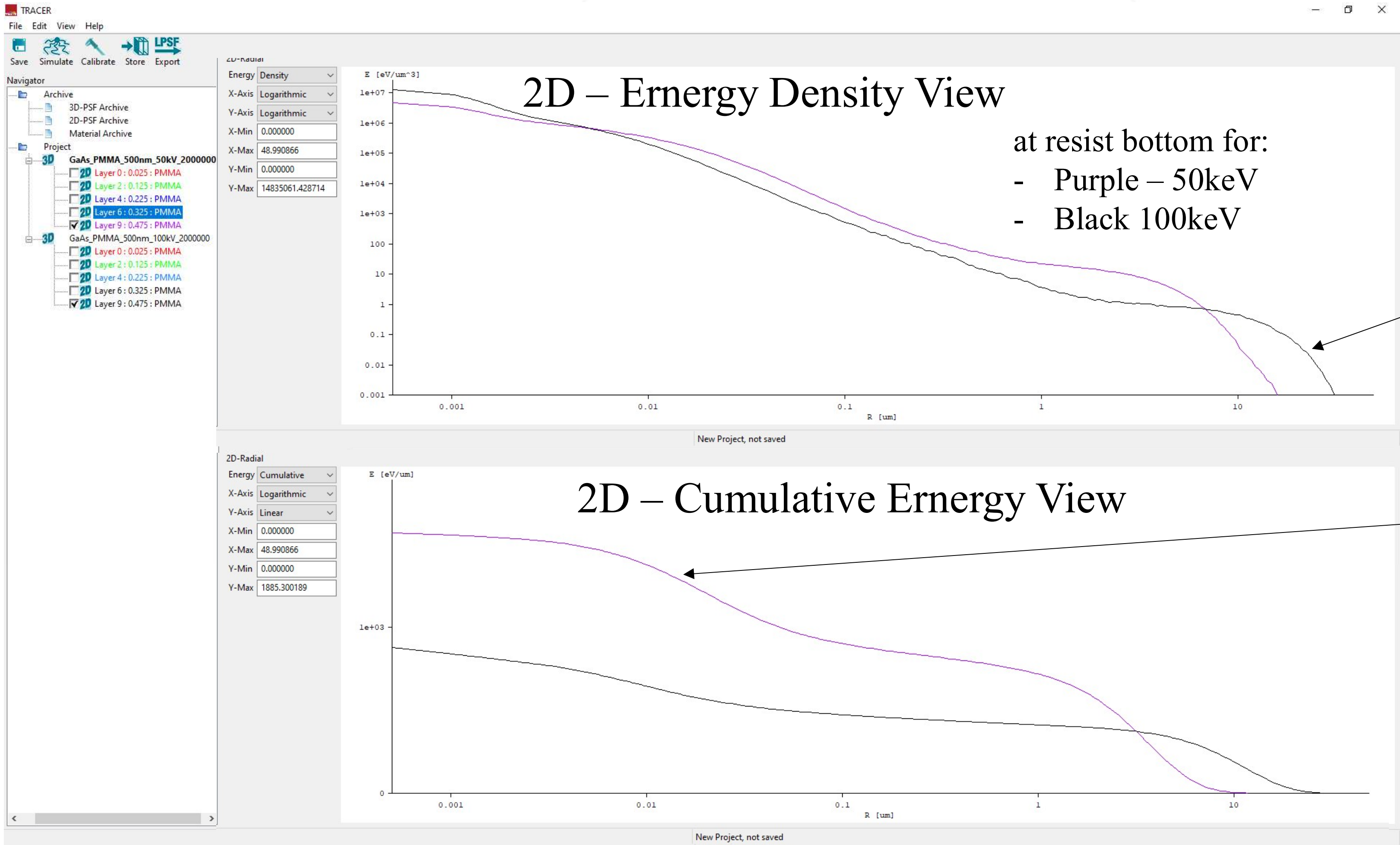
Impact of acceration voltage

- GaAs wafer with 500nm PMMA at 50keV vs 100keV



Impact of acceration voltage

- GaAs wafer with 500nm PMMA at 50keV vs 100keV



Black 100keV has longer influence range

Purple 50keV has higher cumulative energy

100keV needs 79% higher dose:

Dose Factor

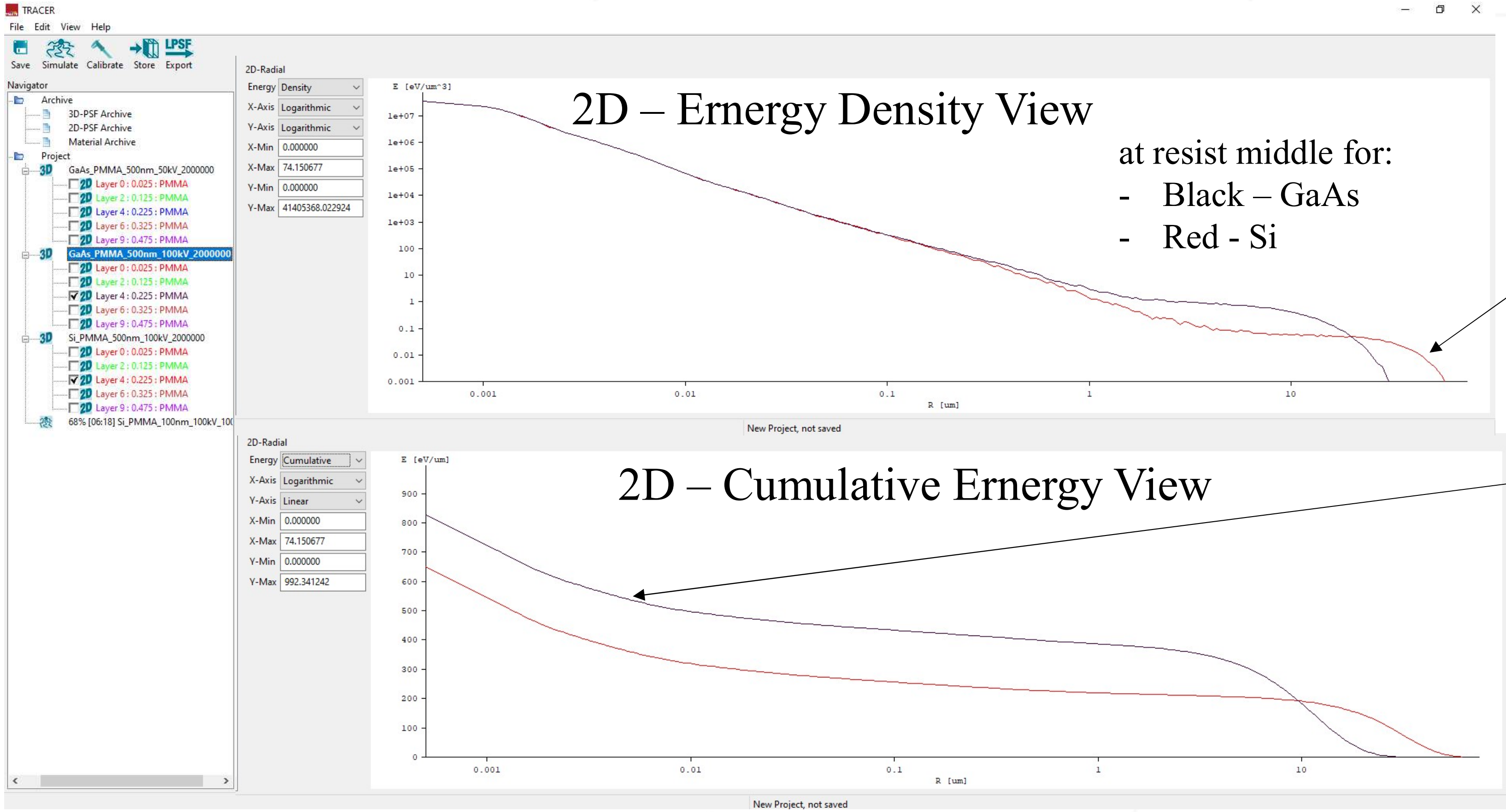
Reference absorbed energy per incident electron and vertical distance [eV/um]: 1571.083491

Dose Factor	Energy [eV/um]	Name of 2D-PSF
1.000000	1571.083491	GaAs_PMMA_500nm_50kV_z475nm
1.788760	878.308845	GaAs_PMMA_500nm_100kV_z475nm

OK

Impact of Substrate Material

- GaAs vs. Si with 500nm PMMA at 100keV



Red Si has longer influence range

Black GaAs has higher cumulative energy

Si needs 27% higher dose:

Dose Factor

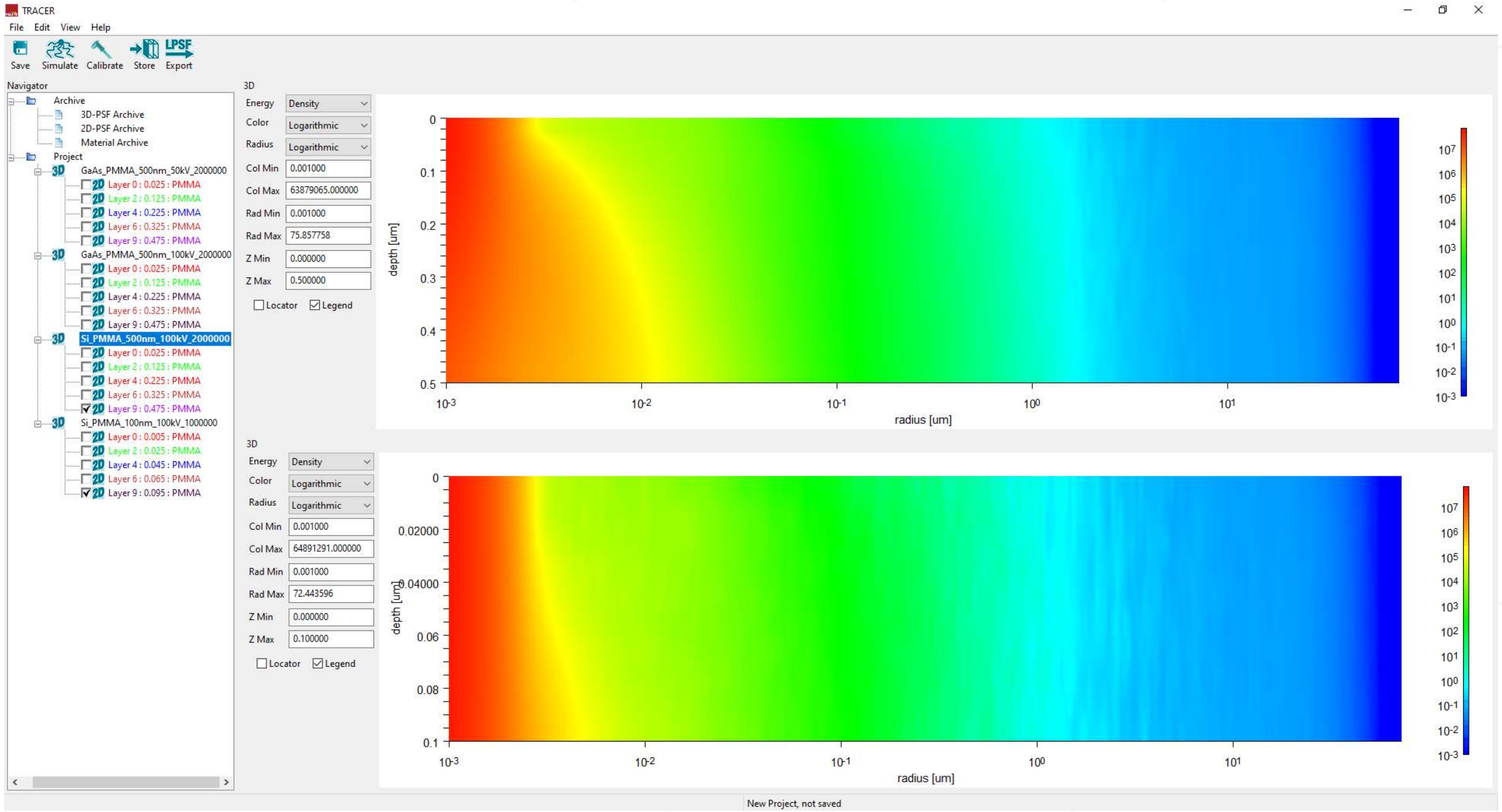
Reference absorbed energy per incident electron and vertical distance [eV/um]: 826.951035

Dose Factor	Energy [eV/um]	Name of 2D-PSF
1.000000	826.951035	GaAs_PMMA_500nm_100kV_z225nm
1.274273	648.959243	Si_PMMA_500nm_100kV_z225nm

OK

Impact of Resist Thickness

- Si with 500nm vs. 100nm PMMA at 100keV



500nm – Thick PMMA
- More blur in depth
- Better for lift-off

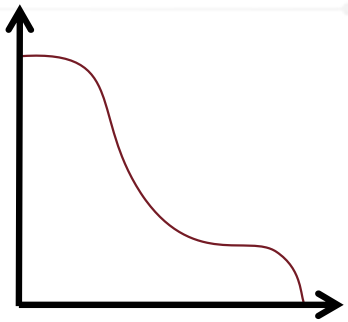
100nm – Thin PMMA
- Less short range blur
- More directional
- Higer resolution

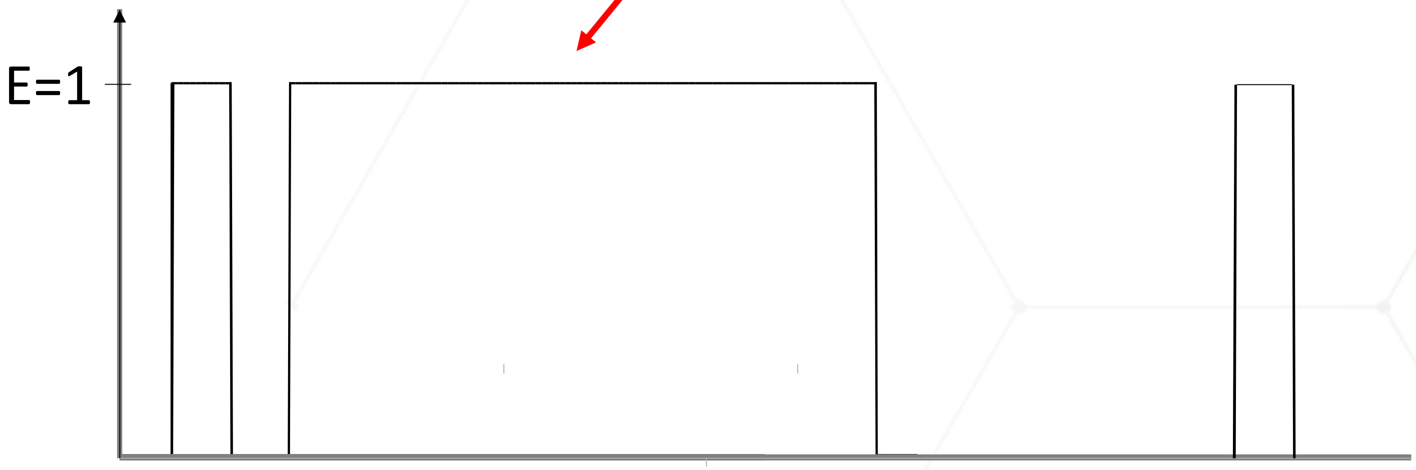
Outline

- E-Beam Lithography Primer
- Monte Carlo Simulation with TRACER
- **Simulation of Proximity Effect**
  - Layout: Iso – Dense
  - PSF: Acceleration voltage, stack
  - CD - Sensitivity
- Proximity Effect Correction
- Summary
- Q&A

Knowing the PSF, the absorbed energy at any position *x* can be calculated:

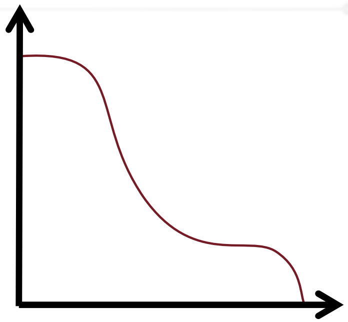
$$E(x) = P(x) \otimes PSF$$

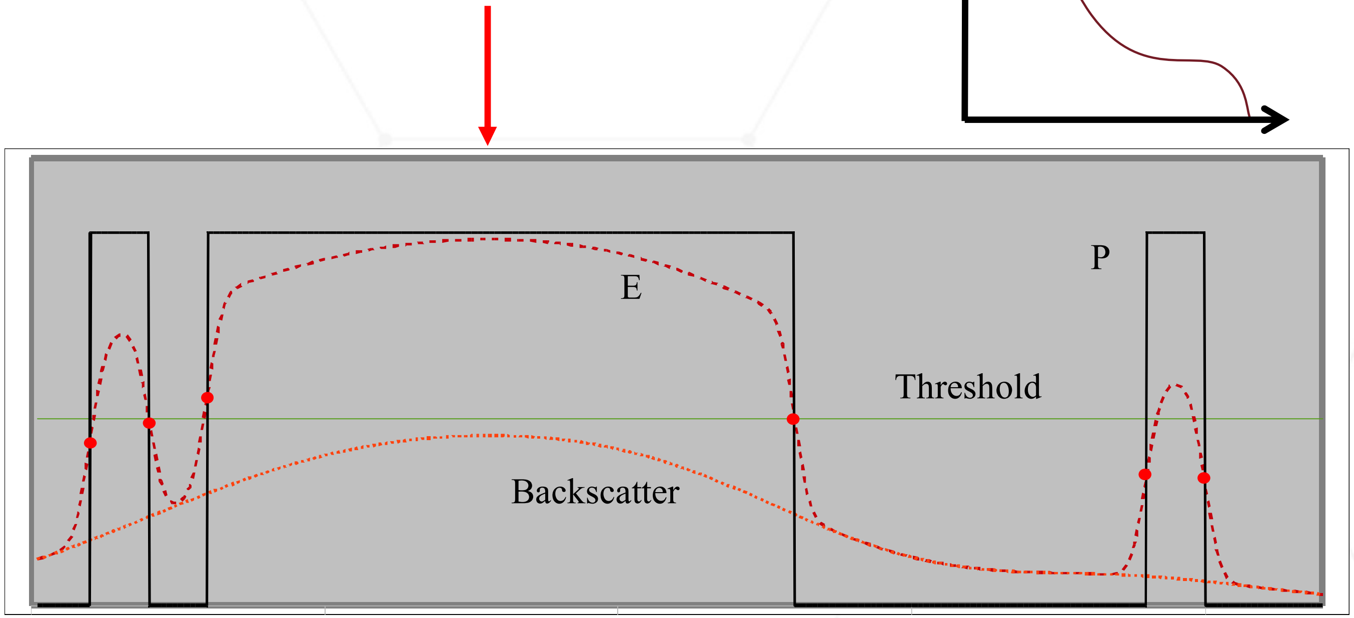




Knowing the PSF, the absorbed energy at any position *x* can be calculated:

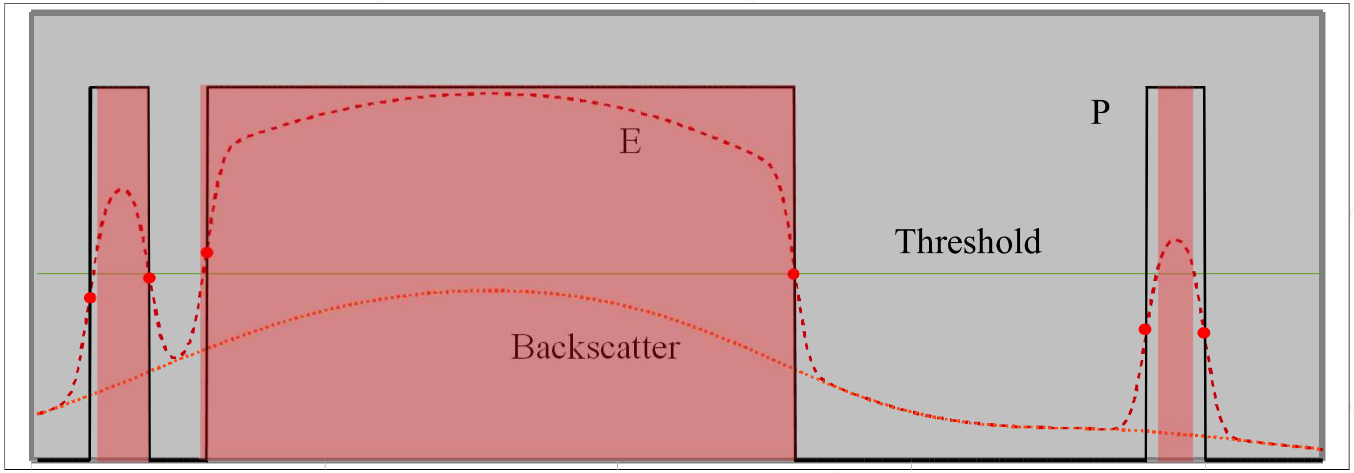
$$E(x) = P(x) \otimes PSF$$



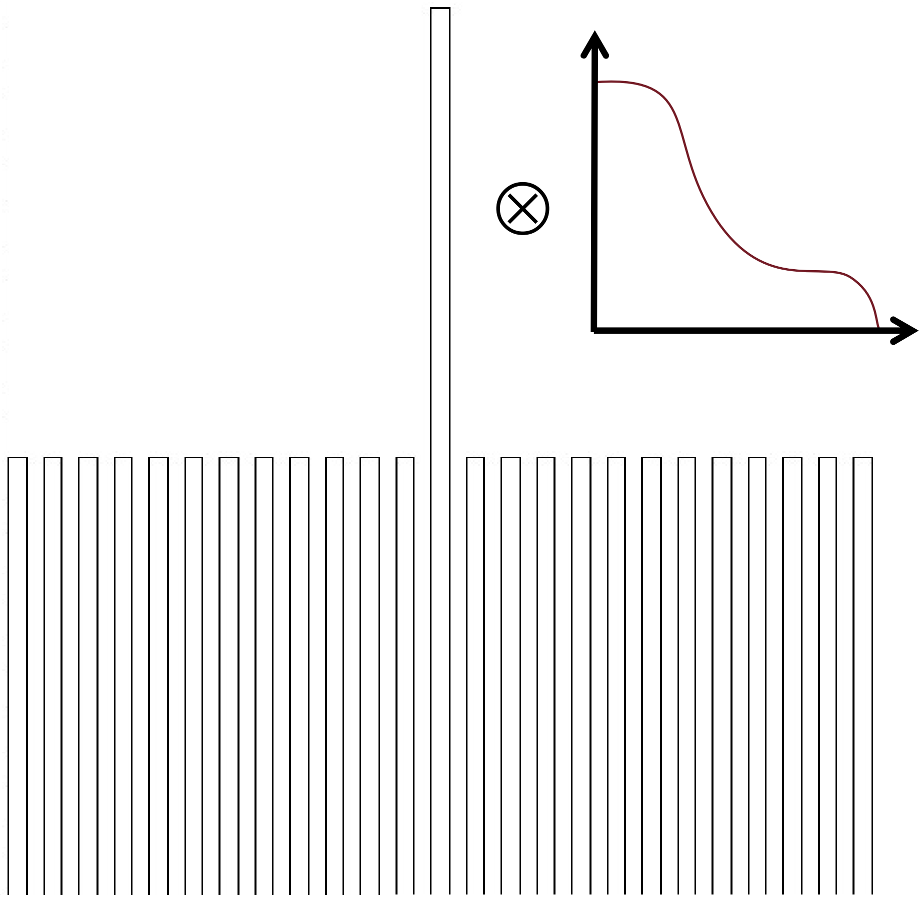


Knowing the PSF, the absorbed energy at any position x can be calculated:

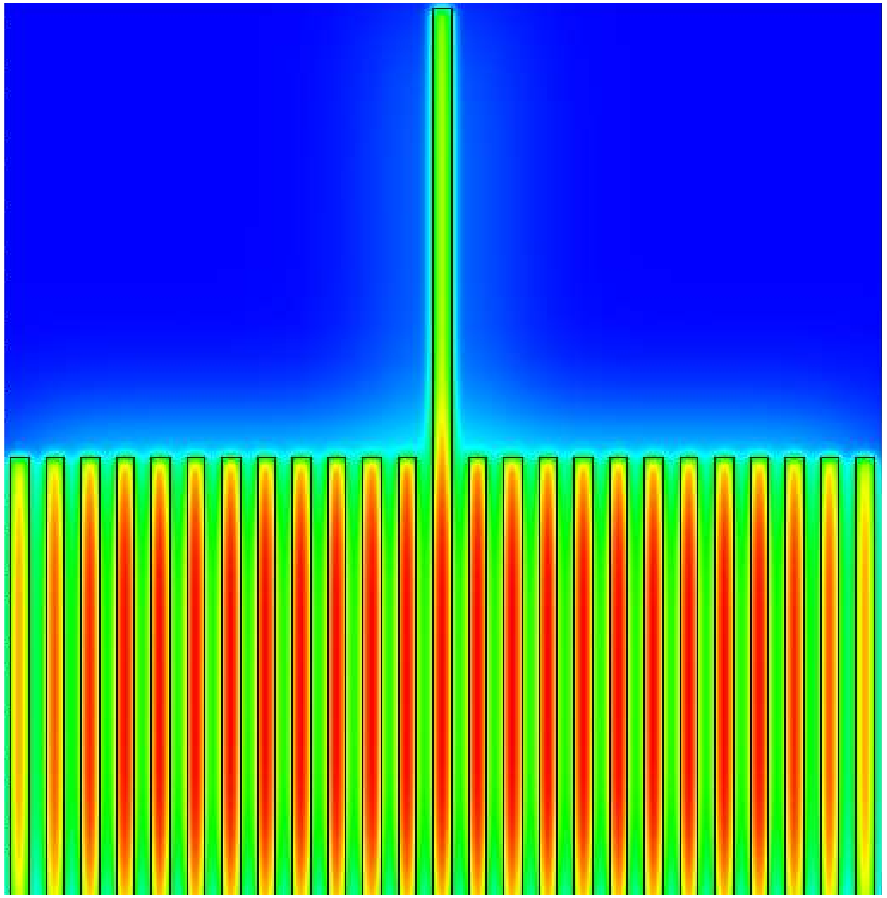
$$E(x) = P(x) \otimes PSF$$



Modeling Absorbed Energy

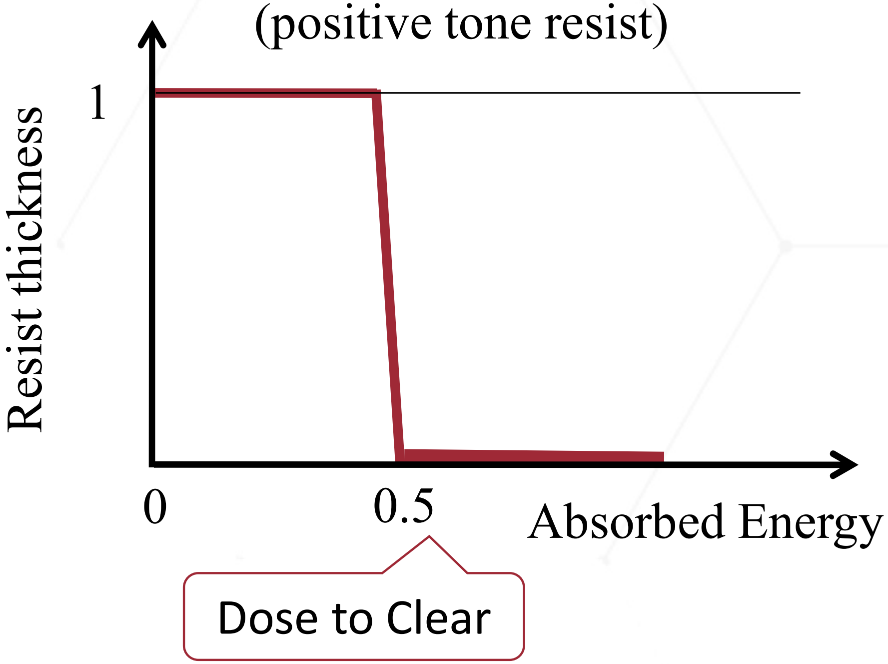


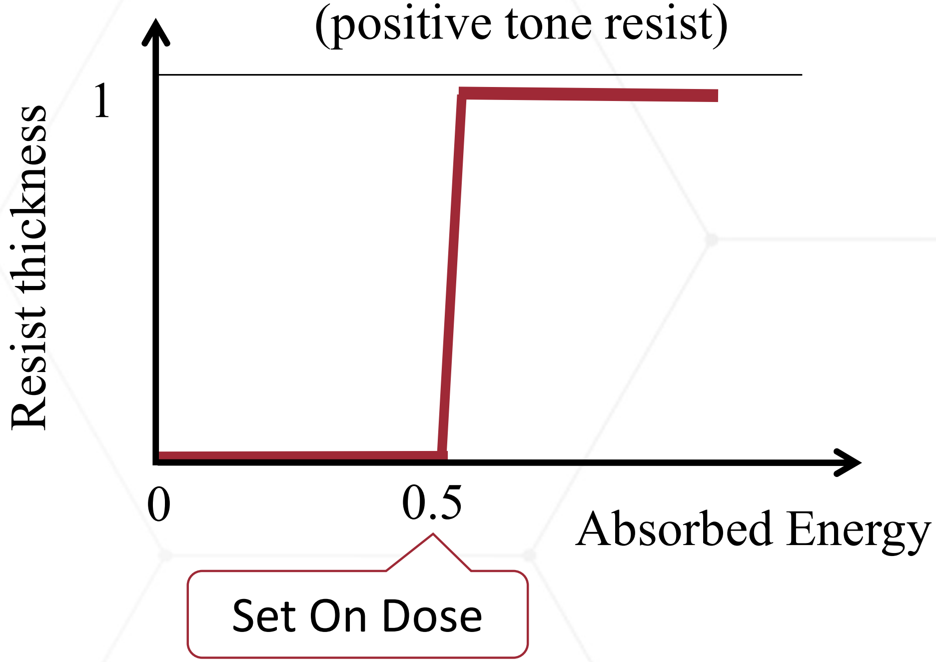
Absorbed Energy in Resist



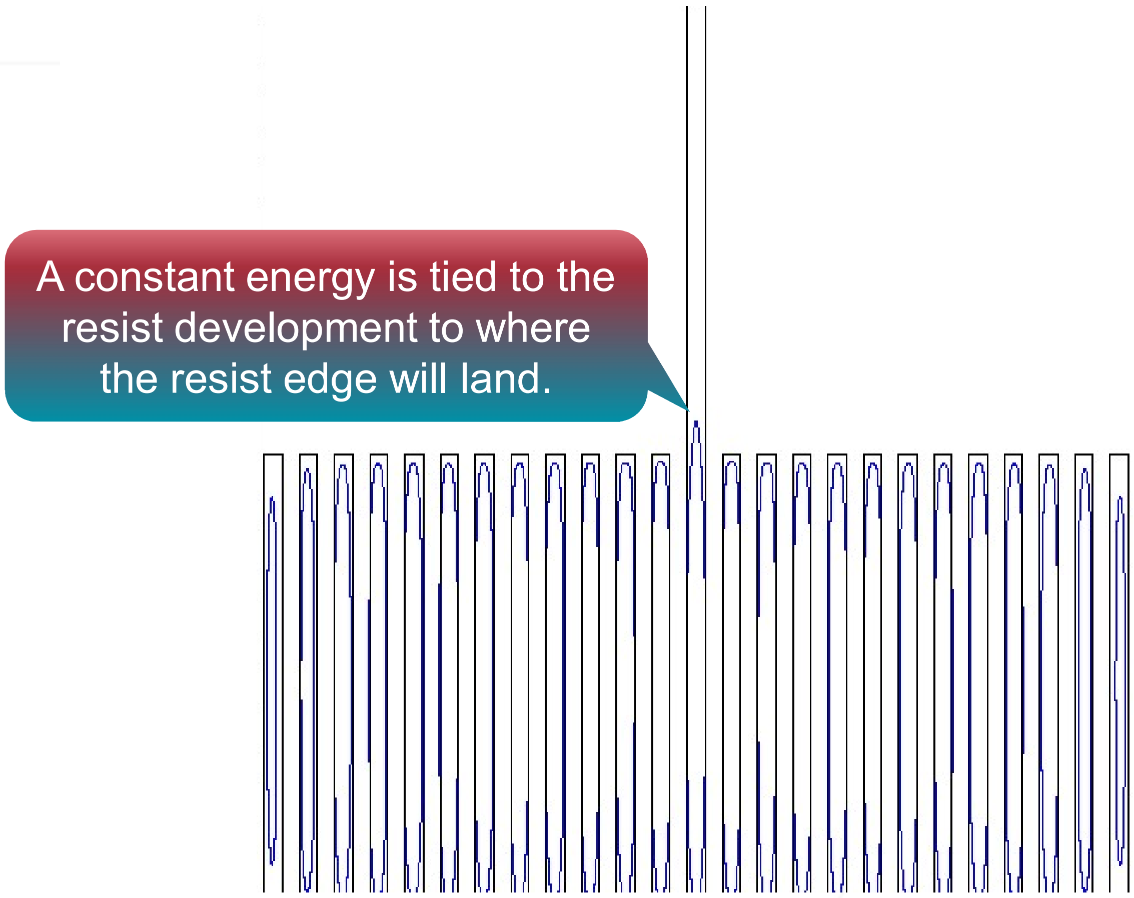
Resist Development

The development rate is a function of absorbed energy in resist





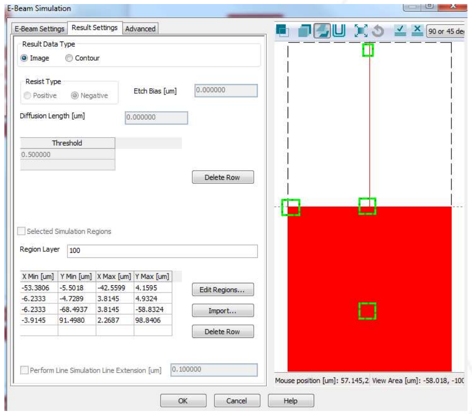
Resist Contour

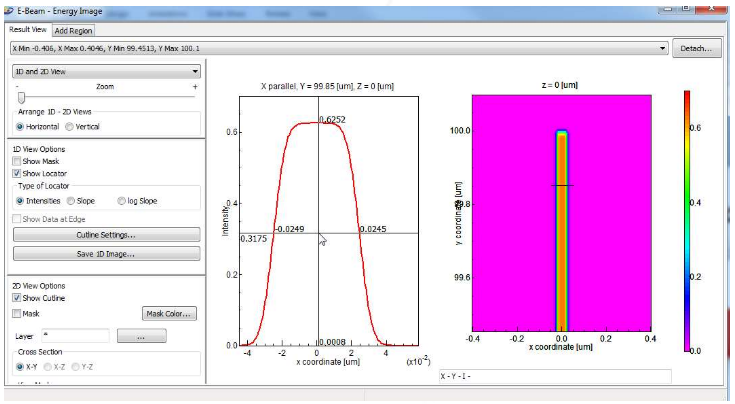


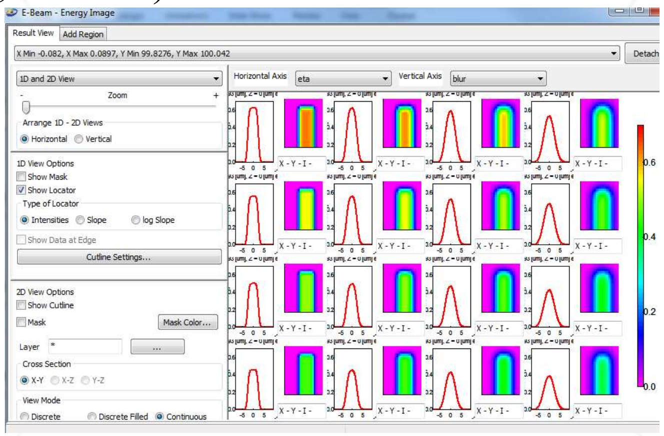
Simulation / Verification

Extended e-beam simulation functions

- Intensity image simulation of multiple regions
- Extended viewing
  - 2D only, 1D only, 1D + 2D views
  - 1D image at user defined cut-line
  - Multiple region selectable by drop-down
  - Easy simulation of additional regions
  - Matrix-view for loops
- Powerful evaluation
  - Measure image intensity, slope, log slope at 1D view
  - Export data for external evaluation (e.g. Excel, MatLab)



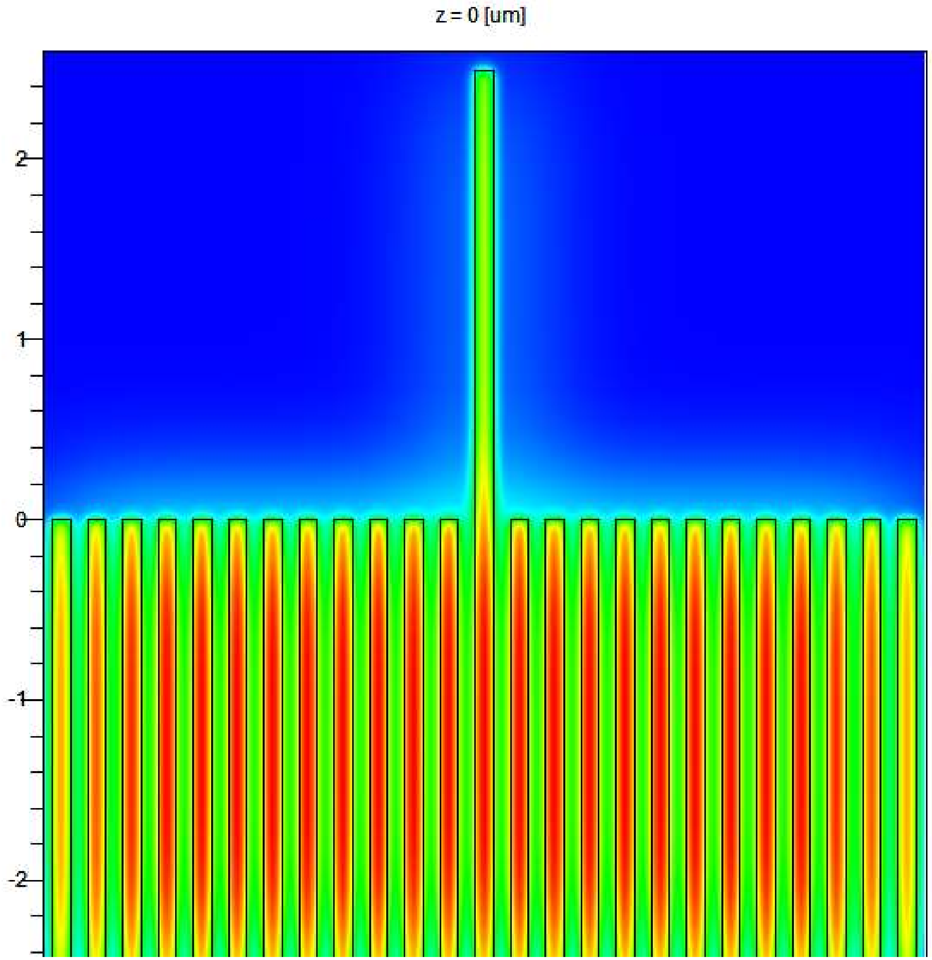


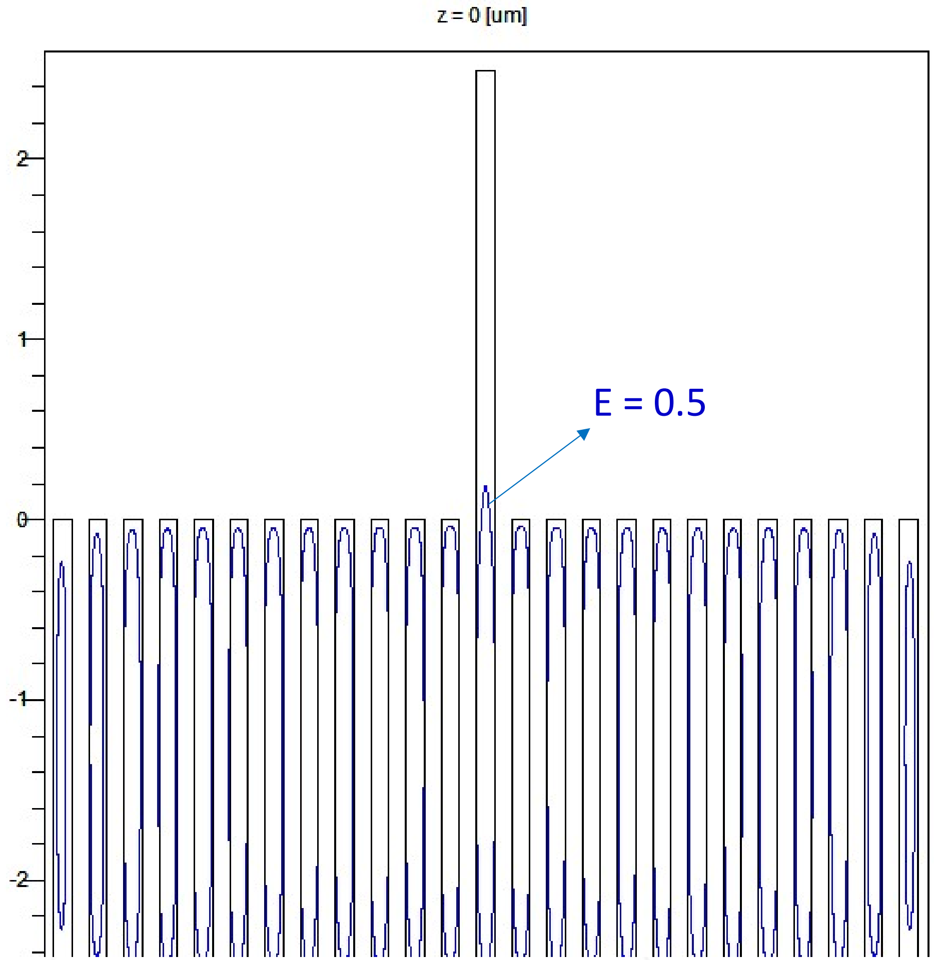


Outline

- E-Beam Lithography Primer
- Monte Carlo Simulation with TRACER
- Simulation of Proximity Effect
- Proximity Effect Correction
    - Basic Intro
- Summary
- Q&A

Absorbed Energy in Resist

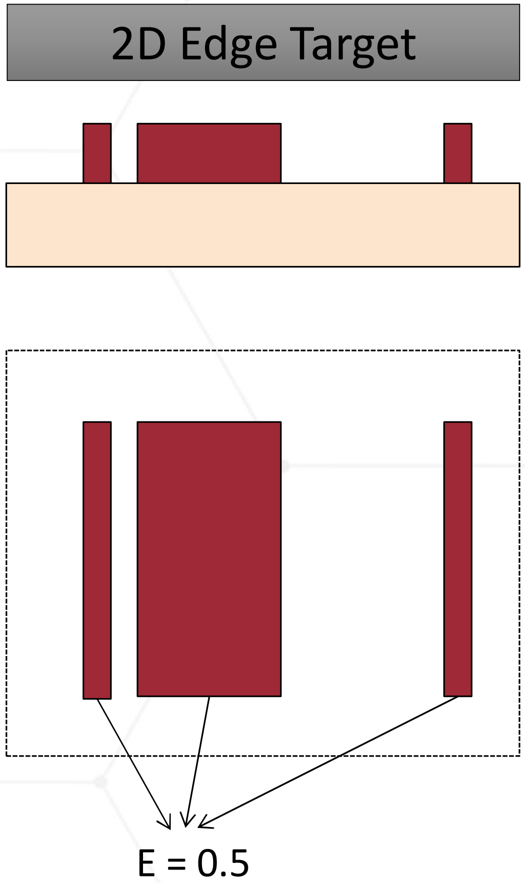


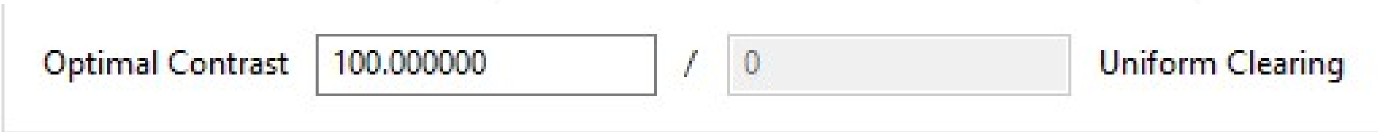


Default Proximity Effect Correction

Edge Equalization Target: Adjust all feature edges to the same absorbed energy (On-et Dose)

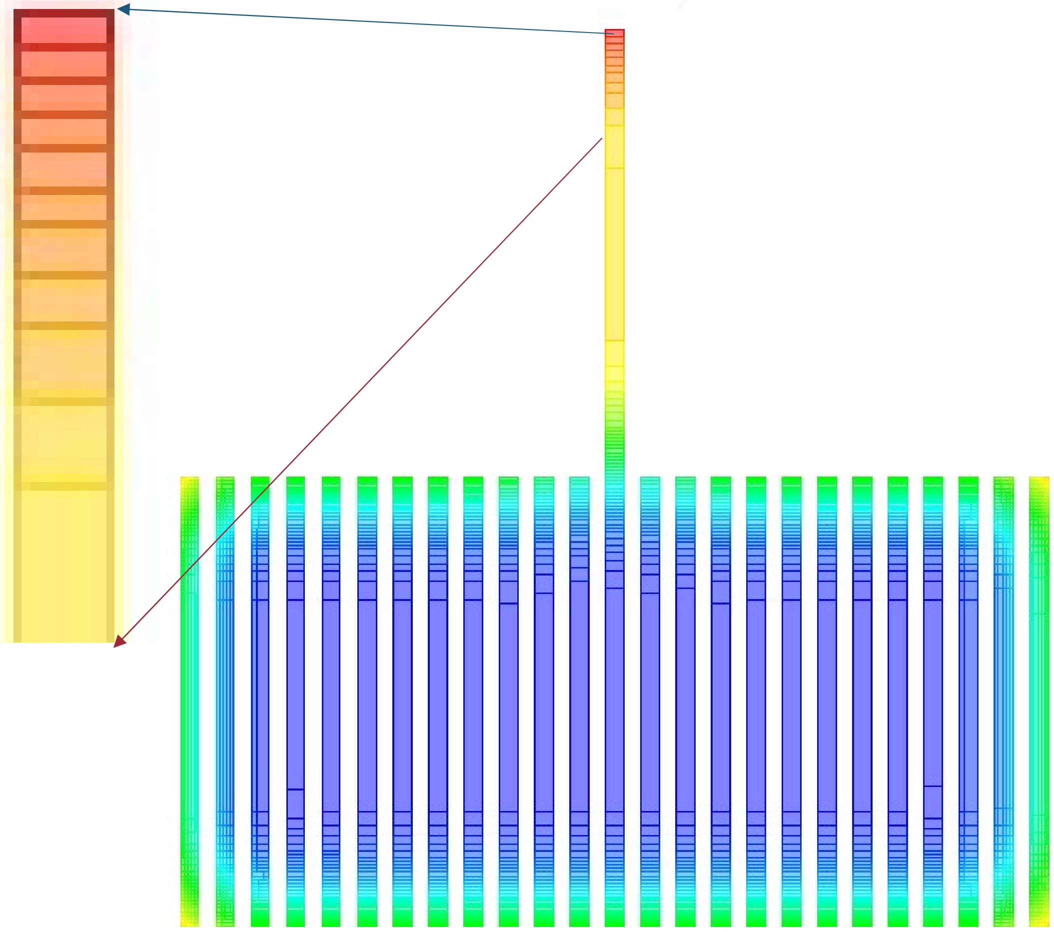
- Inside the feature E(x) > On-Set Dose:
  Resist will remain (negative)
- Outside the feature E(x) < On-Set Dose:
  Resist will be removed (negative)
- Equation: $E(edge) = 0.5 = D(x) \otimes PSF$

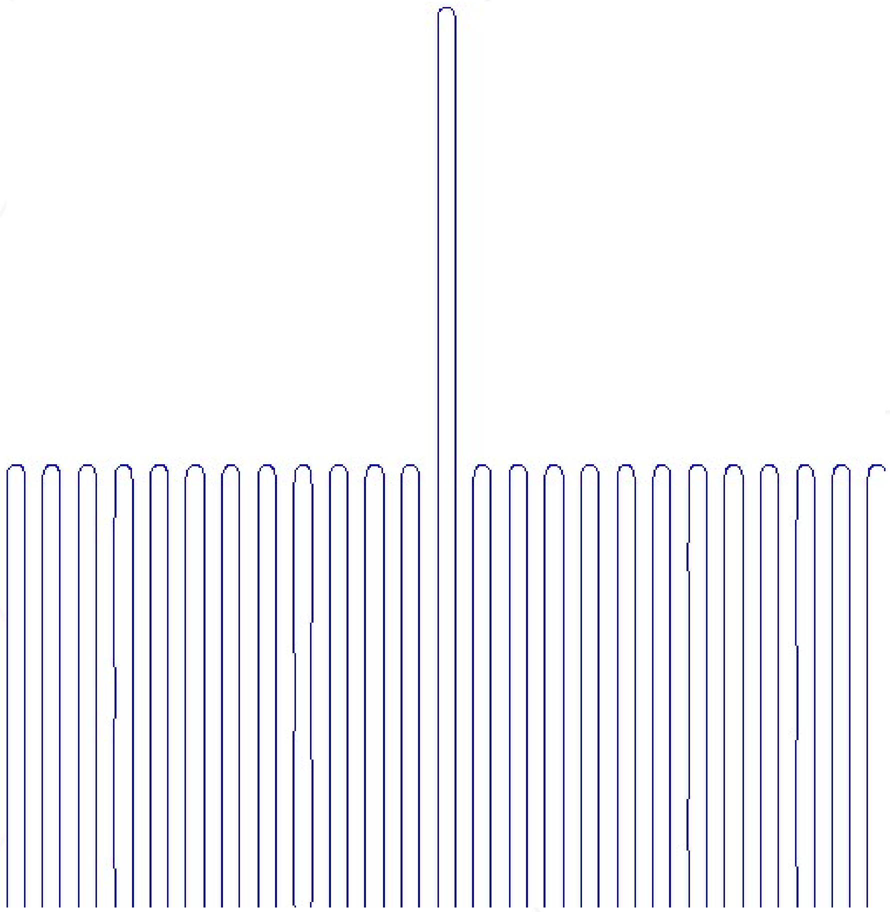




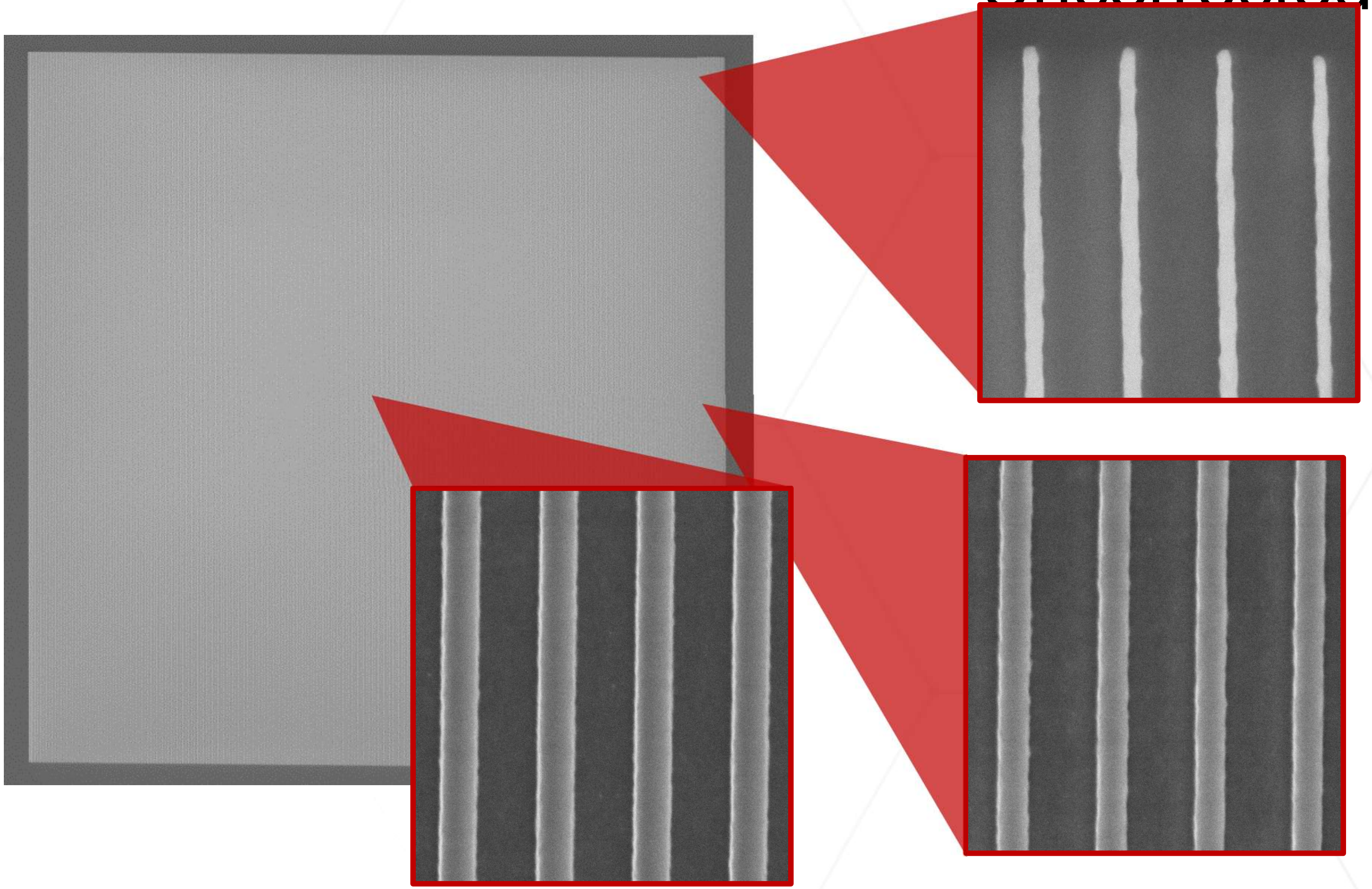
J. Pavkovich, *J. Vac.Sci. Technol.*, B, Vol.4, No.1, Jan/Feb 1986

PEC -> Contour

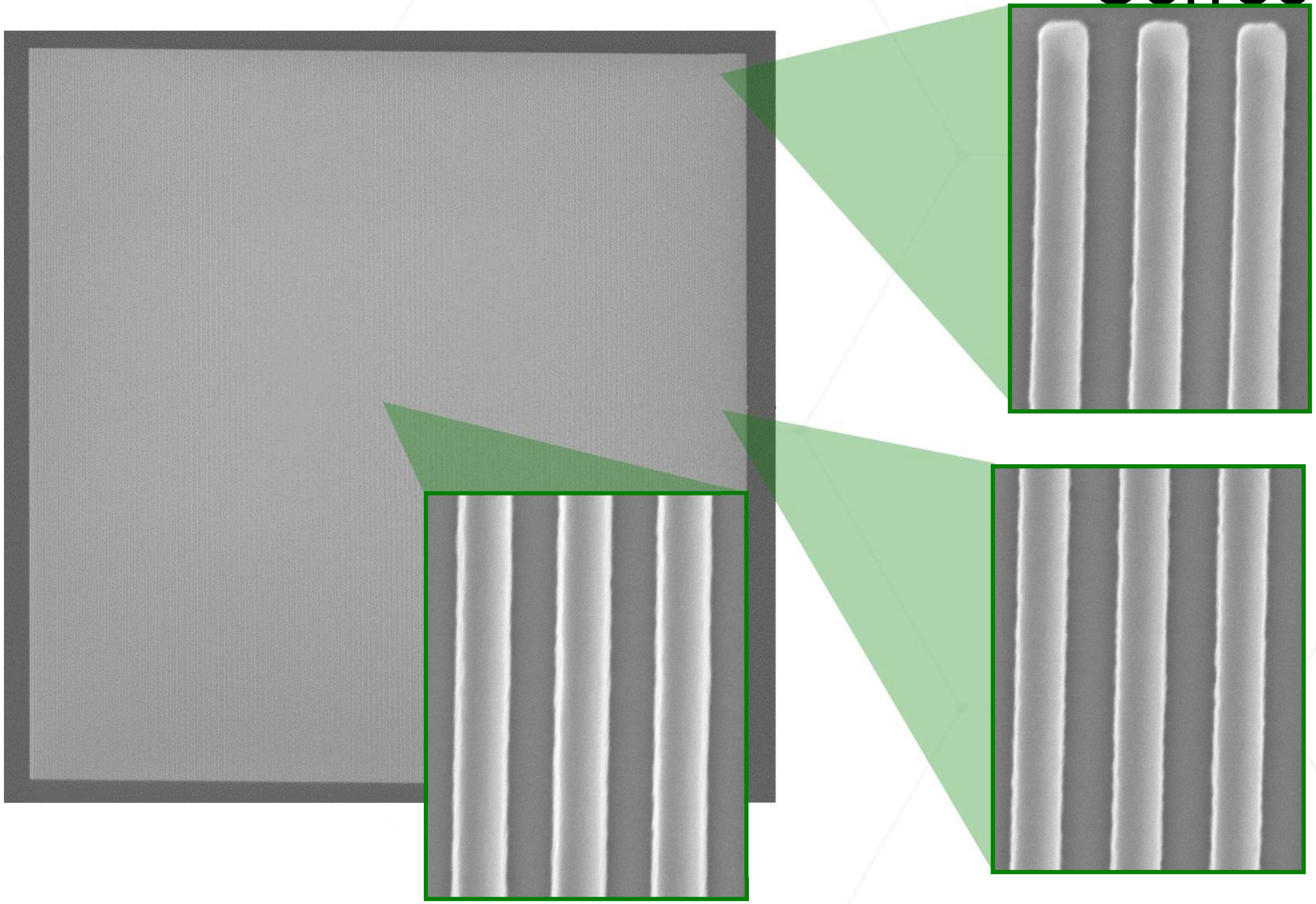




Uncorrected Pattern

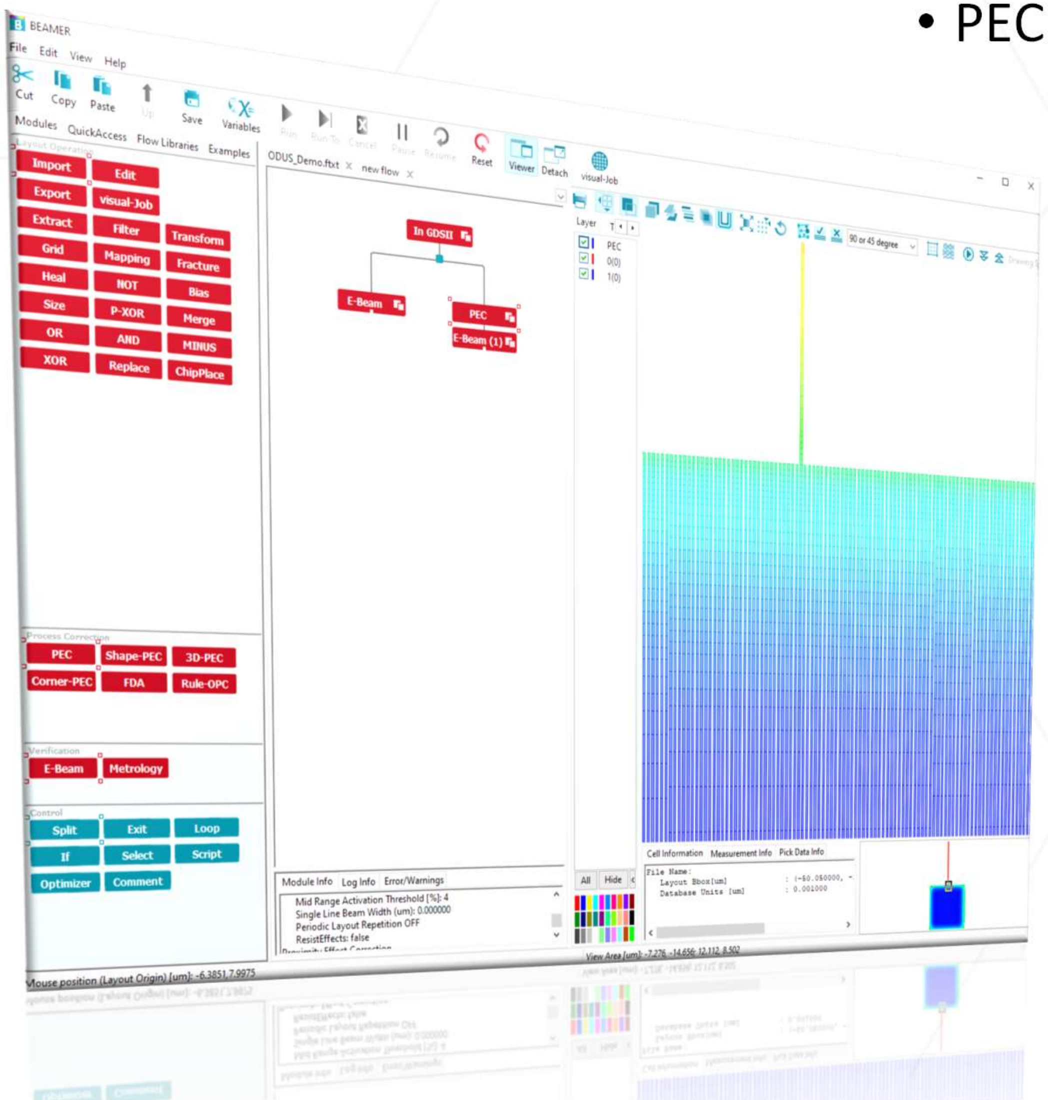


Corrected Pattern



BEAMER Demo

- PEC



Outline

- E-Beam Lithography Primer
- Monte Carlo Simulation with TRACER
- Simulation of Proximity Effect
- Proximity Effect Correction
- Summary
- Q&A

Summary

- 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
  - Adjacent features interact with each other, leading to a layout (density) dependent absorbed energy
- Impact of proximity effect on lithography result depends on tool and process parameter
  - The effective short range blur transferes absorbed energy variation to CD variation
  - The efective 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
- Monte-Carlo Simulation is an excellent technique to modell electron scattering
  - Point Spread Function (PSF) for different stacks and acceleration voltages
- Absorbed energy and resist contour at threshold can be simulated by convolution of the layout with the PSF
- Proximity effect can be corrected by adjusting the dose for uniform absorbed energy

Outline

- E-Beam Lithography Primer
- Monte Carlo Simulation with TRACER
- Simulation of Proximity Effect
- Proximity Effect Correction
- Summary
- Q&A