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Advancing the Standard

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December 16th, 2020

Simulation of E-Beam Lithography

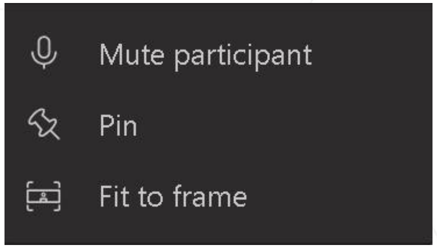
2D and 3D Simulation
BEAMER & LAB

BEAMER LAB TRACER ProSEM MASKER

eBeam Simulation Webinar

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 to e-beam lithograpyh simulation
  - Initiated by simulation results presented at Proximity Effect webinar series
  - It picks out essential ingredients, focus on example from Proximity Effect Webinar
  - In case you want / need more depth -> Contact support@genisys-gmbh.com

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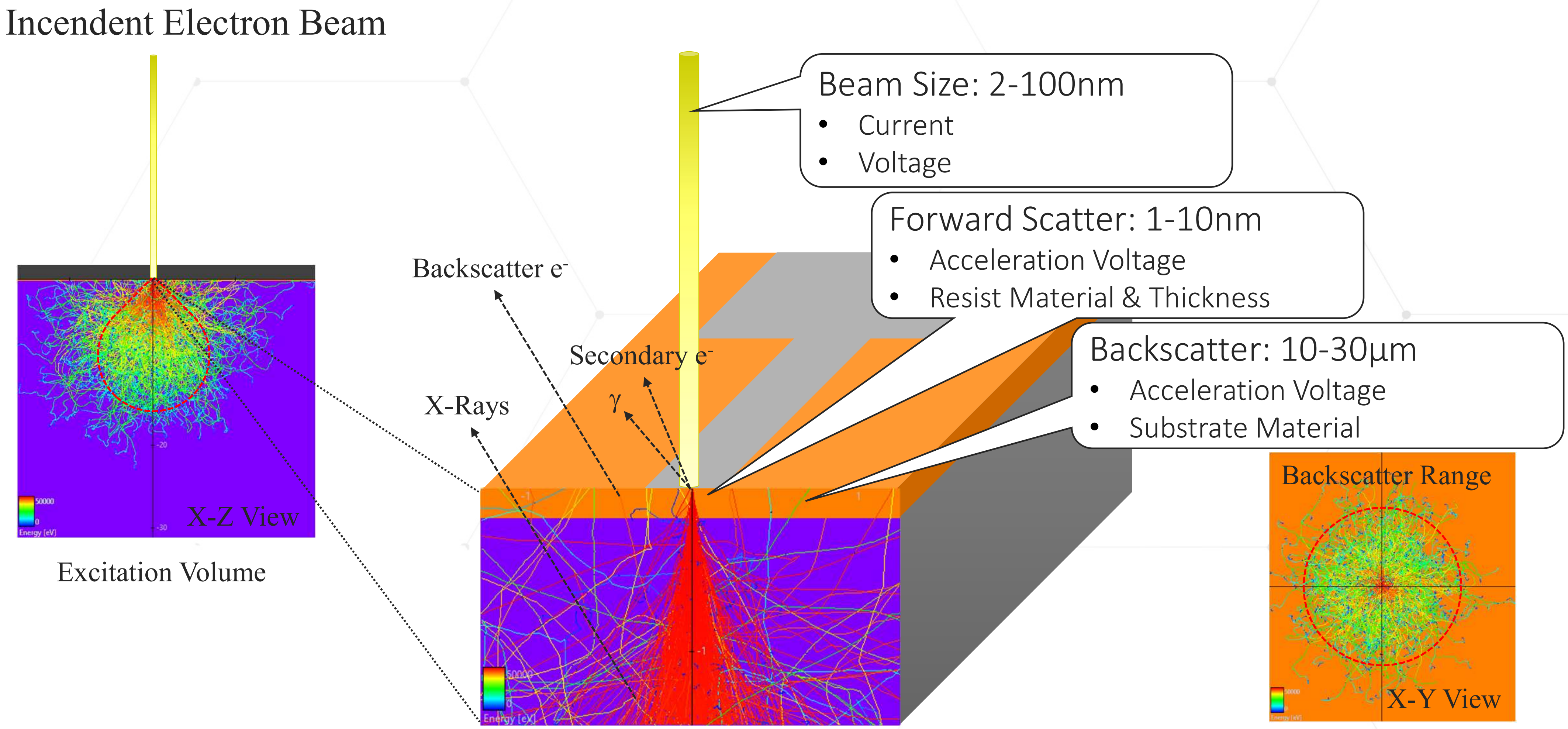
Outline

- E-Beam Exposure Simulation
- 3D Resist Development Simulation
  - 3D Simulation using LAB
  - Lateral development effect
- Over-Dose-Under-Size ODUS
- Multi Layer Resist Processes
- Greyscale (3D) Lithography
- Summary
- Q&A

Electron-Solid Interactions



Beam Size: 2-100nm

- Current
- Voltage

Forward Scatter: 1-10nm

- Acceleration Voltage
- Resist Material & Thickness

Backscatter: 10-30µm

- Acceleration Voltage
- Substrate Material

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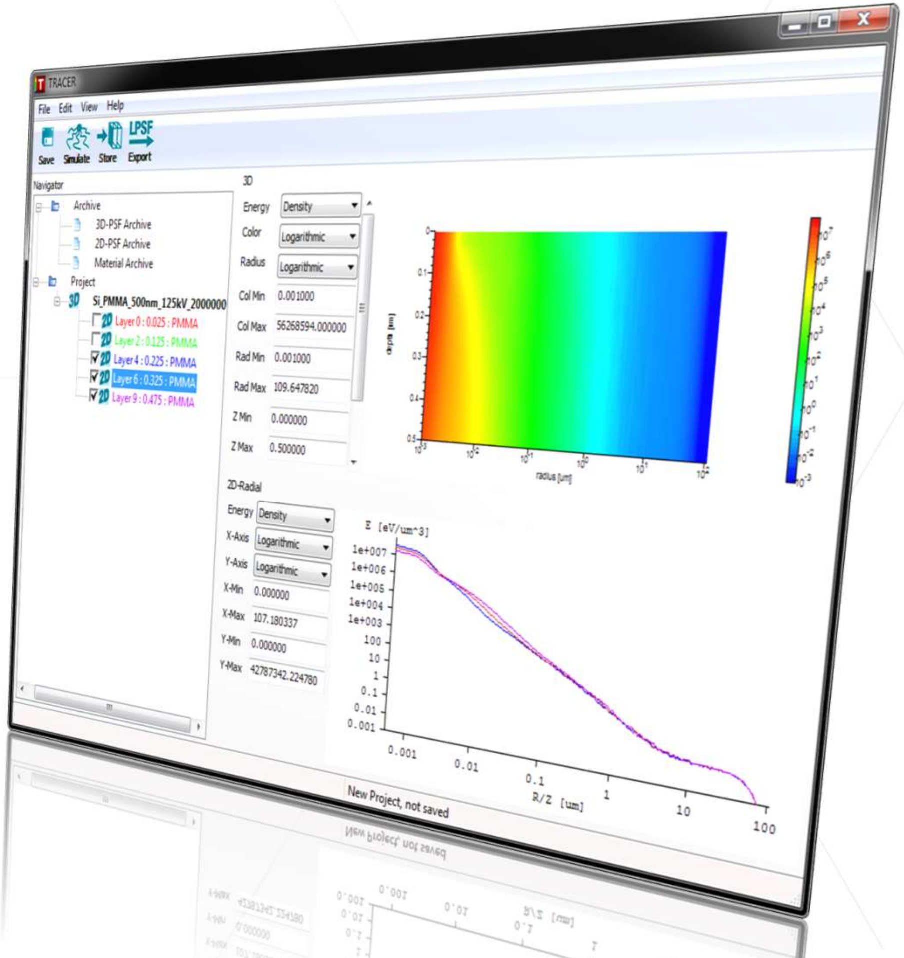
Live Demo

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

TRACER



Si_PMMA_500nm_125kV_2000000
☐ Layer 0 : 0.025 : PMMA
☐ Layer 2 : 0.125 : PMMA
☑ Layer 4 : 0.225 : PMMA
☑ Layer 6 : 0.325 : PMMA
☑ Layer 9 : 0.475 : PMMA

3D

Energy	Density
Color	Logarithmic
Radius	Logarithmic
Col Min	0.001000
Col Max	56268594.000000
Rad Min	0.001000
Rad Max	109.647820
Z Min	0.000000
Z Max	0.500000

2D-Radial

Energy	Density
X-Axis	Logarithmic
Y-Axis	Logarithmic
X-Min	0.000000
X-Max	107.180337
Y-Min	0.000000
Y-Max	42787342.224780

New Project, not saved

Simulation Result

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

GaAs_PMMA_500nm_50kV_20000

☑ 2D Layer 0 : 0.025 : PMMA
☑ 2D Layer 2 : 0.125 : PMMA
☑ 2D Layer 4 : 0.225 : PMMA
☑ 2D Layer 6 : 0.325 : PMMA
☑ 2D Layer 9 : 0.475 : PMMA

3D

Energy	Density
Color	Logarithmic
Radius	Logarithmic
Col Min	0.001000
Col Max	97293645.000000
Rad Min	0.001000
Rad Max	21.877616
Z Min	0.000000
Z Max	0.500000

☐ Locator ☑ Legend

2D-Radial

Energy	Density
X-Axis	Logarithmic
Y-Axis	Logarithmic
X-Min	0.000000
X-Max	21.385289
Y-Min	0.000000
Y-Max	116752373.857535

New Project, not saved

Beam incident point

Resist-Top

3D - View

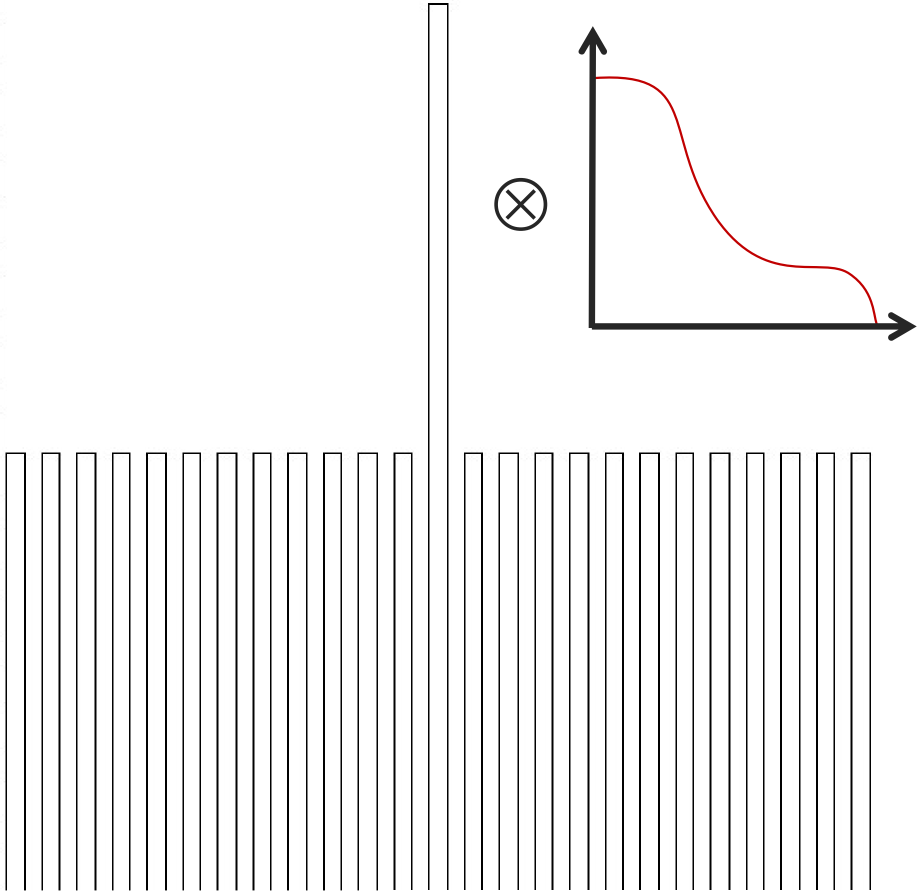
Distance from beam incident point

Resist-Bottom

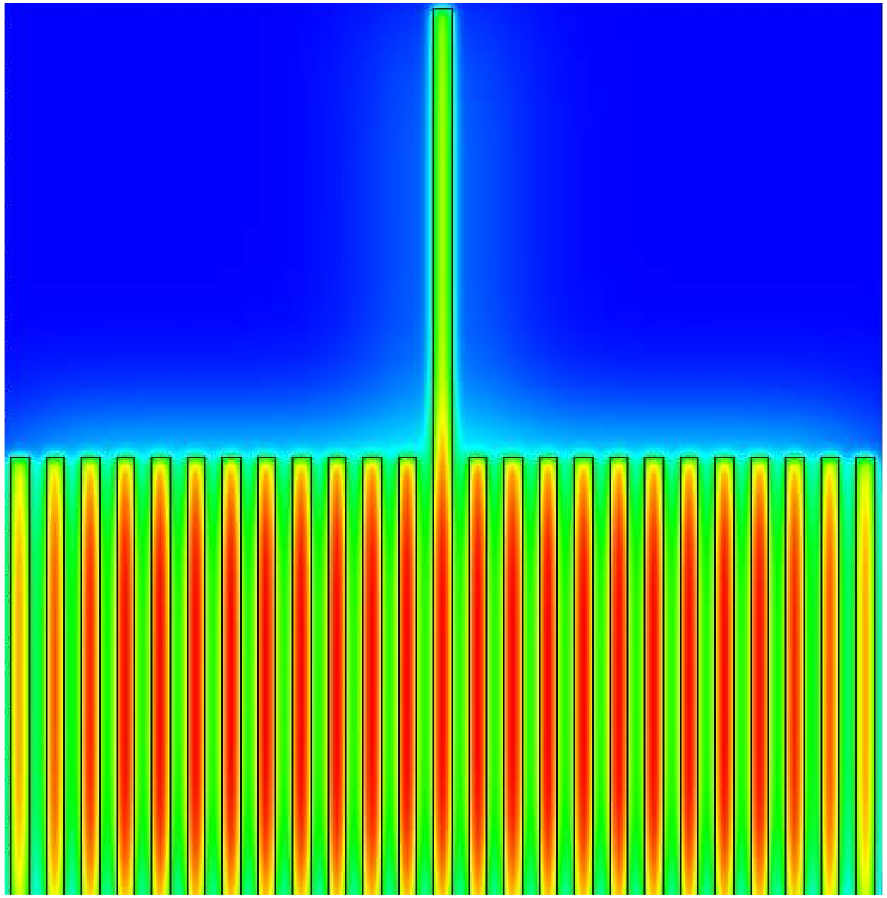
2D - View

At different resist depth
- Red - resist top
- Blue – resist center
- Purple – resist bottom

Modeling Absorbed Energy

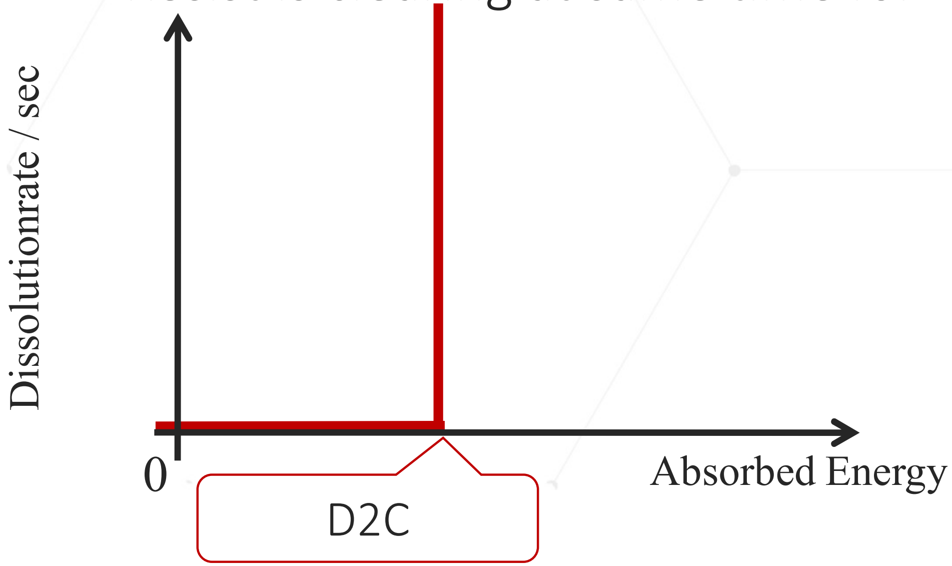


Absorbed Energy in Resist

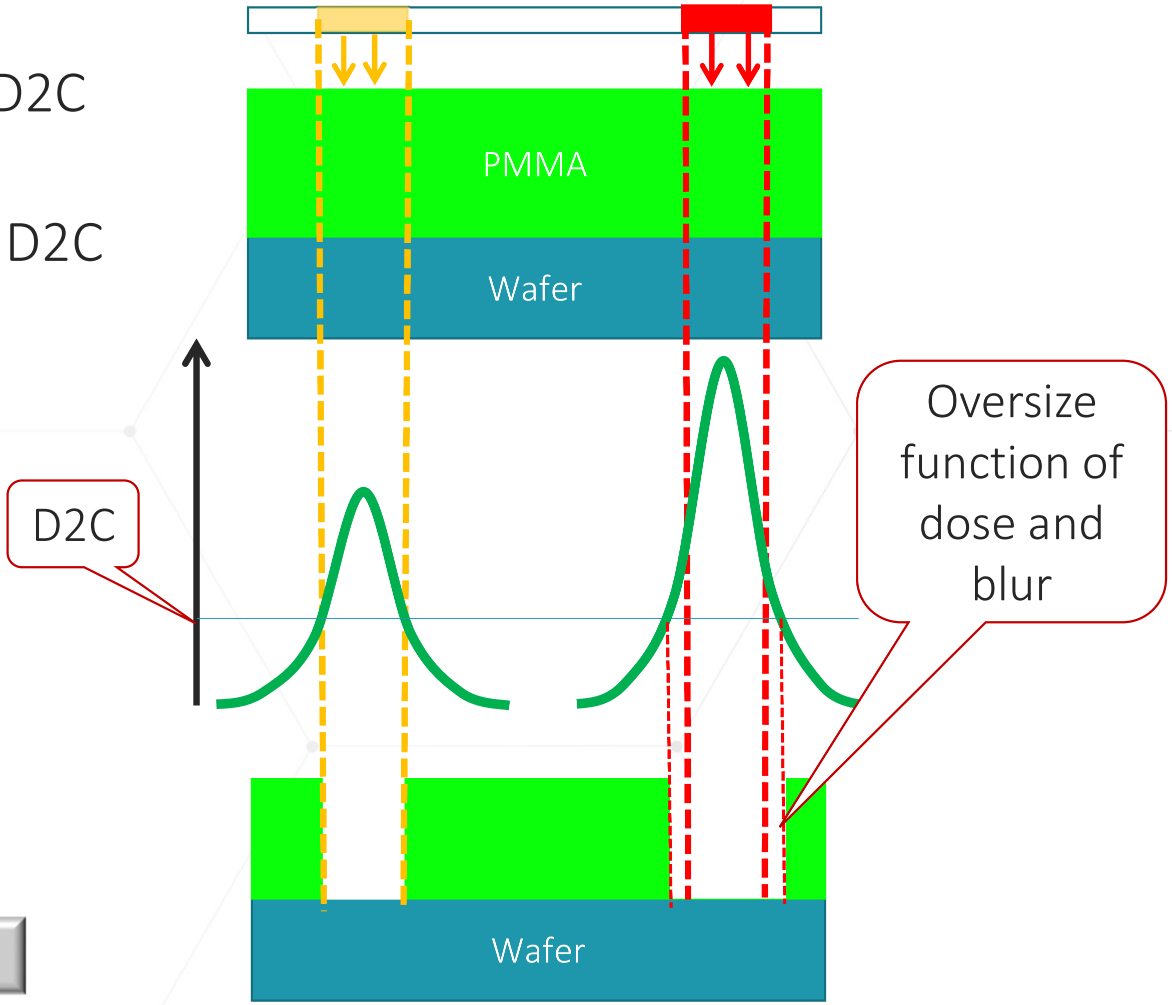


2D Intensity Simulation

- Threshold model assumes
  - 0 development (dissolution) rate < D2C
  - ∞ development rate > D2C
  - Resist is clearing at same time for > D2C

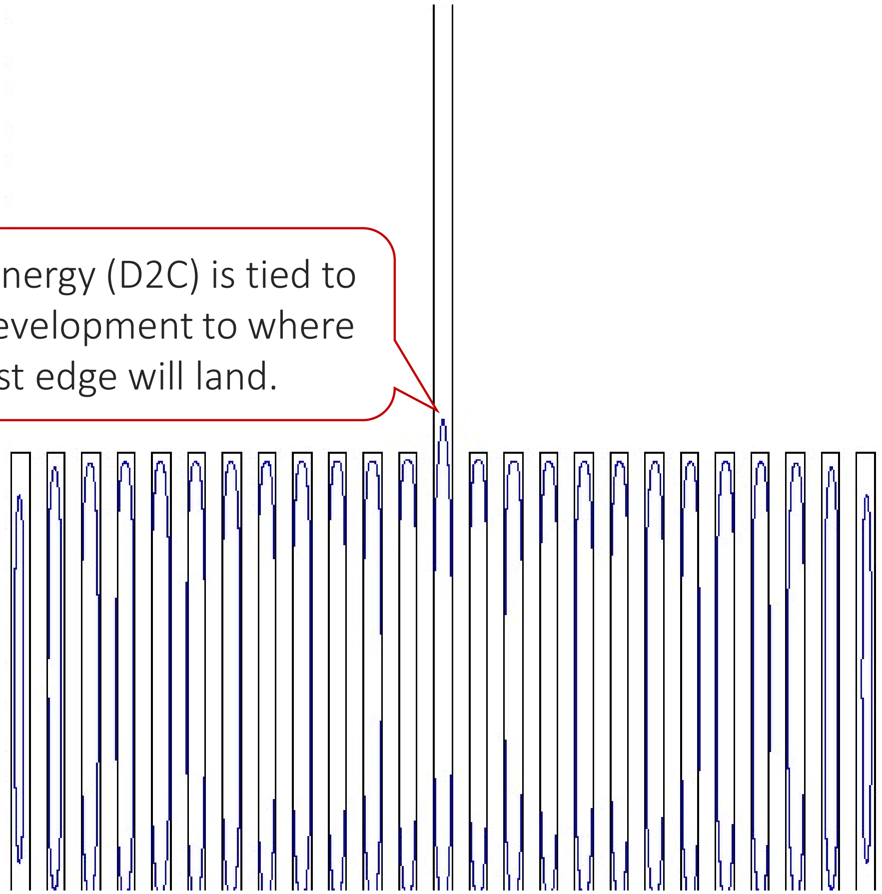


Works well for thin resist & high-contrast



Oversize function of dose and blur

Resist Contour

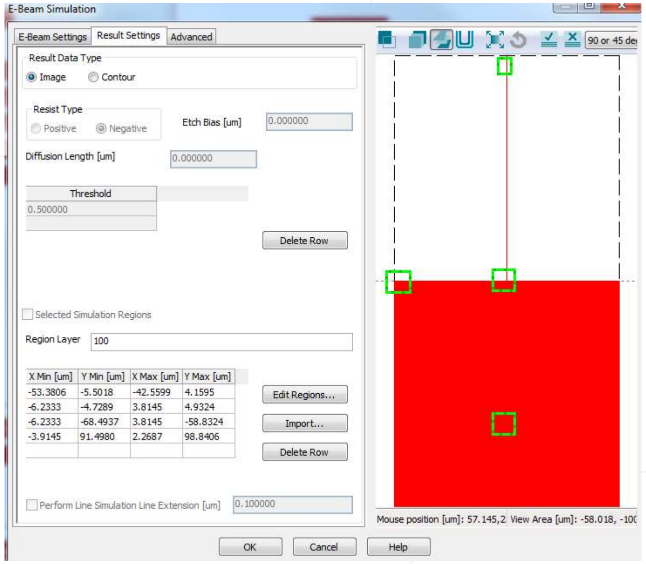


A constant energy (D2C) is tied to the resist development to where the resist edge will land.

BEAMER 2D Simulation

Extended e-beam simulation functions

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



Result Data Type: ● Image ○ Contour

Resist Type: ○ Positive ● Negative

Etch Bias [um]: 0.000000

Diffusion Length [um]: 0.000000

Threshold
0.500000

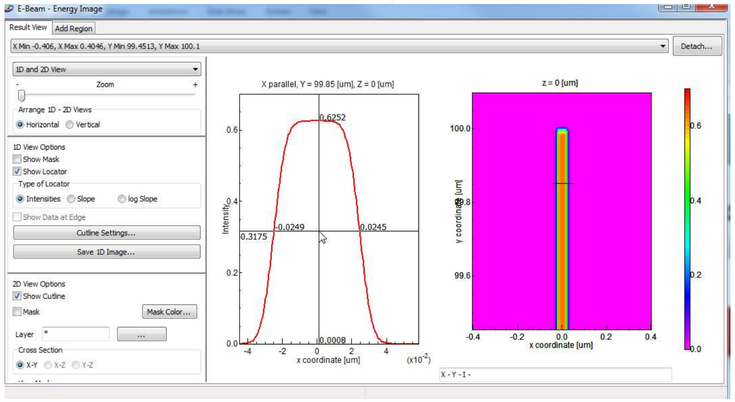
☐ Selected Simulation Regions

Region Layer: 100

X Min [um]	Y Min [um]	X Max [um]	Y Max [um]
-53.3806	-5.5018	-42.5599	4.1595
-6.2333	-4.7289	3.8145	4.9324
-6.2333	-68.4937	3.8145	-58.8324
-3.9145	91.4980	2.2687	98.8406

☐ Perform Line Simulation Line Extension [um]: 0.100000

Mouse position [um]: 57.145,2 View Area [um]: -58.018, -10C



X Min -0.406, X Max 0.4046, Y Min 99.4513, Y Max 100.1

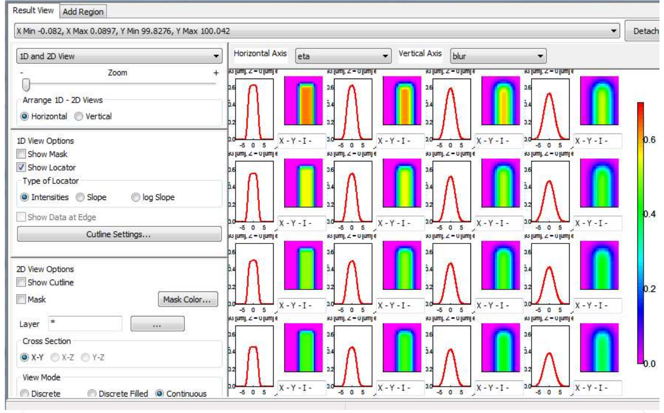
1D and 2D View

Arrange 1D - 2D Views: ● Horizontal ○ Vertical

1D View Options
☐ Show Mask
☑ Show Locator
Type of Locator: ● Intensities ○ Slope ○ log Slope
☐ Show Data at Edge

2D View Options
☑ Show Cutline
☐ Mask
Layer: *

Cross Section: ● X-Y ○ X-Z ○ Y-Z



X Min -0.082, X Max 0.0897, Y Min 99.8276, Y Max 100.042

1D and 2D View

Horizontal Axis: eta

Vertical Axis: blur

Arrange 1D - 2D Views: ● Horizontal ○ Vertical

1D View Options
☐ Show Mask
☑ Show Locator
Type of Locator: ● Intensities ○ Slope ○ log Slope
☐ Show Data at Edge

2D View Options
☐ Show Cutline
☐ Mask
Layer: *

Cross Section: ● X-Y ○ X-Z ○ Y-Z

View Mode: ○ Discrete ○ Discrete Filled ● Continuous

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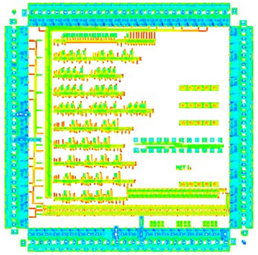
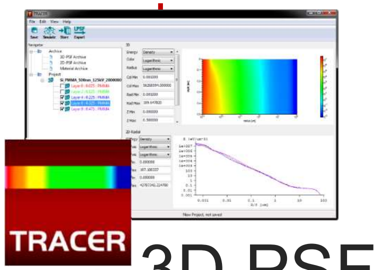
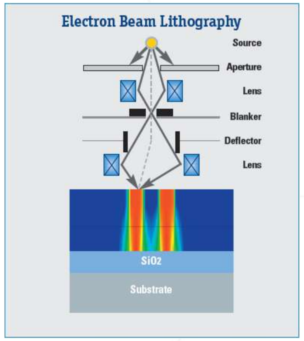
3D e-Beam Lithography Simulation

Layout

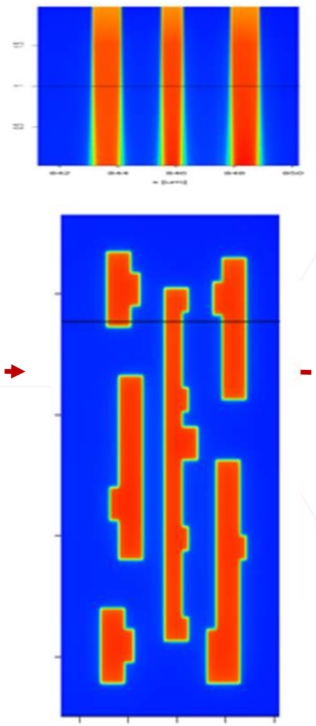




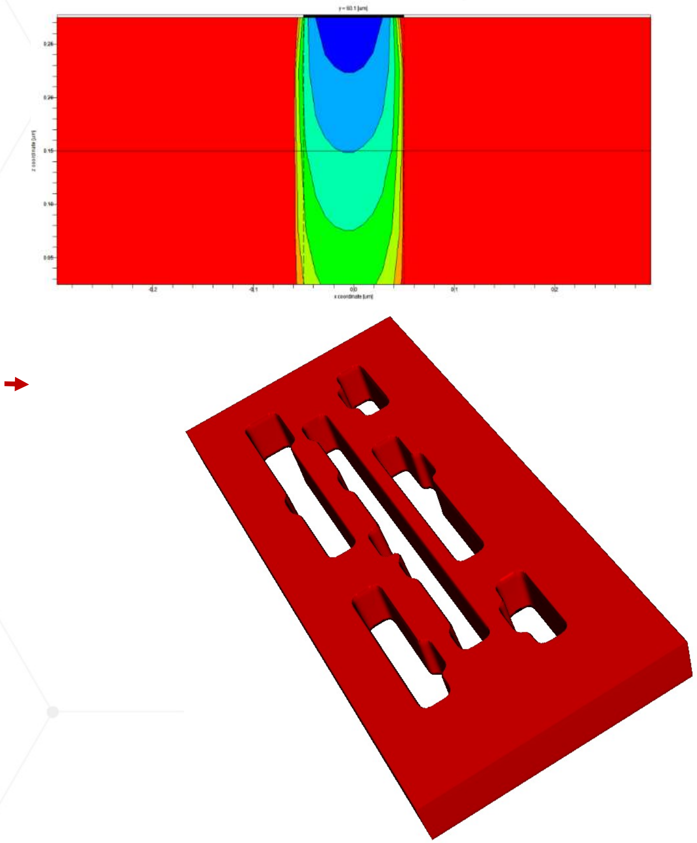
3D PSF



E-Beam
Exposure



3D
Bulk Energy



3D Resist Development

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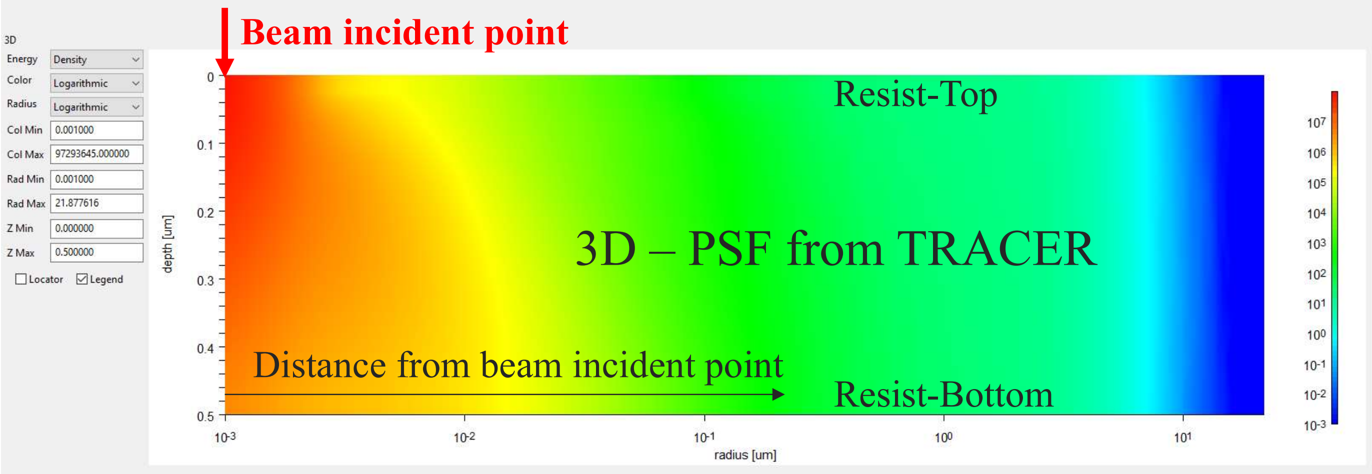
3D Energy Modelling

3D absorbed energy in the resist:

- Convolving the (dose modulated) layout with 3D PSF
- 3D PSF and stack definition need to match



3D
Energy: Density
Color: Logarithmic
Radius: Logarithmic
Col Min: 0.001000
Col Max: 97293645.000000
Rad Min: 0.001000
Rad Max: 21.877616
Z Min: 0.000000
Z Max: 0.500000
☐ Locator ☑ Legend

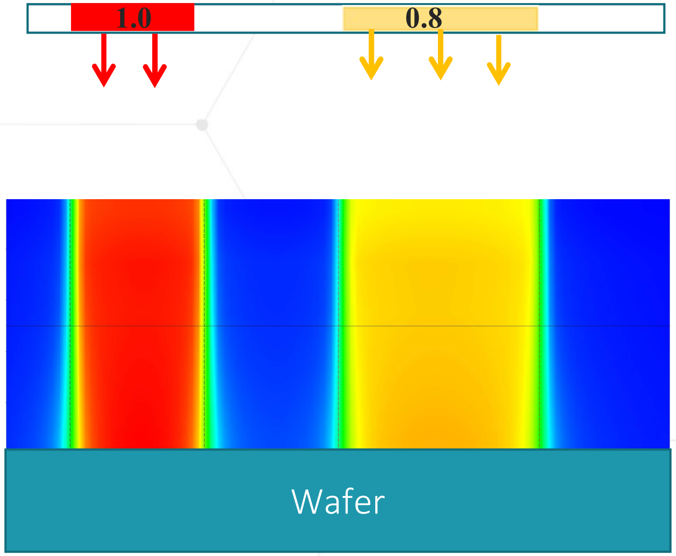
Beam incident point

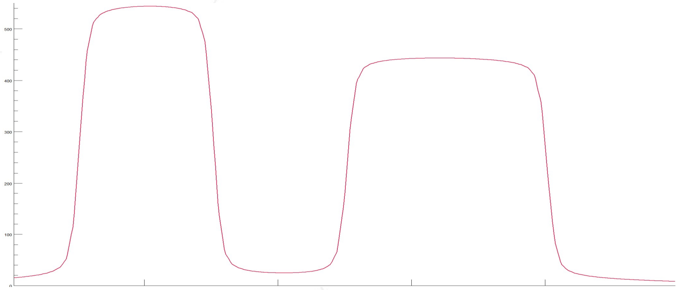
Resist-Top

3D – PSF from TRACER

Distance from beam incident point

Resist-Bottom



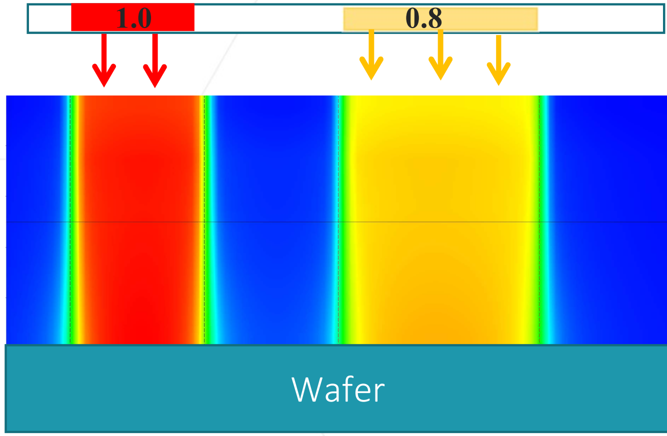


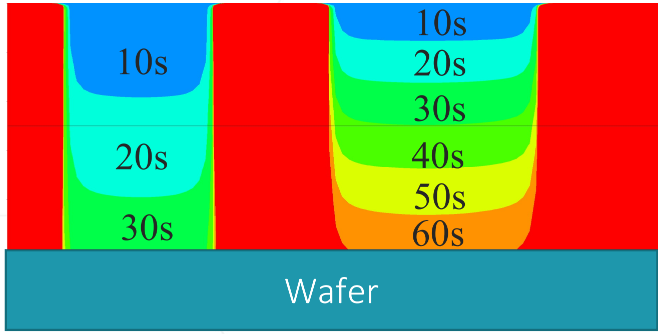
3D Resist Modelling

3D resist development model based on development rate model parameter:

- Bulk image intensities are converted in dissolution rate
  - Threshold / Diffused Threshold
  - Development rate model preferred for e-beam lithography
  - MACK 4 Model preferred for optical lithography, but may also be used for e-beam with DNQ type resists
  - CAR Models for chemically amplified resists

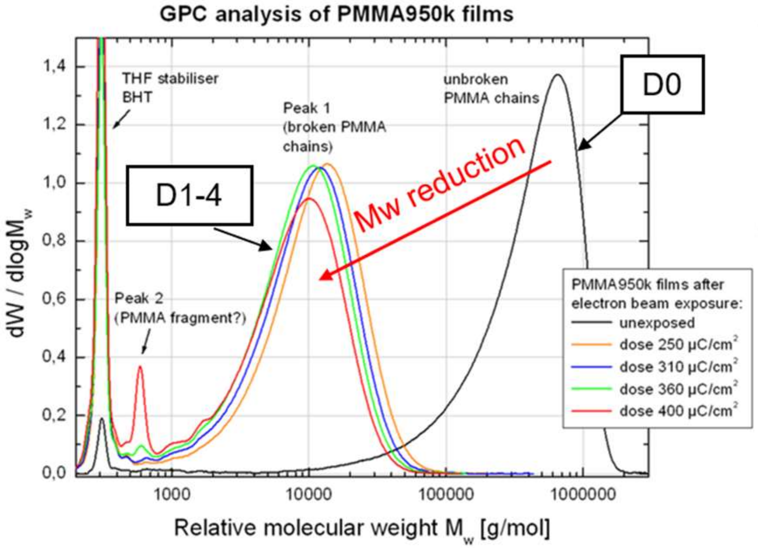
- The development front over is modeled removing the resist from top to bottom over development time using a fast marching algorithm
  - Moving in all direction (isotropic “etching”) depending on local dissolution rate



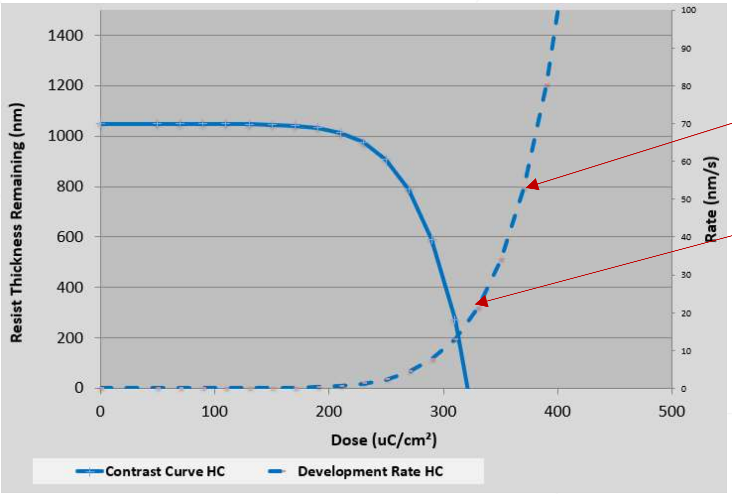


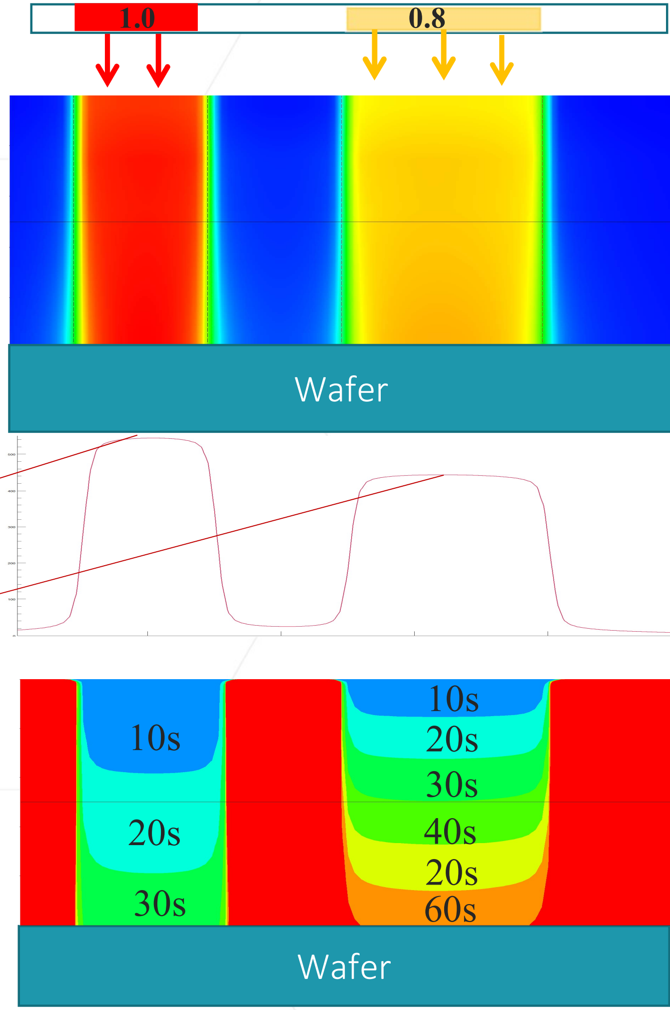
Development Rate Model

- Typical positive Resist (PMMA) process
  - Exposure is changing resist chemistry (e.g. molecular weight)
  - Dissolution rate is depending on local change of chemistry (e.g. higher rate for lower molecular weight)
  - Development rate is function of developer and temperature



PSI: Schleunitz A., et al. (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.





Simplest way to measure Development Rate: Contrast Curve

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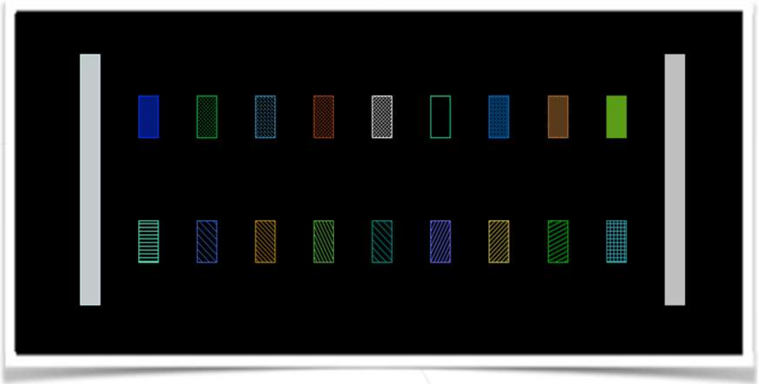
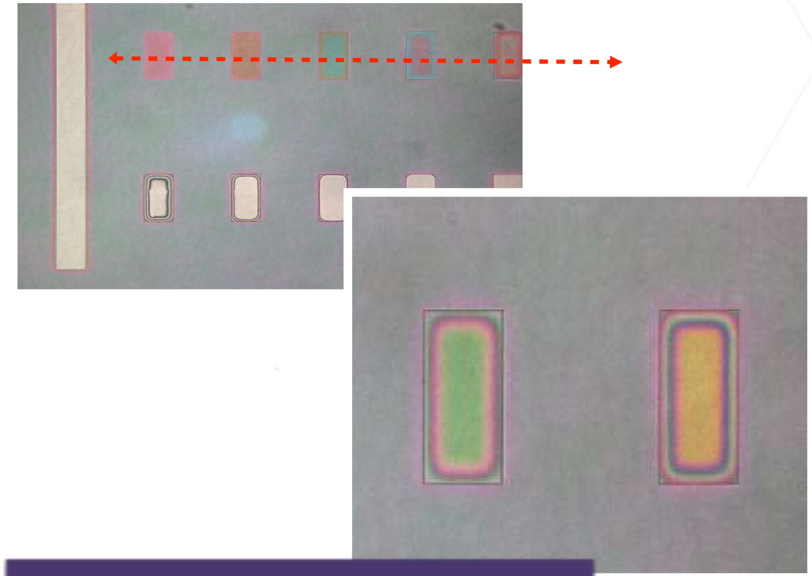
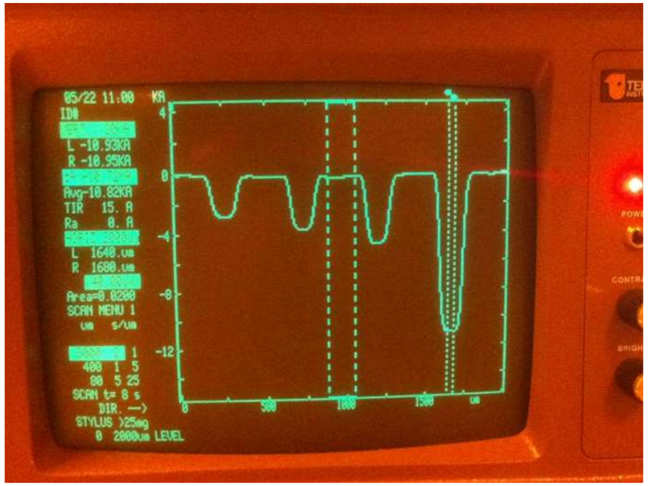
Measuring Resist Contrast Curve

- Expose pattern of shapes with varying dose
  - Width > 3 × Beta or PEC corrected (want flat region)
  - Size easy to measure with profilometer, spectrophotometer ellipsometer, AFM
  - This example, for 100 kV on Si, uses 150 um x 300 um rectangles

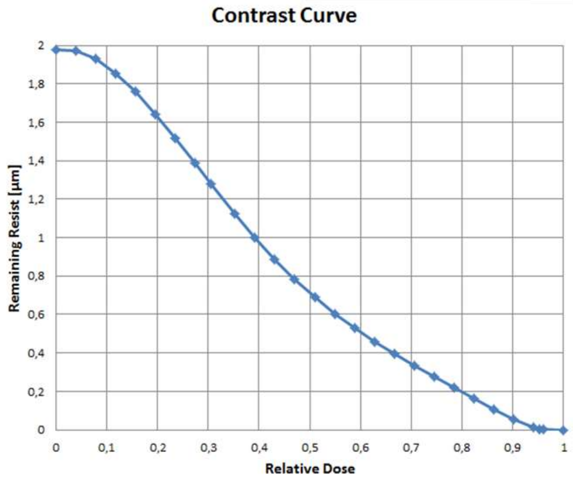




UNIVERSITY of WASHINGTON

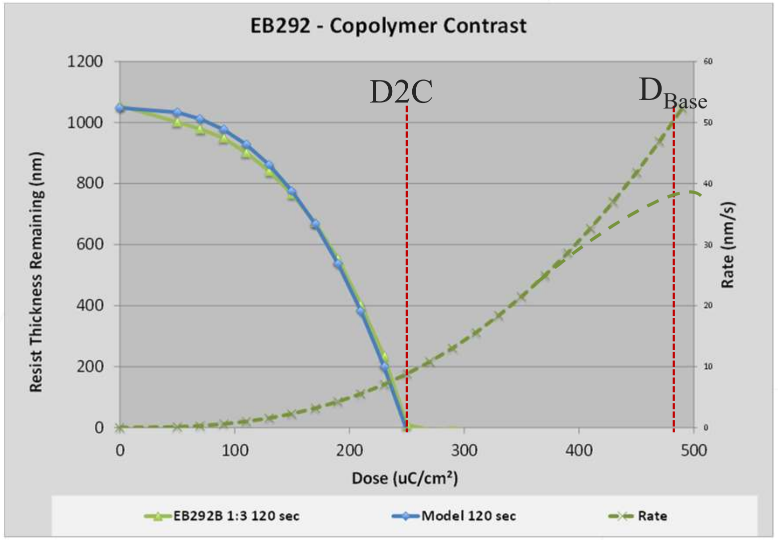


```
05/22 11:00
ID#
L -10.93KA
R -10.95KA
Avg-10.82KA
TIR   15. A
Ra     0. A
L  1640.um
R  1680.um
Area=0.0200
SCAN MENU 1
  um   s/um
           1
 400   1   5
  80   5  25
SCAN t= 8 s
   DIR. —>
STYLUS >25mg
  0  2000um LEVEL
```



Rate Extrapolation

- Development rate table/curve can be generated from the contrast curve

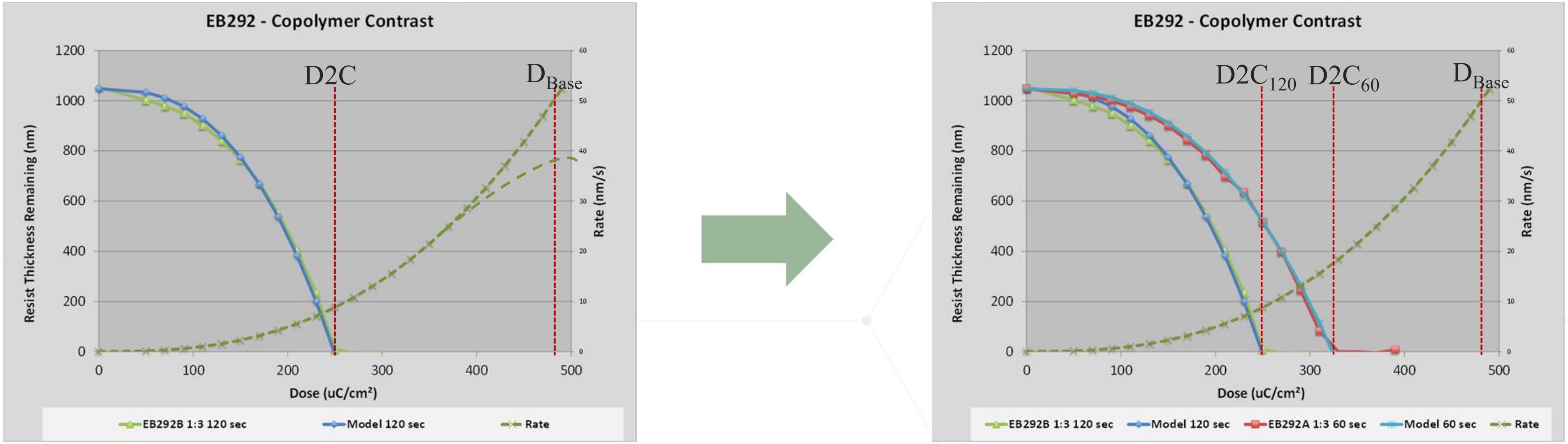


IMPORTANT:

- Contrast Curve is measured only until D2C , binary lithography is using much higher doses (~x2)
- Development rates for higher doses need to be extrapolated (to this Base Dose)
  - How good is this extrapolation? Does it follow a power law, or does it “saturate”?

Rate Extrapolation

- Development rate table/curve can be generated from the contrast curve

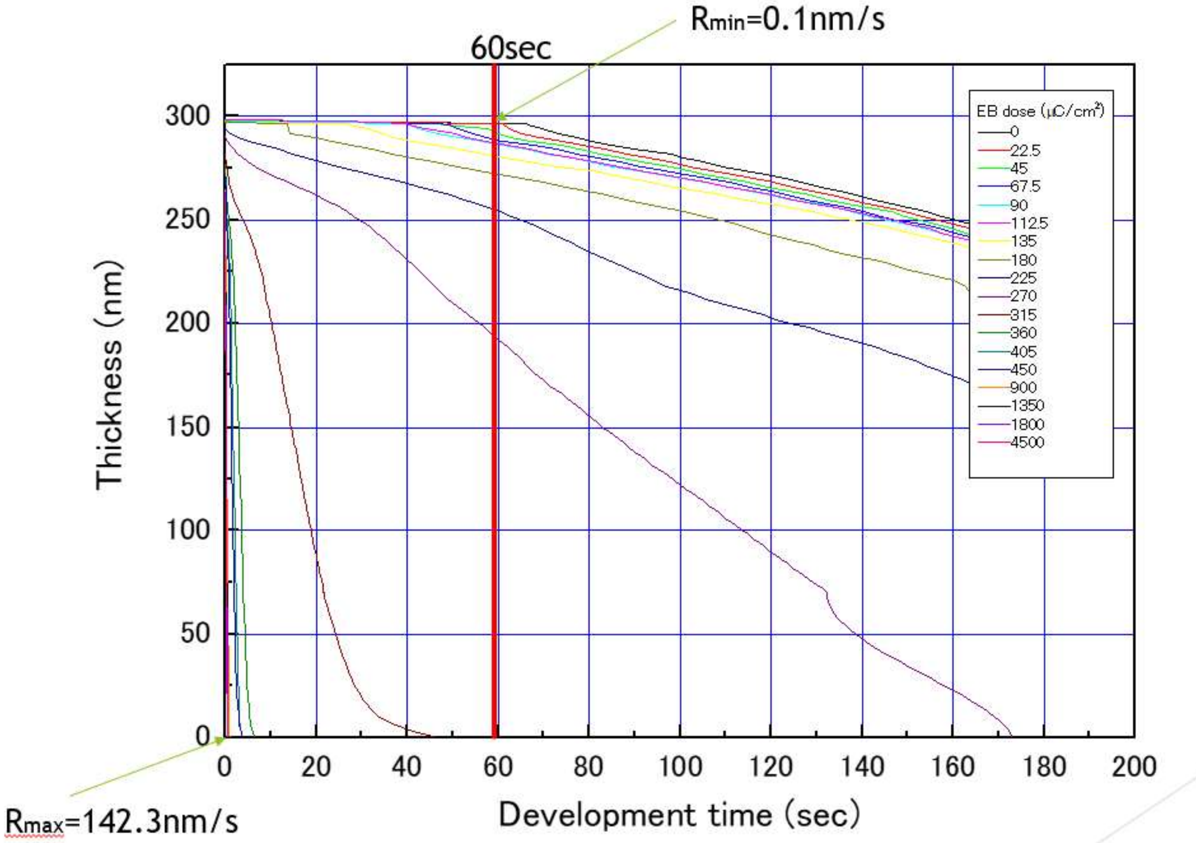


IMPORTANT:

- Contrast Curve is measured only until D2C , binary lithography is using much higher doses (~x2)
- Development rates for higher doses need to be extrapolated (to this Base Dose)
  - How good is this extrapolation? Does it follow a power law, or does it “saturate”?
- Measure CC at shorter development time
  - Identical rate model for both – this supports power law extrapolation beyond the measurable part

$r = r_0 (D / D_0)^{\gamma}$
r : rate at dose D
r_0 : rate at dose D_0

Development Rate with RDA system



Thickness and development time depend on exposure dose

RDA-800 LTJ リソテックジャパン株式会社 Litho Tech Japan

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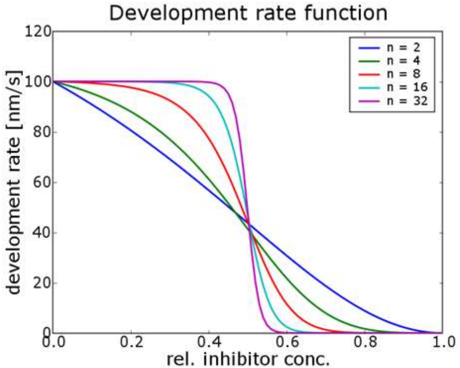
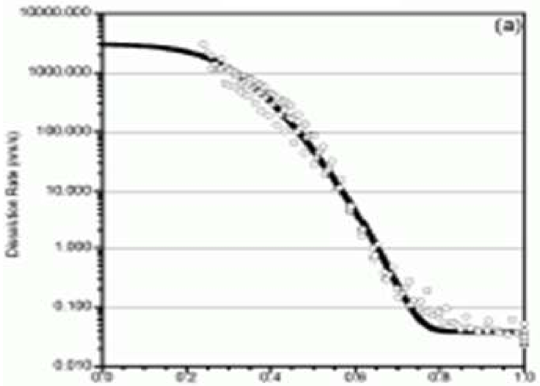
Mack Development Model

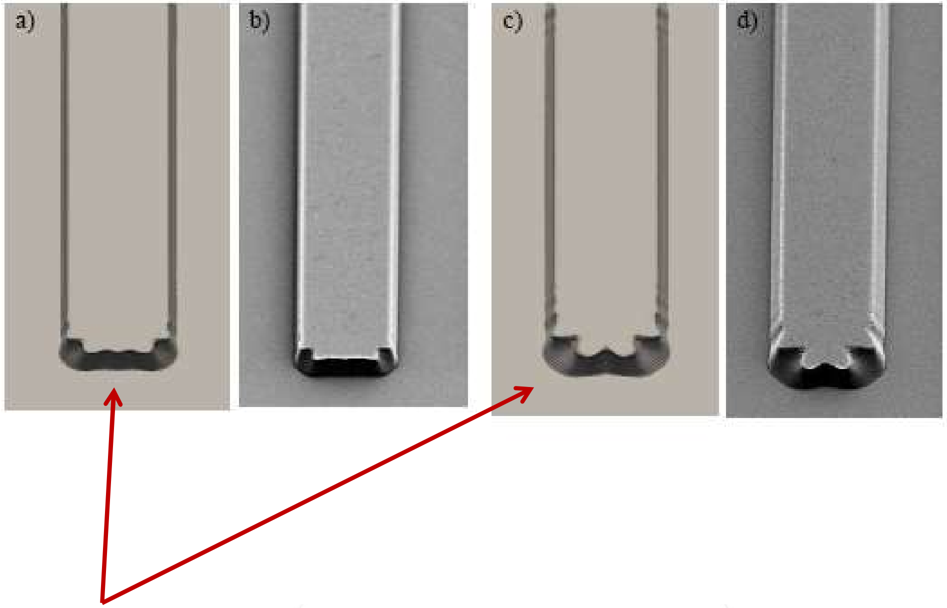
Some Typical Mack Development Rate Parameters



fit of experimental data with Mack model



3D resist simulation vs. experiment after resist parameter calibration



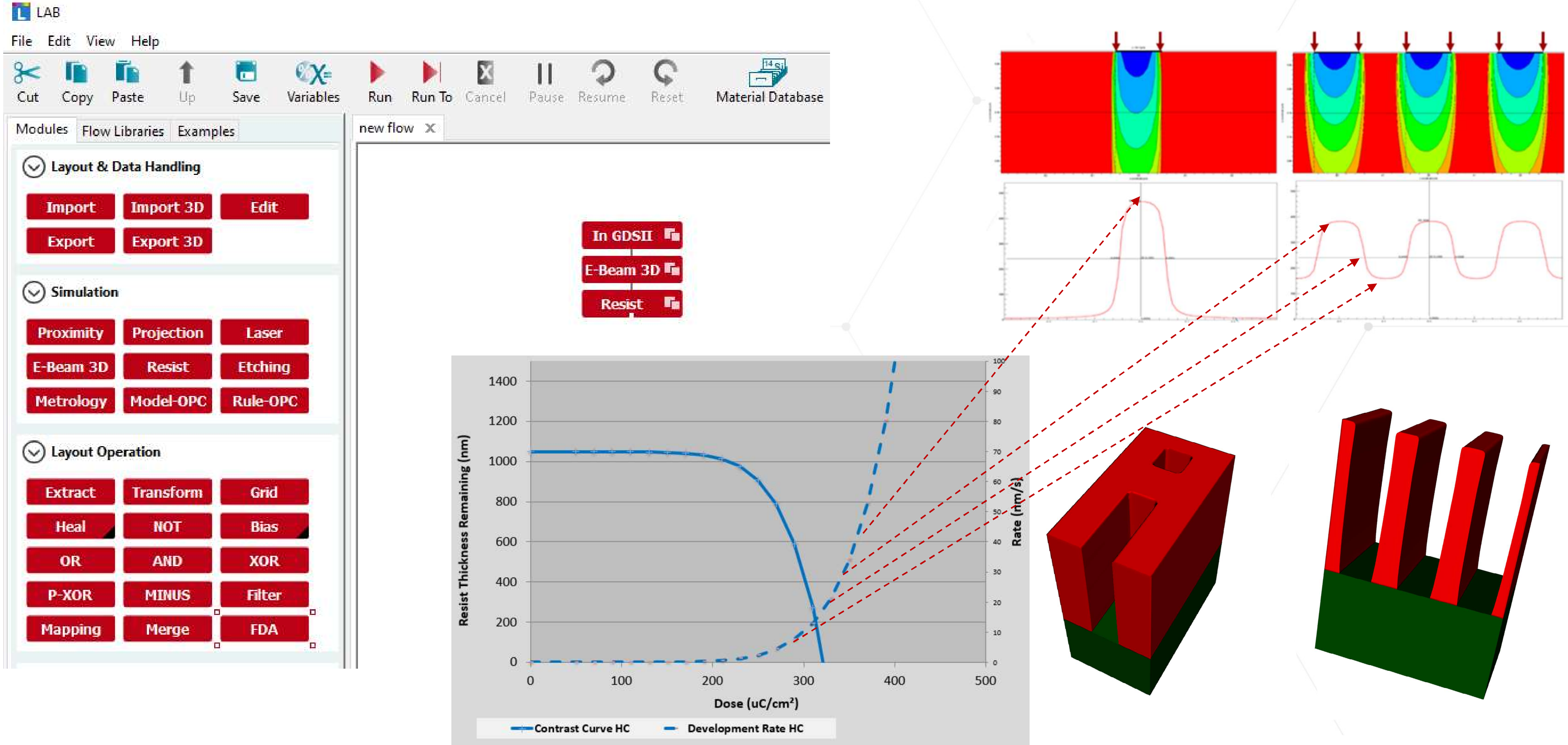
Simulation

Lithography Simulation

from A. Erdmann: Lithography Lecture

Fraunhofer
IISB

LAB Simulation: Origin of Lateral Development



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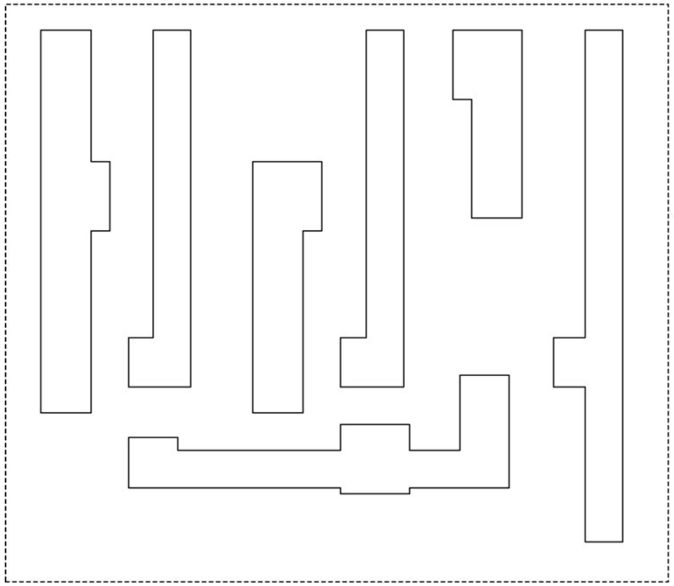
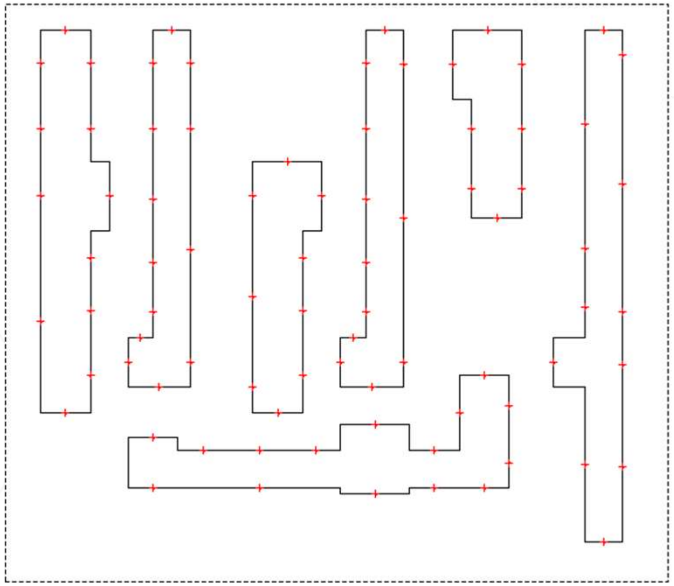
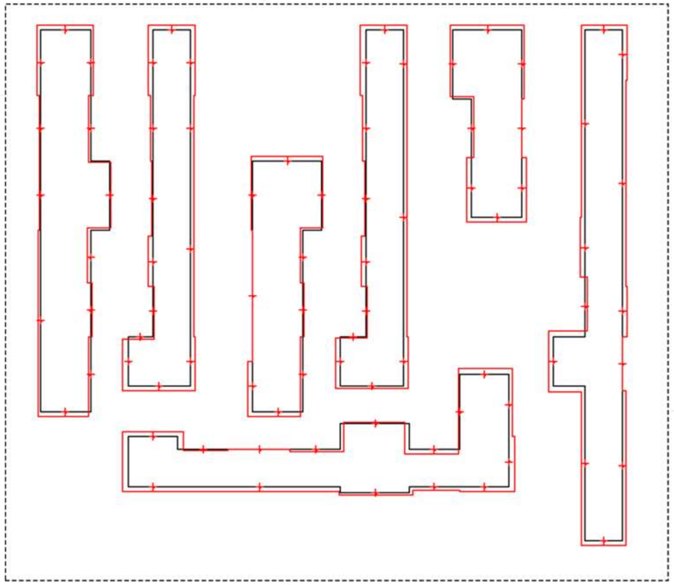
Shape PEC Principle







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

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

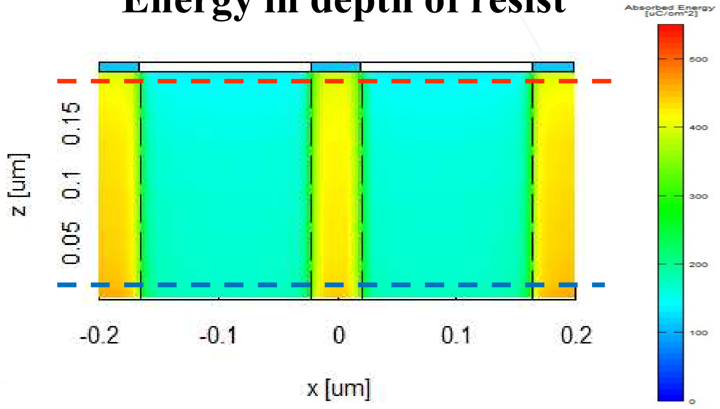
Move for all PEC segments (eval. points) are iteratively adjusted.

Bulk Energy

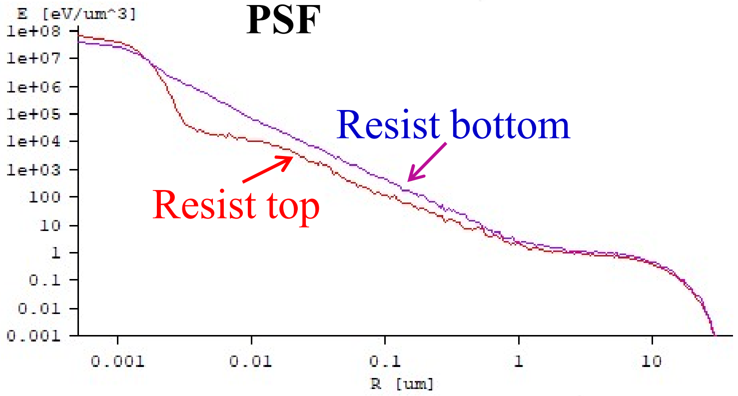
- Simulation is carried out for 100keV electron exposure on 200nm PMMA on GaAs substrate
- The PSF varies with beam scattering into the resist.
- 20% more energy at the bottom for unexposed area.

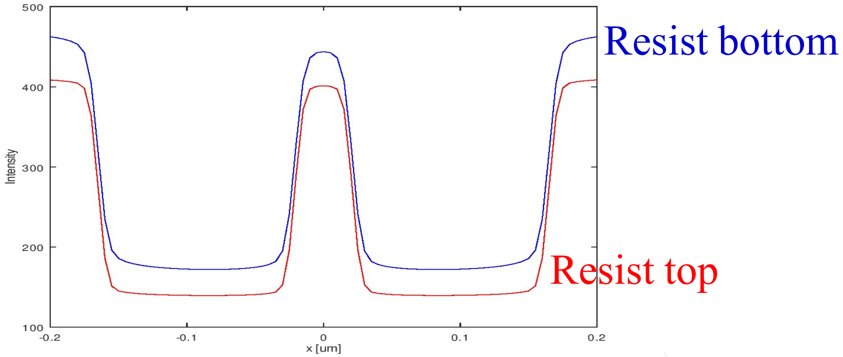
Energy in depth of resist

ODUS (overdose = 2)



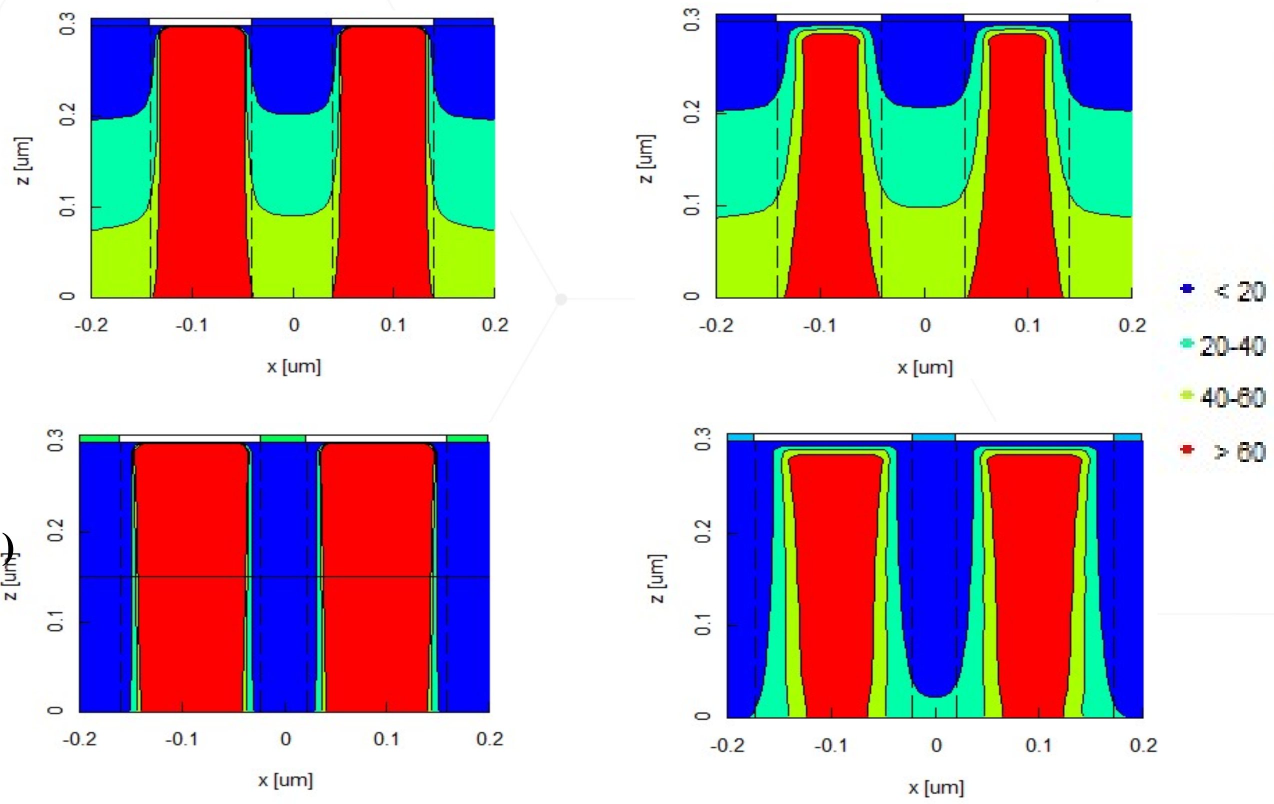
PSF





Substrate

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

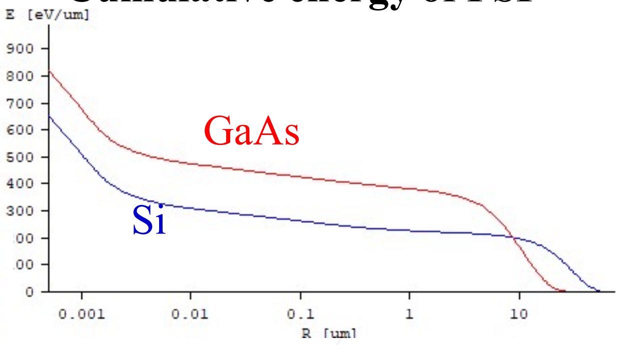


Si

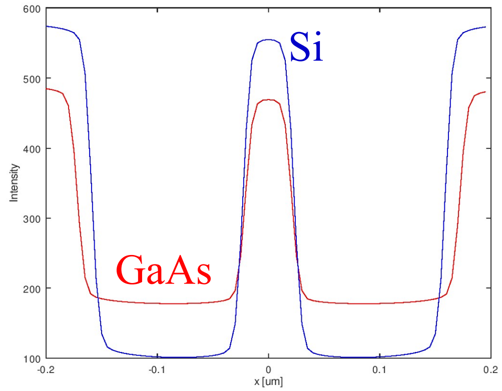
GaAs

Dose PEC

ODUS (overdose = 2)

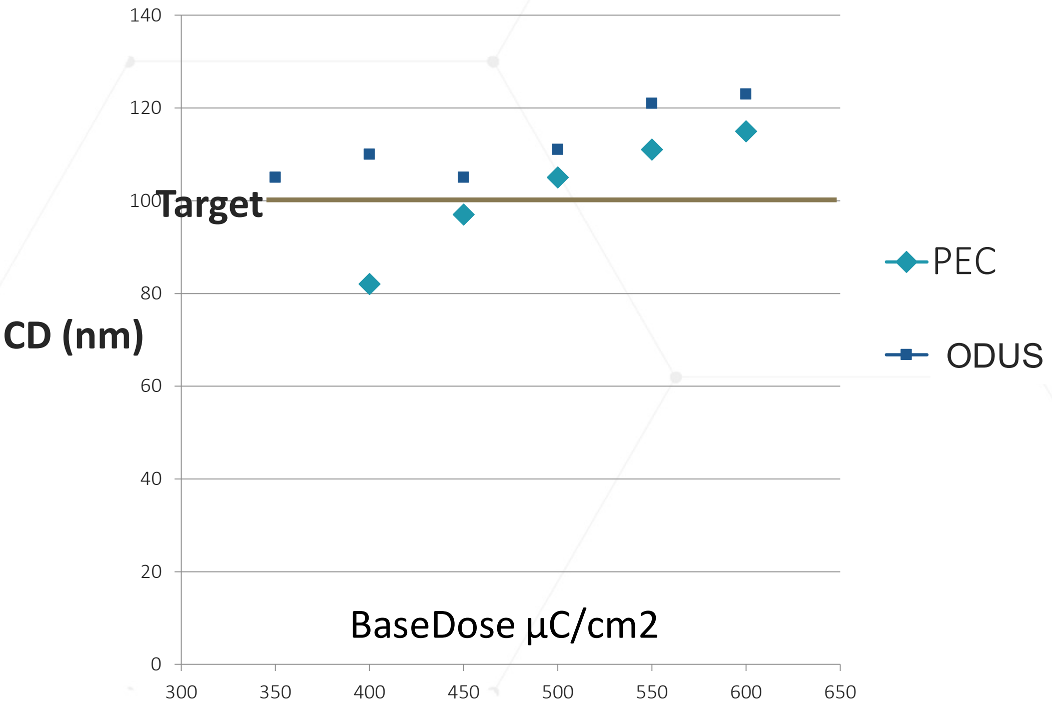


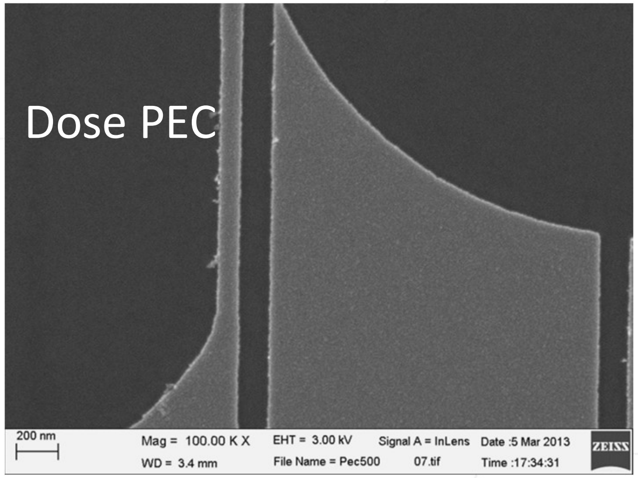
Cumulative energy of PSF

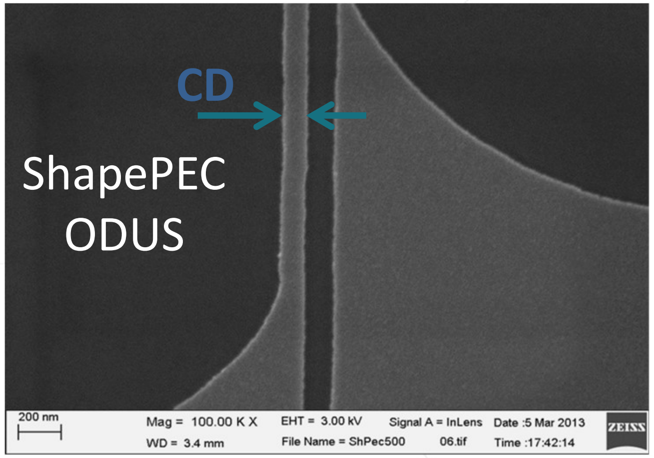


Application: Single Layer Lift-off

Base dose effect on CD



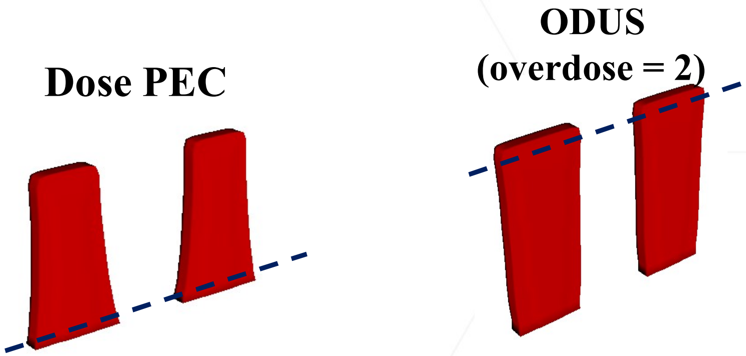




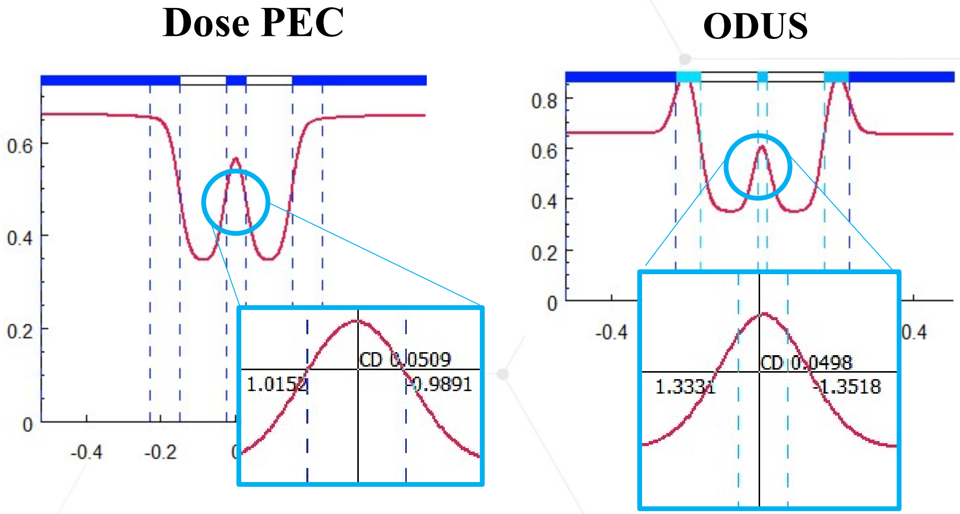
Bigger lift-off process window
when using ODUS
(resist edge-slope)

Simulated CD Sensitivity

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



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

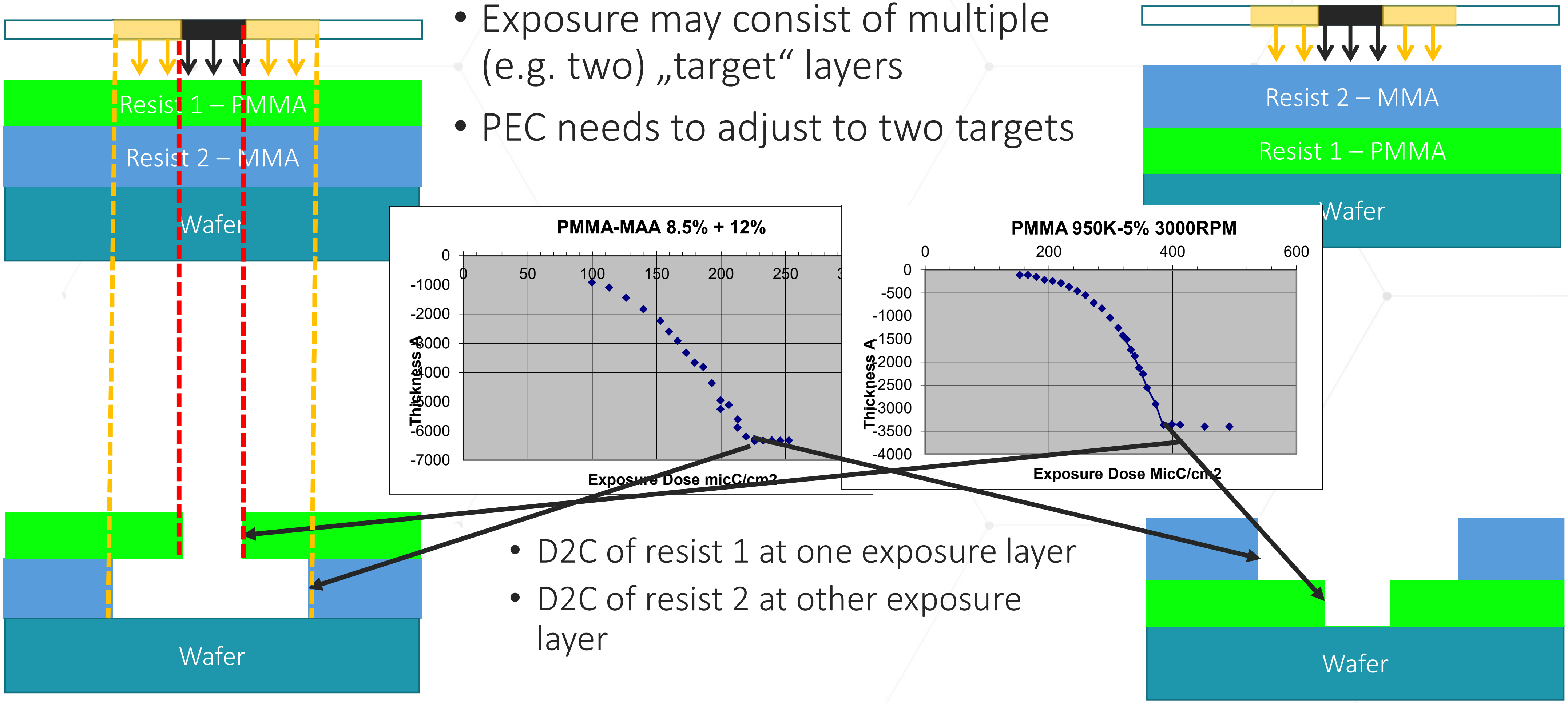


Outline

- E-Beam Exposure Simulation
- 3D Resist Development Simulation
  - 3D Simulation using LAB
  - Lateral development effect
- Over-Dose-Under-Size ODUS
- Multi Layer Resist Processes
- Greyscale (3D) Lithography
- Summary
- Q&A

Multi Layer Resist Process

- Exposure may consist of multiple (e.g. two) „target“ layers
- PEC needs to adjust to two targets



- D2C of resist 1 at one exposure layer
- D2C of resist 2 at other exposure layer

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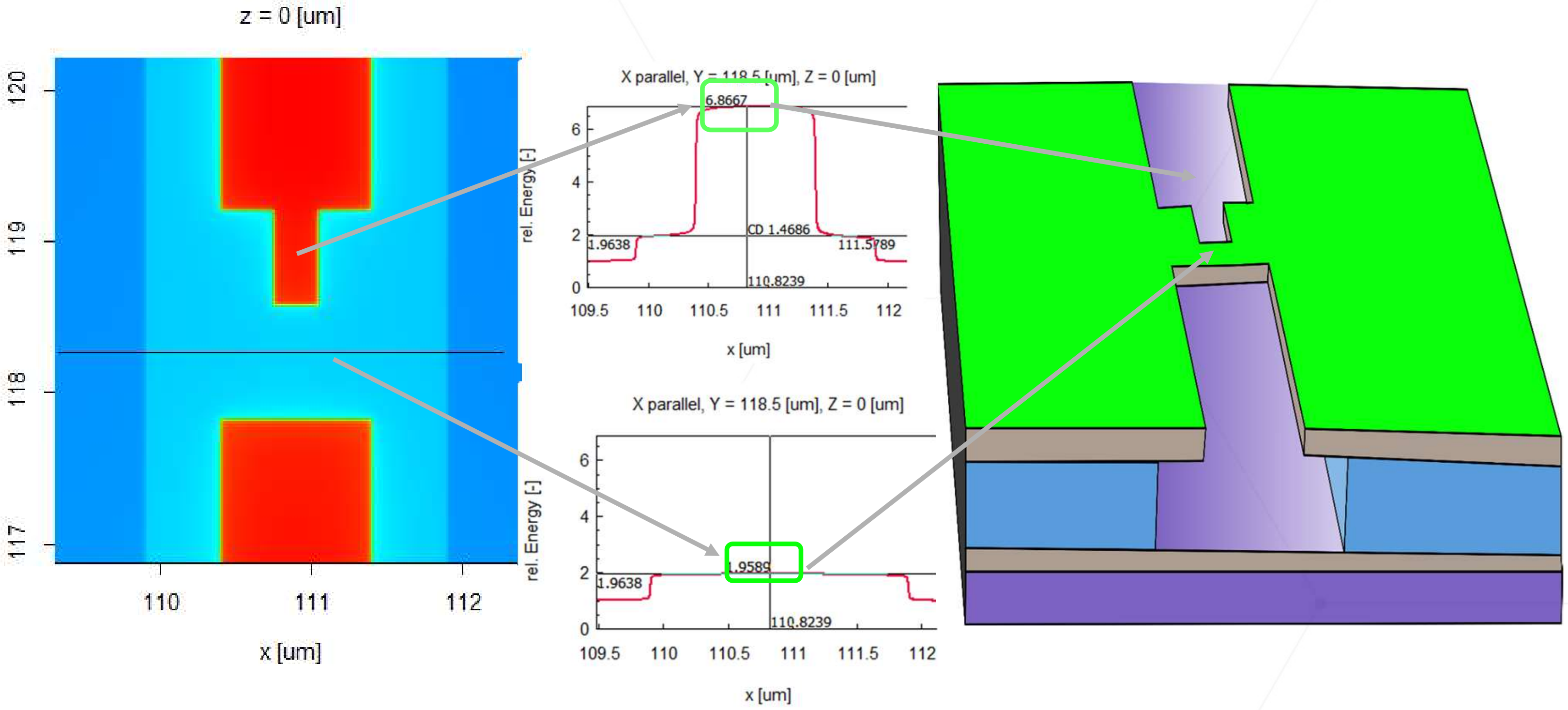
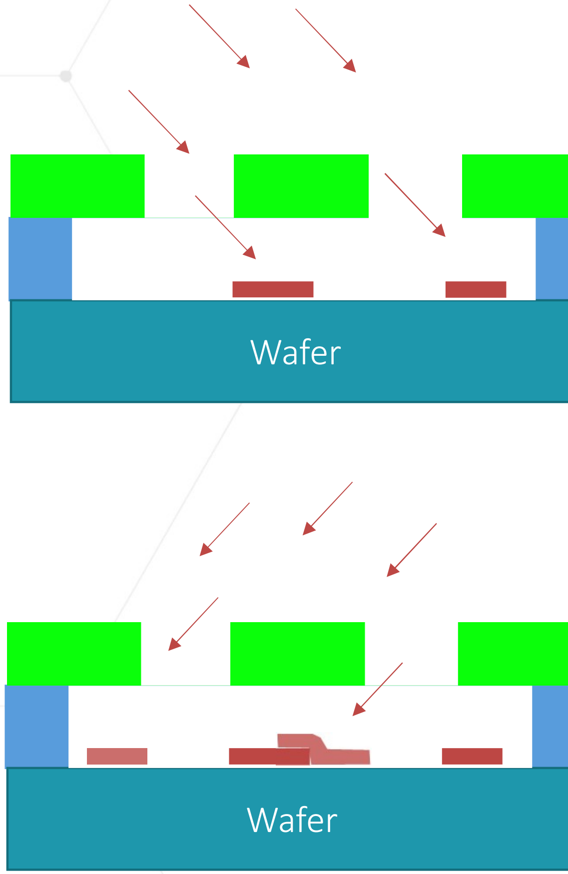
Application Case: Dolan Bridge



E-beam Simulation

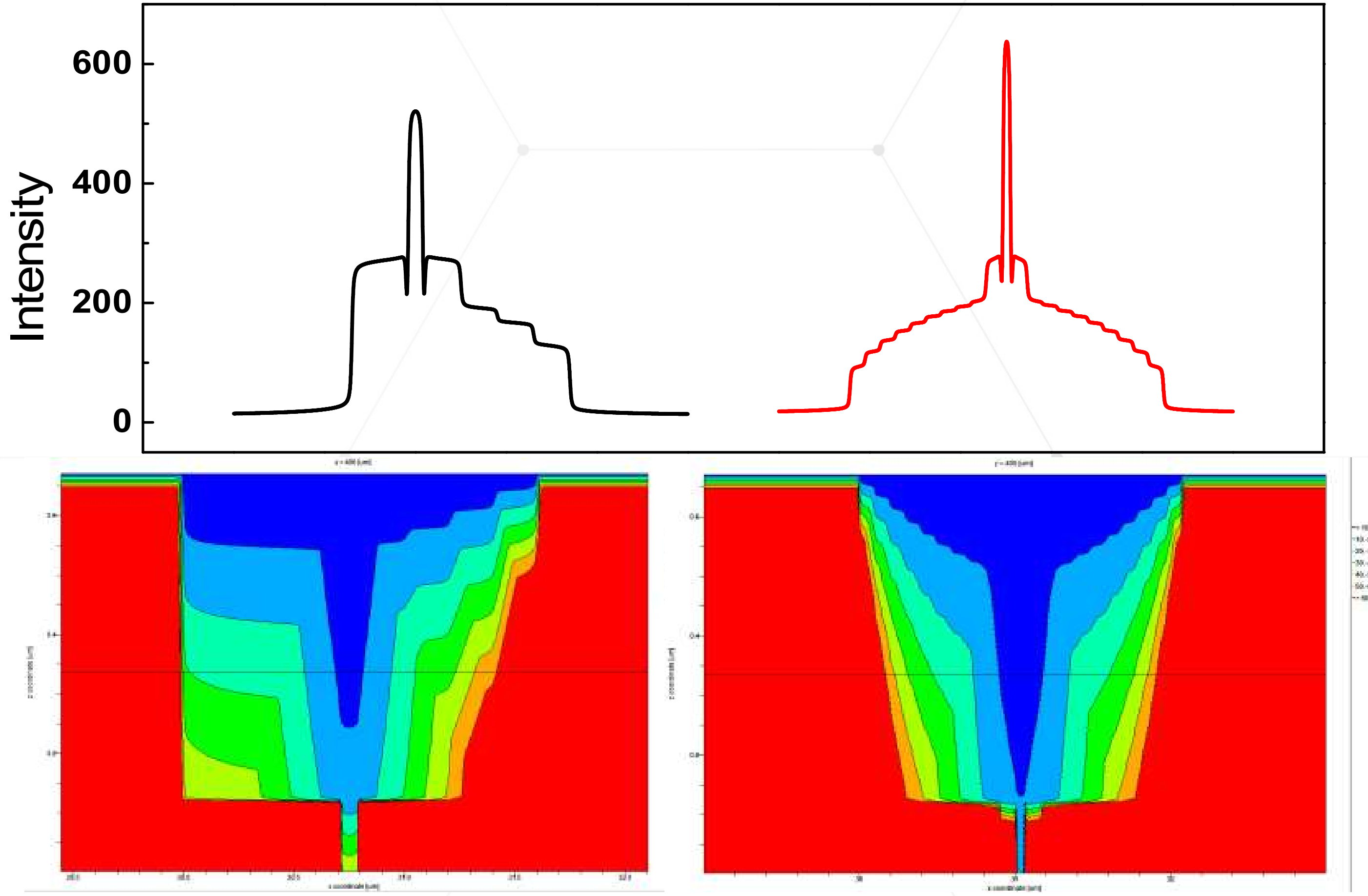
After Development



Evaporation with 2 angle

Application Case: T-Gate

- Combination of multi-layer resist and dose steps on the wing.
- Energy and resist development front after BEAMER correction



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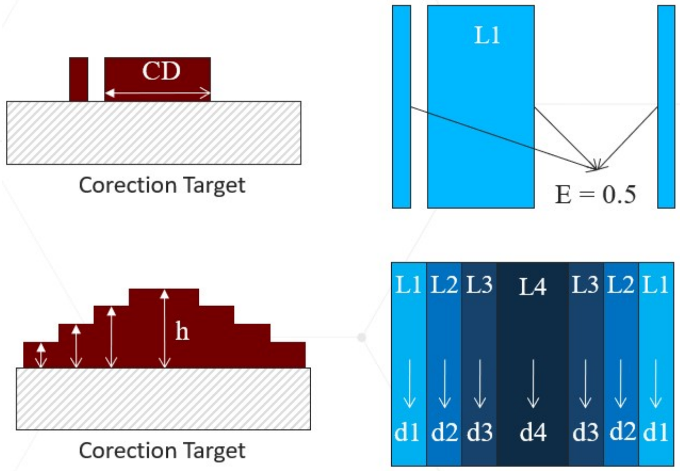
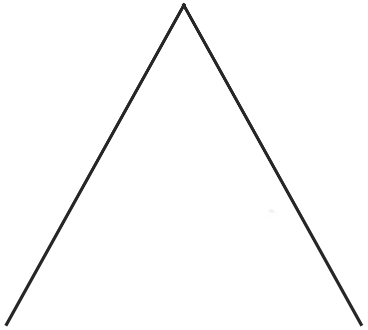
3D Grayscale

- Grayscale lithography requires
  - Adjust absorbed energy at all location
  - Consider contrast curve (development rate) for target
  - Consider proximity effect, also over z (resist thickness)
  - Consider 3D development front

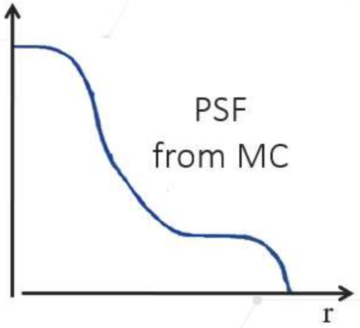


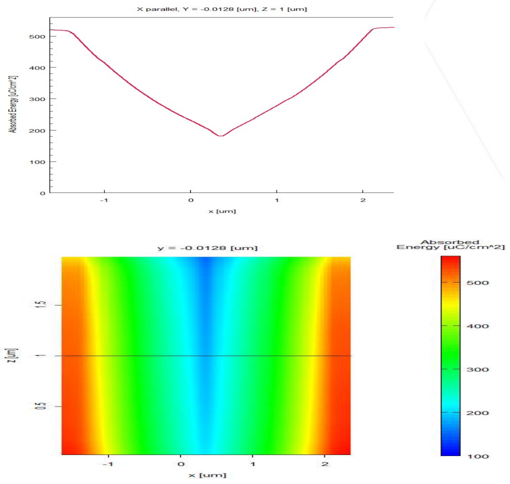
Corection Target

Corection Target

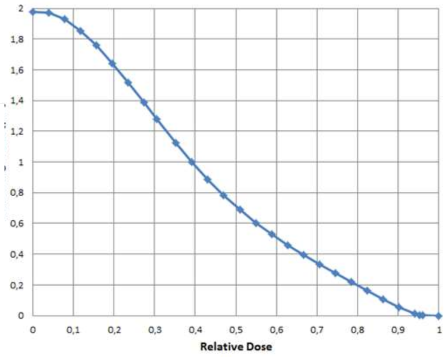


Target Shape

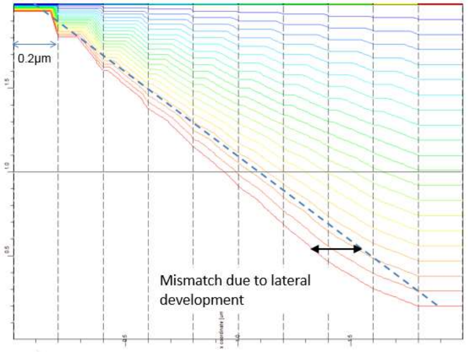




x – z Absorbed Energy



Contrast Curve

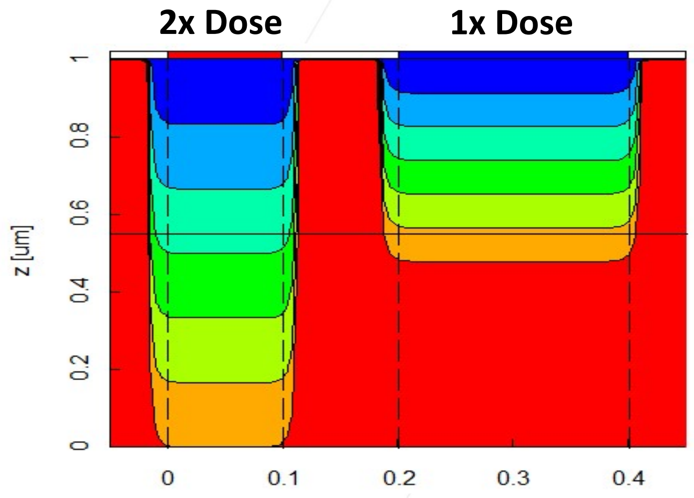


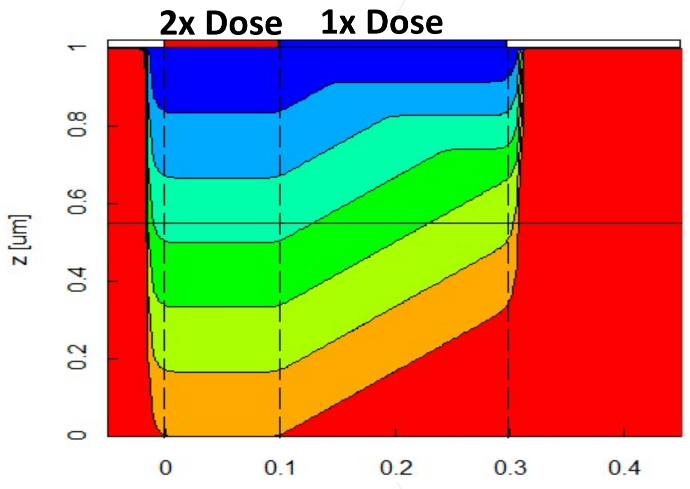
Lateral Development

Lateral Development

- Isolated shapes develop independently, with development rate depending on exposure dose

- When regions of different dose are adjacent, as in 3D lithography, the regions have a large interaction, and lateral development correction is essential if you want the correct height in each





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Summary

- Absorbed energy simulation of e-beam lithography is straight forward
  - Electron scattering PSF is modelled well by Monte-Carlo simulation
  - Absorbed energy in the resist iscomputed by convolution of PSF with the (dose modulated) layout
  - Absorbed image analisys enables optimization of litho quality (image contrast, cd/dose sensitivity)
  - 1st leve approach: x-y resist contour can be modelled using threshold model using
- 3D e-beam simulation including resist development process
  - Absorbed energies are transfered to dissolution rate using Development Rate Model
  - Develoment Rate Curve can be generated from Contrast Curve
  - Development front over development time is simulated using a fast marching with local development rates
- Application example for 3D e-beam simulation
  - Density dependent lateral development
  - Overdose-Undersize (ODUS) for improved resist profile
  - Multi-layer resist processes: Dolan Bridge, T-Gate with shaped wing
  - Greyscale (3D) lithography

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