ims chips

Institut für Mikroelektronik Stuttgart

Optimizing chemically amplified photoresist processes in electron beam lithography

Markus Greul & Jan Klikovits

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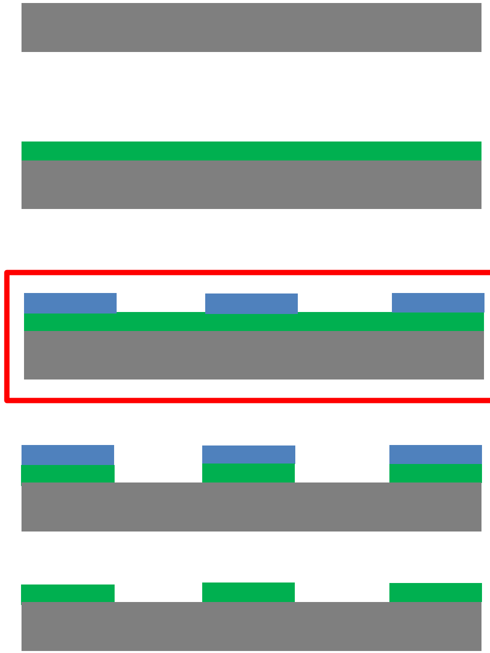
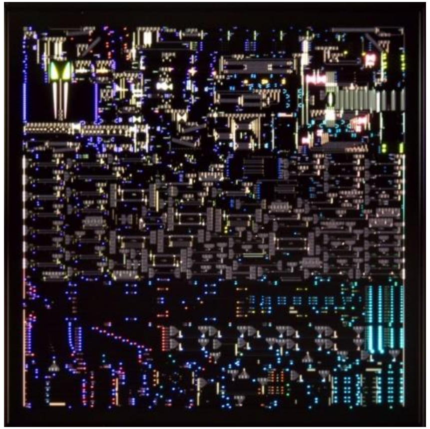
innBW INNOVATIONSALLIANZ BADEN-WÜRTTEMBERG

Precursor

- Schematic processing steps in micro- and nanopatterning





Substrate Cleaning

Layer Deposition

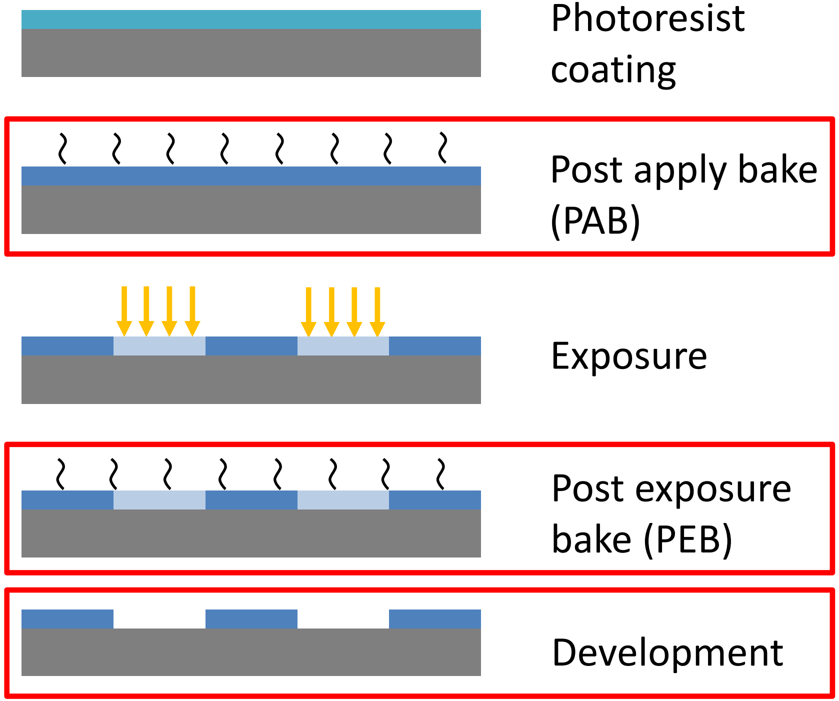
Lithography → Basis for pattern transfer and etched features

Etching

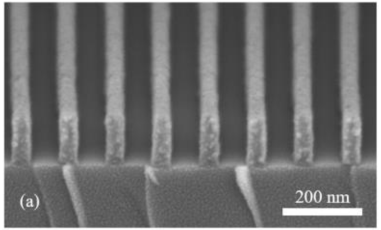
Resist Strip and Cleaning

Motivation

- Processing steps in lithography:



- Performance Characteristics:
  - Resolution limit
  - CD-Linearity
  - Line edge roughness
  - Sidewall angle
  - …



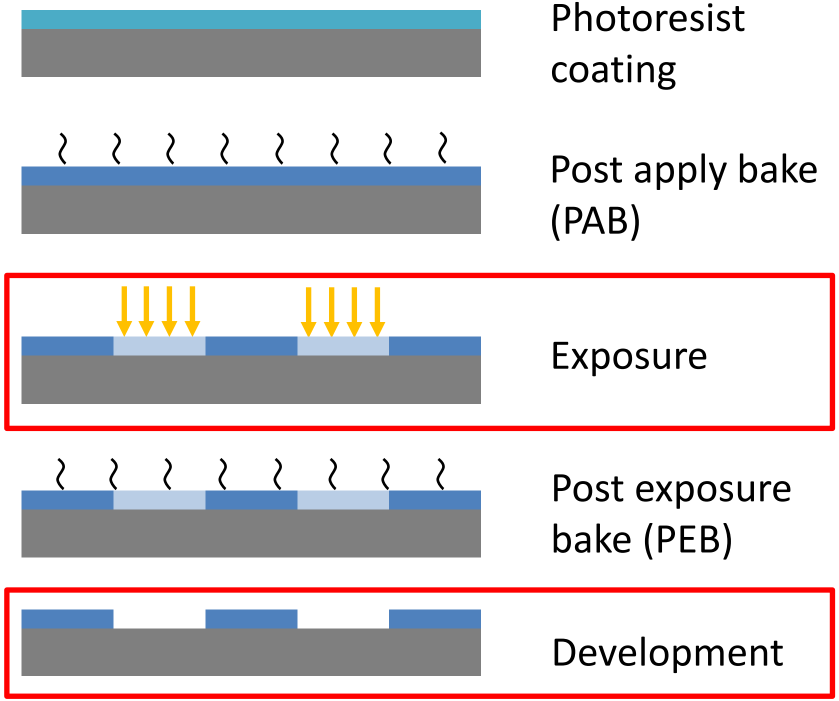
→ How to achieve overall good performance?

The first part will show how to optimize resist preparation and processing efficiently.

Motivation

GenISys Advancing the Standard | ims chips

- Processing steps in lithography:



The second part will show how GenISys software supports exposure and development modeling.

TRACER enables:

- E-beam and development model calibration
- Easy parameter export to BEAMER

BEAMER enables:

- E-beam proximity effect correction
- Non-CAR and CAR resists

LAB enables:

- Visualization of 3D development profiles

E-beam lithography at IMS

- Activities at IMS:
  - Micro- and nanopatterning on full wafer scale
    (research, development and production)
  - Substrate sizes: 100 mm to 430 mm
  - Small batches with different designs

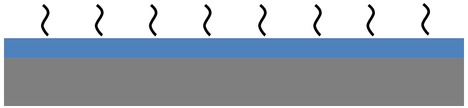
→ Requires: fast, flexible and well controlled high resolution exposure down to 30 nm

- Use of:
  - Variable shaped electron beam lithography (VSB)
  - Cell projection
  - Chemically amplified resists
    (different sensitivities, tonality and thicknesses)

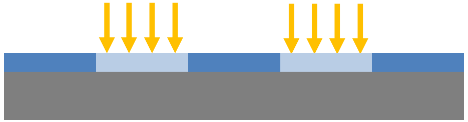
Short introduction to lithography

- Processing steps in lithography:
- Simple description:

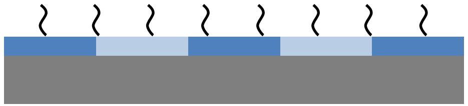
Photoresist coating — 0 Medium to transfer image information



Post apply bake (PAB) — 1 Preparing image information



Exposure — 3 Printing image information

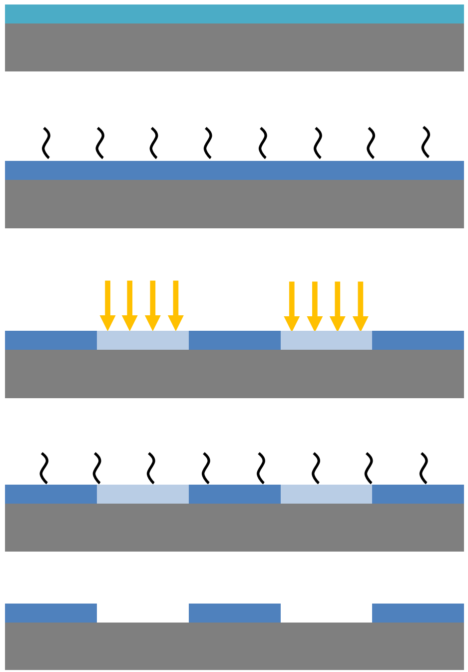


Post exposure bake (PEB) — 1 Preparing image information

Development — 2 Revealing image information

Short introduction to lithography

- Processing steps in lithography:



Photoresist coating

Post apply bake (PAB)

Exposure

Post exposure bake (PEB)

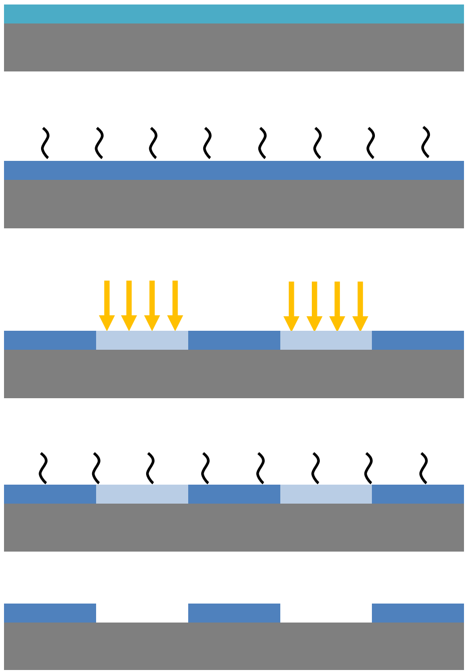
Development

- Parameters:

Step	Priority	Parameters		
Photoresist coating		Resist Thickness		
Post apply bake (PAB)	1	PAB Temperature	PAB Duration	
Exposure	3	Exposure Dose	Sizing	PEC
Post exposure bake (PEB)	1	PEB Temperature	PEB Duration	
Development	2	Development Time		

Short introduction to lithography

- Processing steps in lithography:



Photoresist coating

Post apply bake (PAB)

Exposure

Post exposure bake (PEB)

Development

- Parameters:

Resist Thickness

1 PAB Temperature | PAB Duration

3 Exposure Dose | Sizing | PEC

1 PEB Temperature | PEB Duration

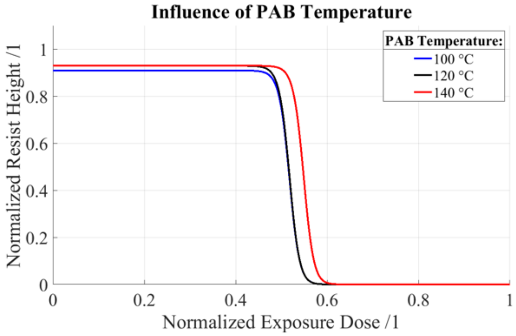
2 Development Time

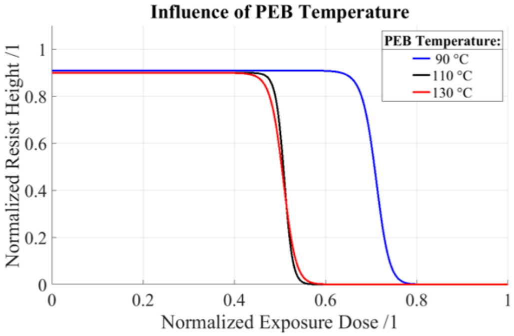
Bake parameter optimization

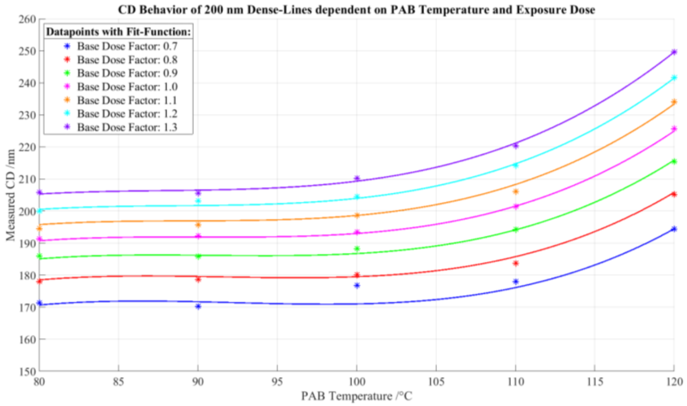
- How to achieve best possible results with minimum use of resources?

PAB Temperature | PAB Duration | PEB Temperature | PEB Duration

1. Use Contrast Curves to determine process impact of parameters
2. Optimize process window from most to least influential with CD measurements

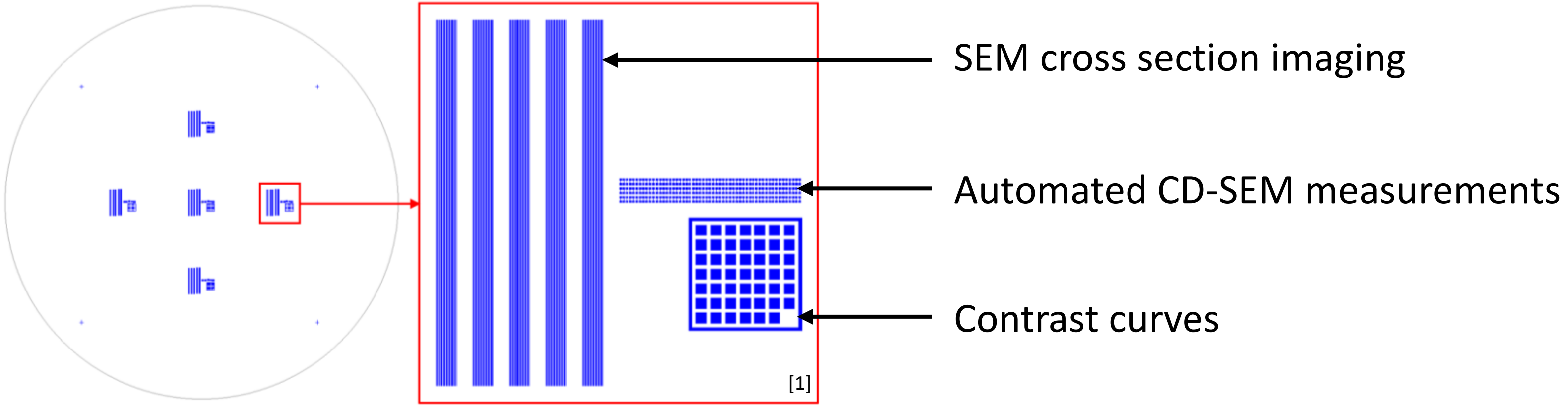






Experimental

- Substrate: 150 mm silicon wafer
- Resist: e-beam chemically amplified (different tonalities, sensitivities and thicknesses)
- Layout: 49x 150 µm squares for resist thickness measurements; Dense-Lines, Iso-Lines and Iso-Spaces from 30 nm to 2000 nm

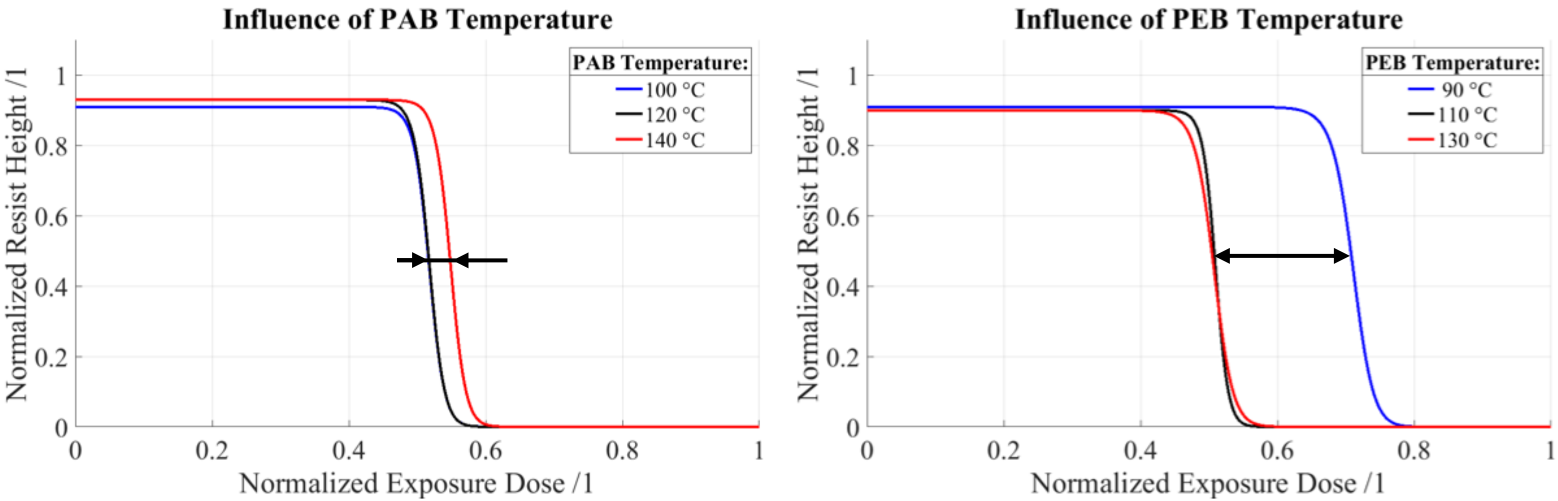


- Exposure: *Vistec VSB4050* - 50 keV acceleration voltage, 20 A/cm^2 current density
- Development: TMAH 2.38% solution
- Metrology: Interferometry, CD-SEM (*Advantest LWM9000*), SEM (*Zeiss LEO 1550*)

[1] Markus Greul, Holger Sailer, Mathias Kaschel, Joachim N. Burghartz, "Multidimensional process optimization of a negative e-beam photoresist for silicon-waveguide manufacturing," Proc. SPIE 11612, Advances in Patterning Materials and Processes XXXVIII, 116120I (22 February 2021); https://doi.org/10.1117/12.2582491

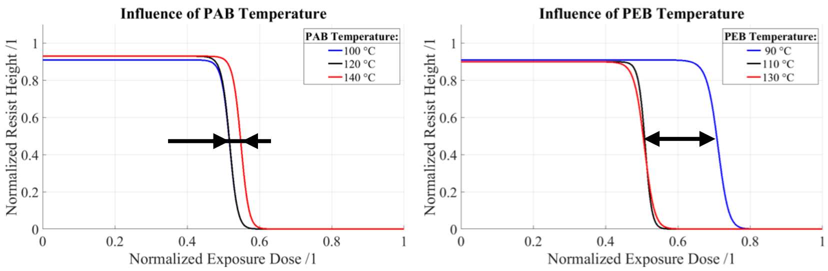
Bake parameter impact

- Stepwise instruction:
  1. Choose a starting/center point for the optimization
  2. Expose contrast pattern to wafers processes with lower, higher, … bakes
  3. Measure contrast curves on wafers
  4. Determine changes in behavior quantitively



Bake parameter impact

- Stepwise instruction:
  1. Choose a starting/center point for the optimization
  2. Expose contrast pattern to wafers processes with lower, higher, … bakes
  3. Measure contrast curves on wafers
  4. Determine changes in behavior quantitively
  5. Compare them



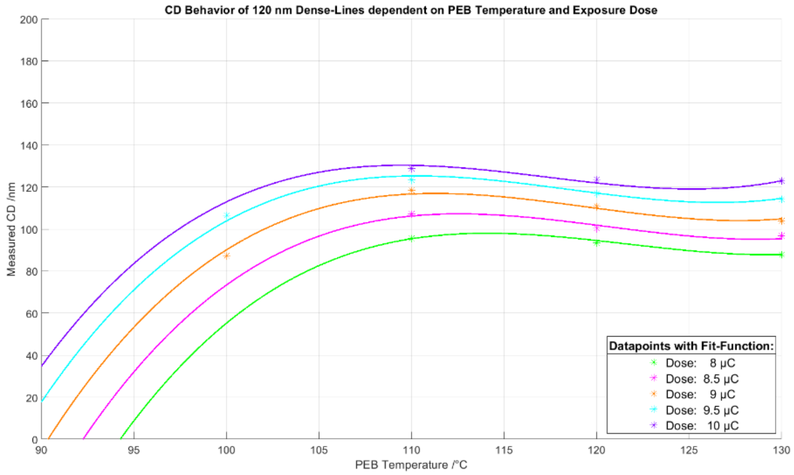
Photoresist type:	Influence PAB		Influence PEB	
	Temperature	Duration	Temperature	Duration
Negative – standard resolution	21 %	4 %	62 %	13 %
Negative – high resolution	52 %	5 %	38 %	5 %
Positive – standard resolution	26 %	7 %	61 %	6 %
Positive – high resolution	84 %	-	16 %	-

Bake parameter optimization

- How to achieve best possible results with minimum use of resources?

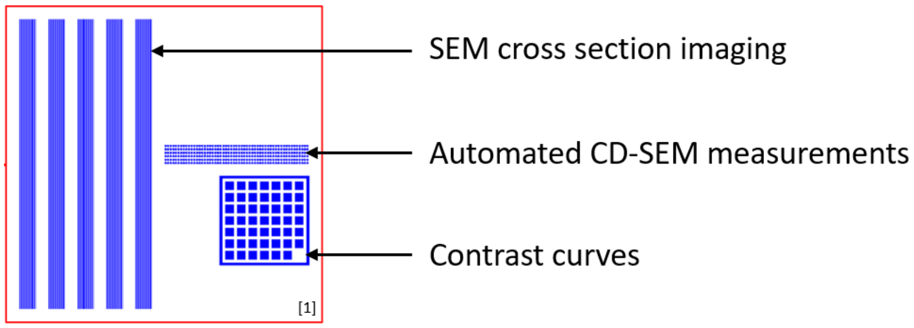
2 PAB Temperature | 3 PAB Duration | 1 PEB Temperature | 4 PEB Duration

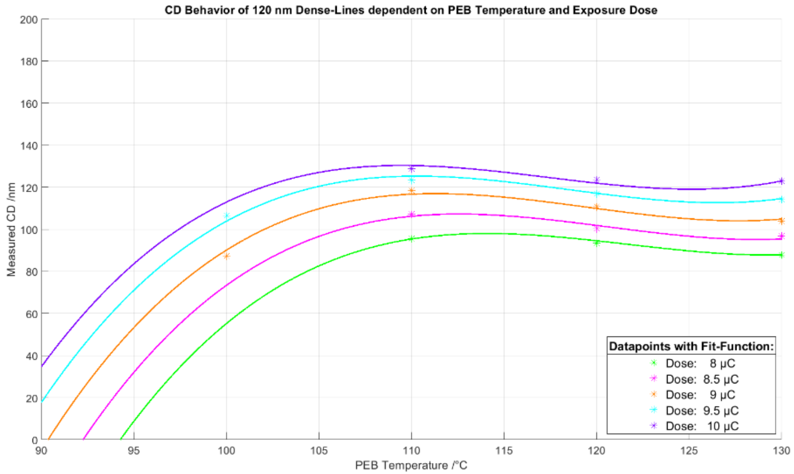
1. Use Contrast Curves to determine process impact of parameters
2. Optimize process window from most to least influential with CD measurements



Bake parameter optimization

- Stepwise instruction:
  1. Use a starting/center point
  2. Expose CD-SEM pattern as dose row processed at different PEB temperatures (e.g. ±20 °C in 10 °C increments)
  3. Measure CDs of dense-line features
  4. Illustrate CD results in respect to bake and exposure dose conditions in graph





Bake parameter optimization

- Stepwise instruction:
  1. Use a starting/center point
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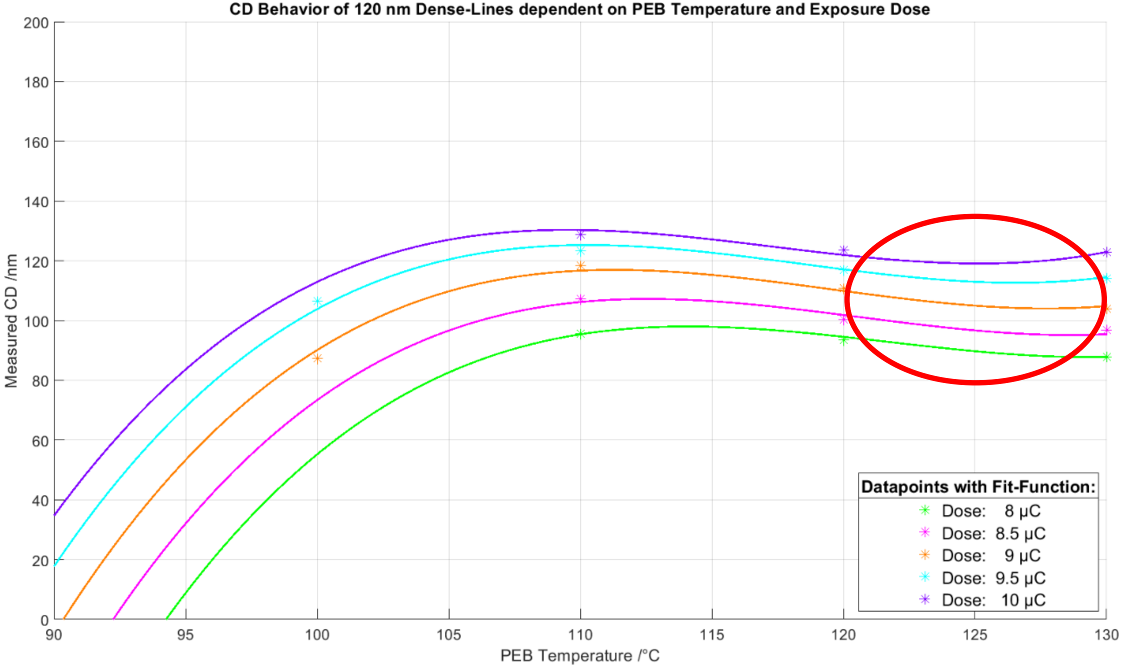
  3. Measure CDs of dense-line fe
  4. Illustrate CD results in respec
  5. Identify best temperature



Bake parameter optimization

- How to achieve best possible results with minimum use of resources?

2 PAB Temperature

3 PAB Duration

1 PEB Temperature

4 PEB Duration

1. Use Contrast Curves to determine process impact of parameters
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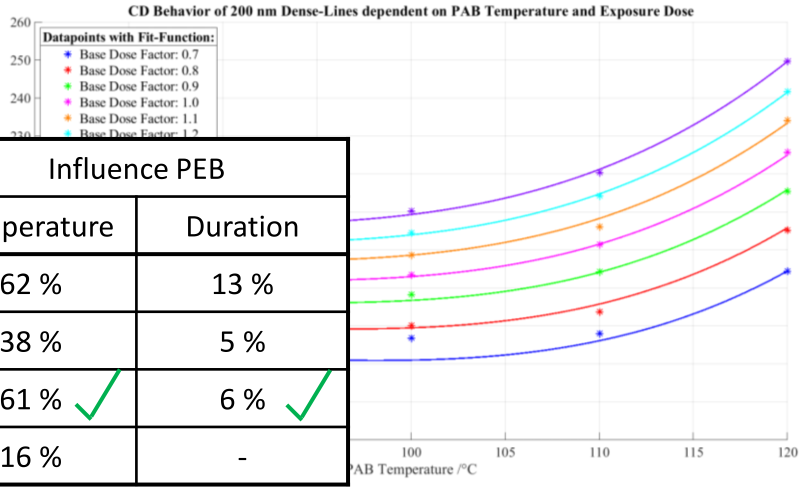
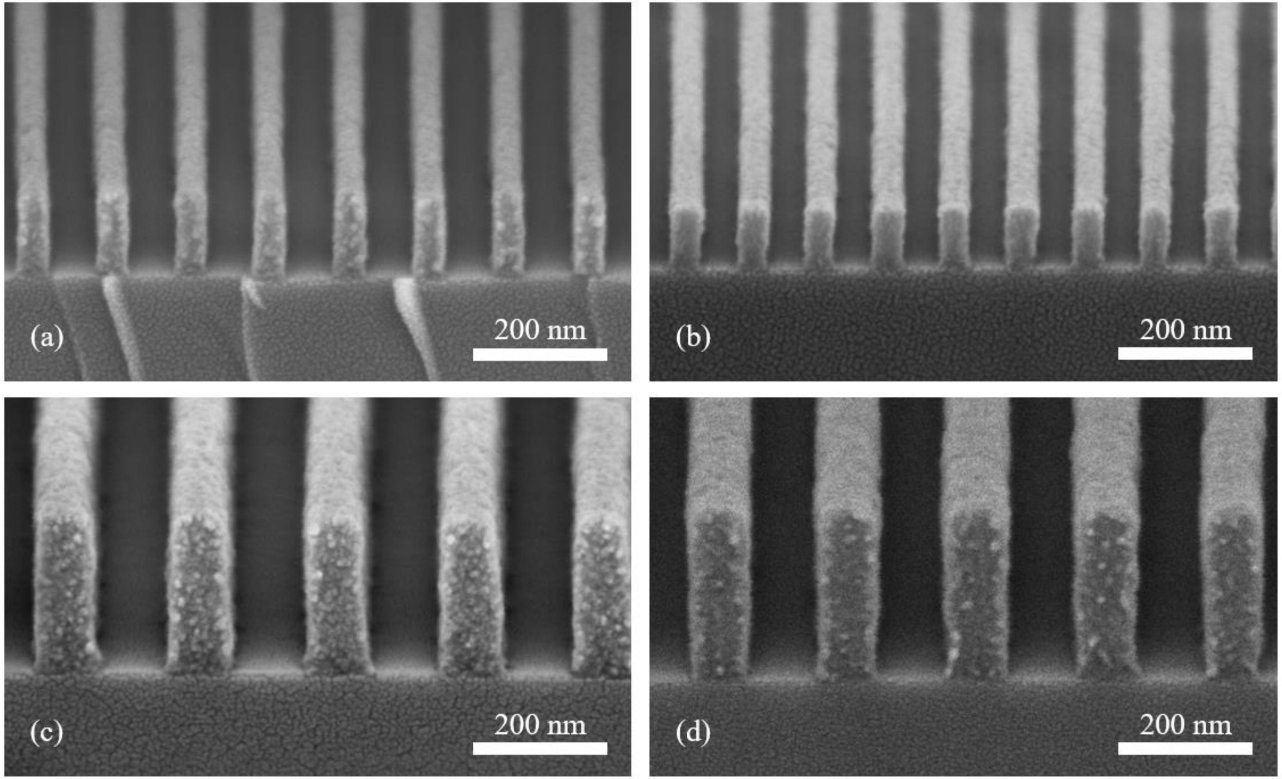


Photoresist type:	Influence PAB		Influence PEB	
	Temperature	Duration	Temperature	Duration
Negative – standard resolution	21 %	4 %	62 %	13 %
Negative – high resolution	52 %	5 %	38 %	5 %
Positive – standard resolution	26 % ✓	7 % ✓	61 % ✓	6 % ✓
Positive – high resolution	84 %	-	16 %	-

Bake optimization results

- Cross section images



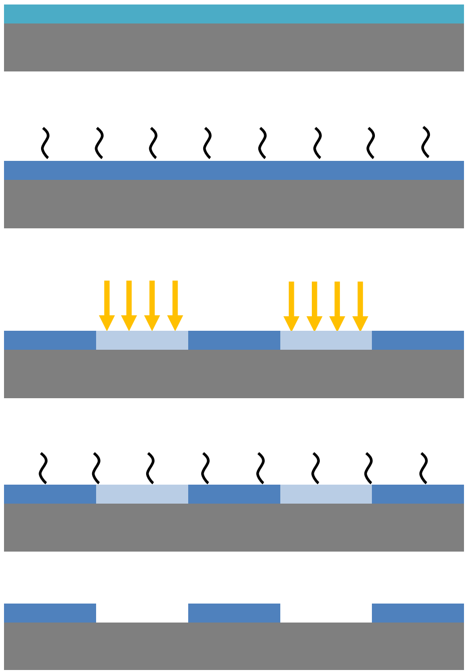
Performance Characteristics:

- Resolution limit ✓
- CD-Linearity
- Line edge roughness ✓
- Sidewall angle ✓
- …

(a)	Negative – high resolution
(b)	Positive – high resolution
(c)	Negative – standard resolution
(d)	Positive – standard resolution

Short introduction to lithography

- Processing steps in lithography:



Photoresist coating

Post apply bake (PAB)

Exposure

Post exposure bake (PEB)

Development

- Parameters:

Resist Thickness

1 PAB Temperature | PAB Duration

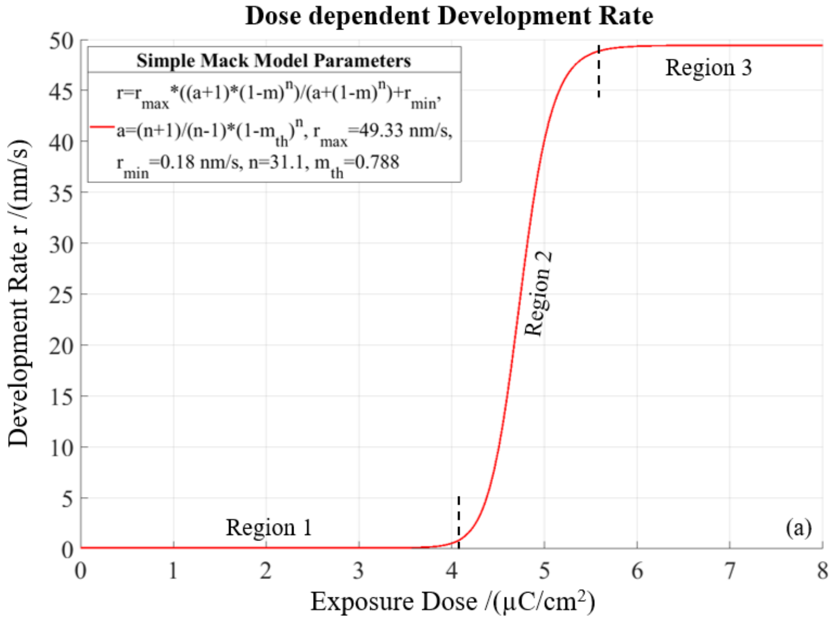
3 Exposure Dose | Sizing | PEC

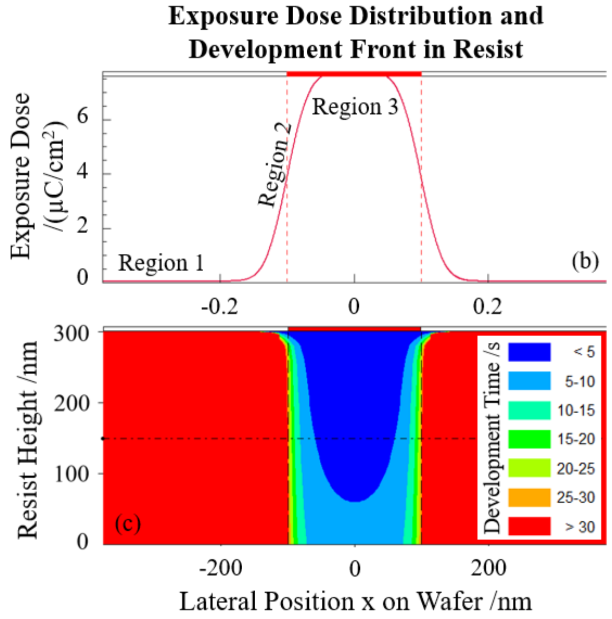
1 PEB Temperature | PEB Duration

2 Development Time

Development time optimization

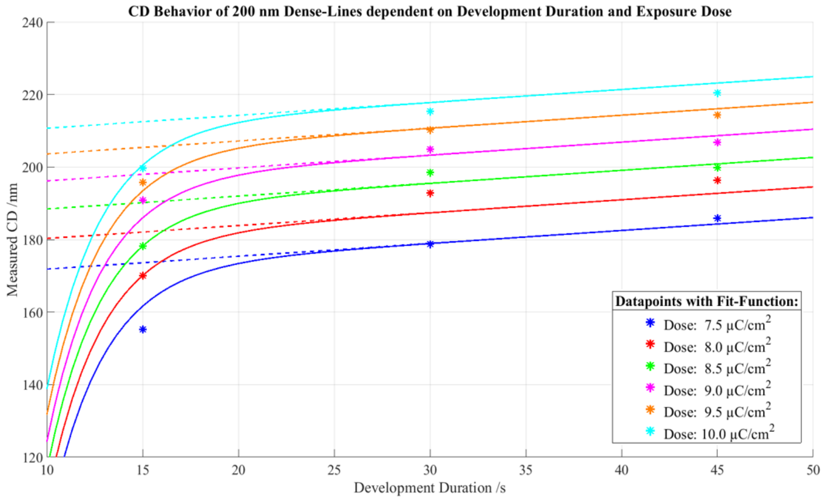
- How to achieve best performance?

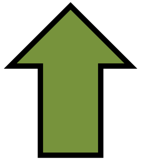




Development time optimization

- Measurement results for standard resolution positive tone resist





optimal development time

- Even unexposed resist molecules have a development rate.
- Resist loss degrades resist as mask for subsequent etching.

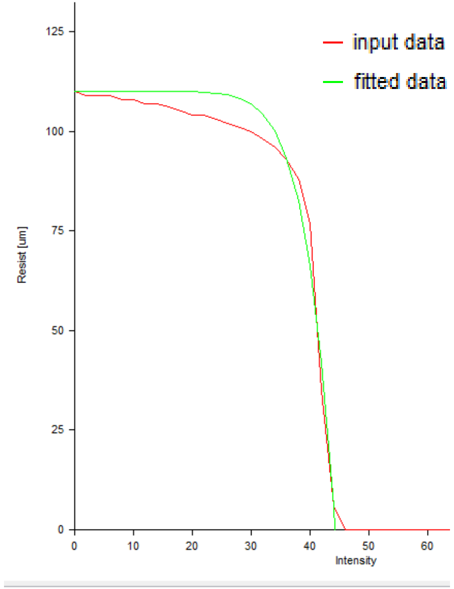
→ Keep development time short as possible
→ But as long as necessary

3D Model for CAR*

- Development rate of the (ebeam) resist is derived from contrast curve

$$\frac{d\ln(\text{Rate})}{d\ln(\text{Dose})} = \text{contrast} = \gamma \quad \Longrightarrow \quad \text{Rate} = R(x,y,z) = r2c * \frac{energy^{\gamma}}{d2c^{\gamma}}$$

$$r2c = resist\ thickness$$



Fitted contrast: 9.11, thickness: 110, D0: 44.27, RMS [um]: 10.57.

Contrast curve measurement provides:

- Resist contrast
- Rate-to-clear
- Dose-to-clear (d2c)

* *Byers, J. D., Smith, M. D. and Mack, C. A., "Lumped parameter model for chemically amplified resists," SPIE Proceedings, 1462 (2004).*

3D Model for CAR*

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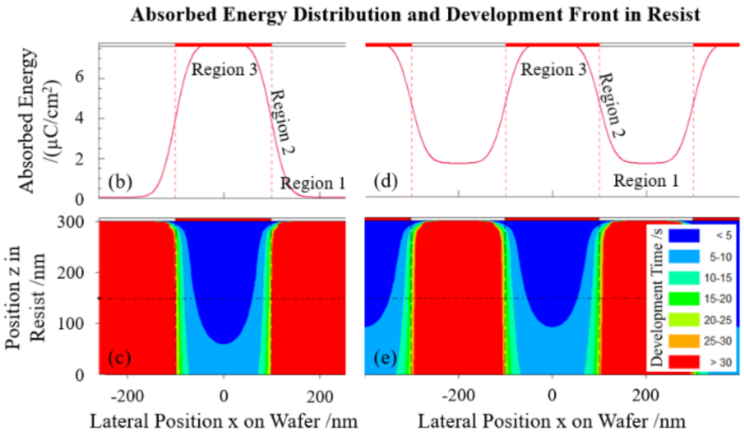
- Final resist profile: Segmented path in (x,y,z) with time-to-clear = develop time

$$\text{Time-to-Clear}(x,y,z) = T(x,y,z) = \int_0^{s_{xyz}} \frac{\sqrt{x'(s)^2 + y'(s)^2 + z'(s)^2}}{R(x(s),y(s),z(s))}\, ds$$



Intensity profiles obtained by convolving layout with MC-simulated PSF.

* *Byers, J. D., Smith, M. D. and Mack, C. A., "Lumped parameter model for chemically amplified resists," SPIE Proceedings, 1462 (2004).*

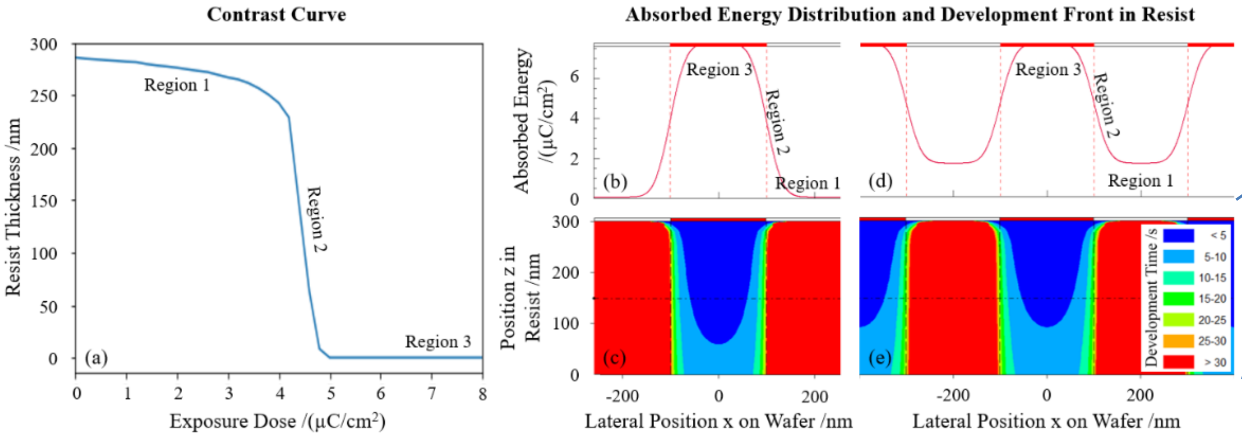
3D Model for CAR*

- Develop rate for the resist is derived from a constant develop contrast*

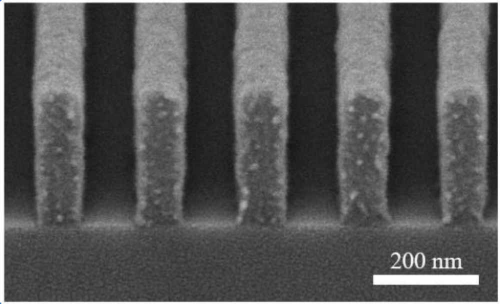
$$\frac{d\ln(\text{Rate})}{d\ln(\text{Dose})} = \text{contrast} = \gamma \quad \Longrightarrow \quad \text{Rate} = R(x,y,z) = r2c * \frac{energy^{\gamma}}{d2c^{\gamma}}$$

- Final resist profile: Segmented path in (x,y,z) with time-to-clear = develop time*

$$\text{Time-to-Clear}(x,y,z) = T(x,y,z) = \int_0^{s_{xyz}} \frac{\sqrt{x'(s)^2 + y'(s)^2 + z'(s)^2}}{R(x(s),y(s),z(s))}\,ds$$



30 s: straight sidewalls



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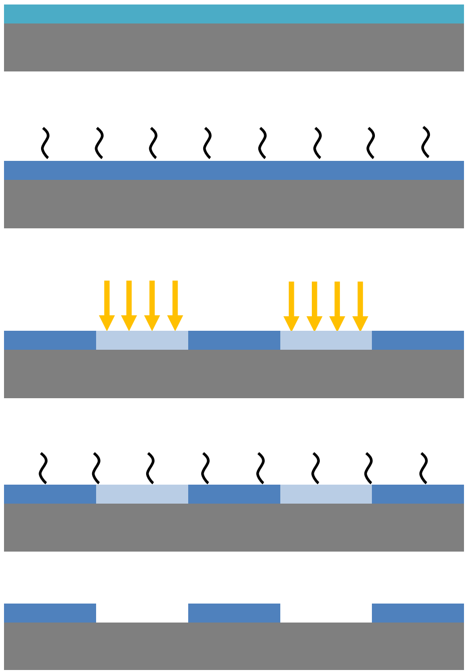
Short introduction to lithography

- Processing steps in lithography:



Photoresist coating

Post apply bake (PAB)

Exposure

Post exposure bake (PEB)

Development

- Parameters:

Resist Thickness

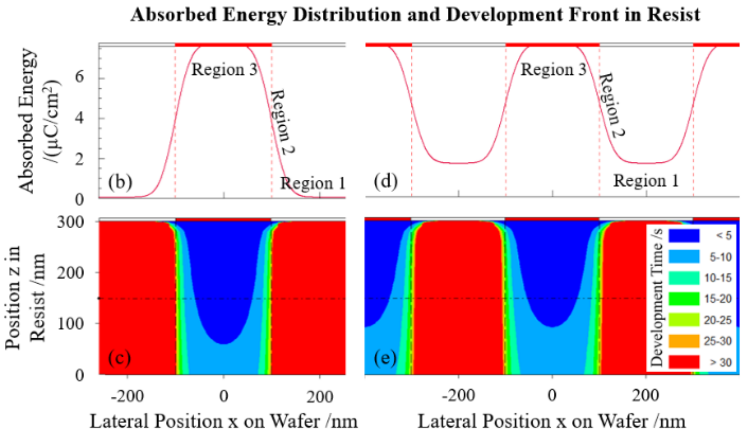
1 PAB Temperature | PAB Duration

3 Exposure Dose | Sizing | PEC

1 PEB Temperature | PEB Duration

2 Development Time

3D Model in TRACER

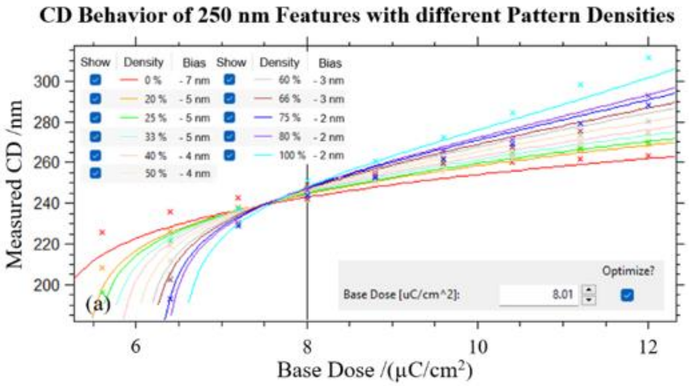


TRACER

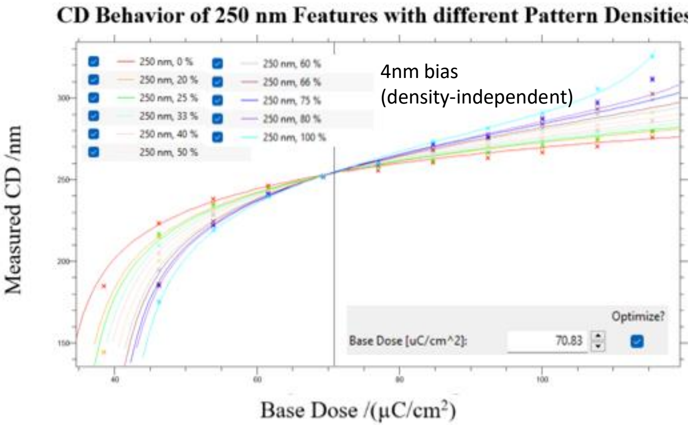
For exposure modeling we evaluate the development front at ½ resist height to obtain dose- and density-dependent CDs.

3D Model for CAR: Calibration

Low-dose pCAR



High-dose nCAR



Calibrate a 3D model to experimental data:

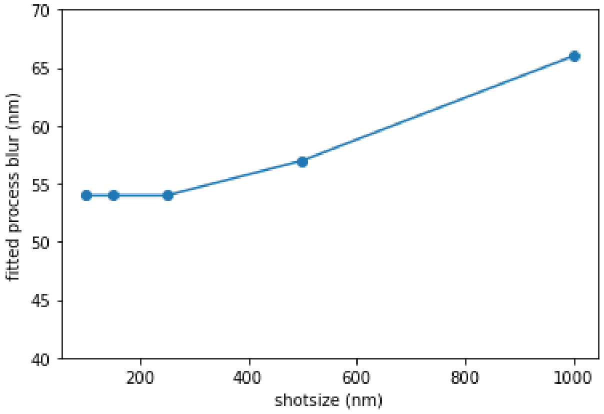
- Fit CD response from resist development
  - Measured CD includes CAR development characteristics
- Shot-size dependent blur from VSB exposure system

(not accessible to MC PSF simulations)

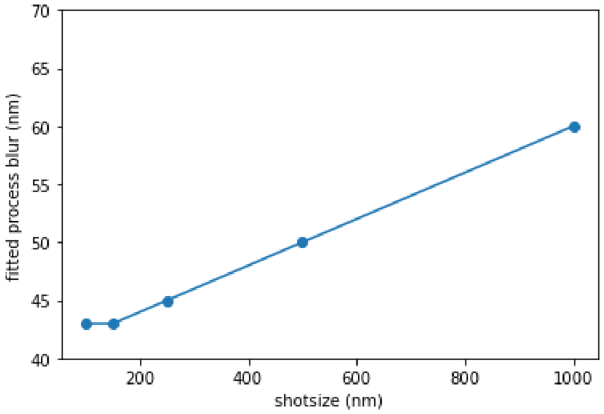
Calibration finds **Isofocal dose condition** (suggested base dose)

VSB: Shotsize-dependent blur

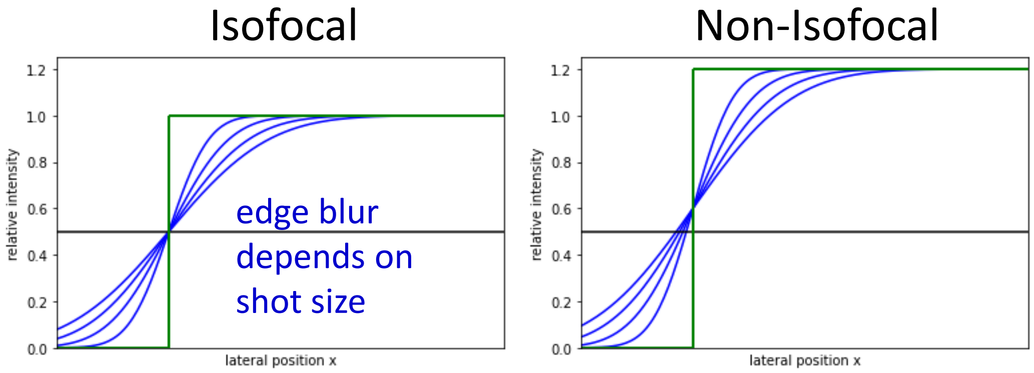
Low-dose pCAR



High-dose nCAR



VSB exposure:
The blur increases with increasing shotsize (writer effect)

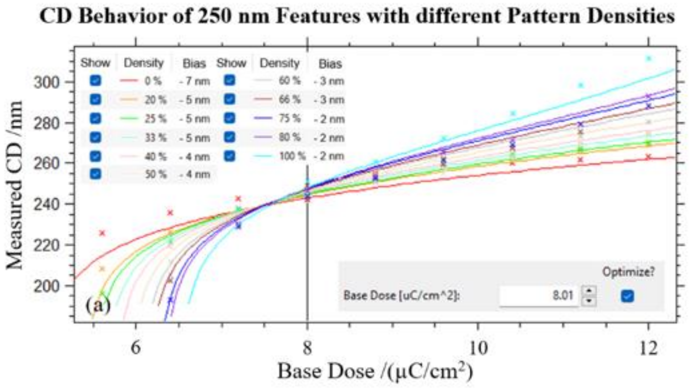


Threshold model representation (applies similarly to 3D model)

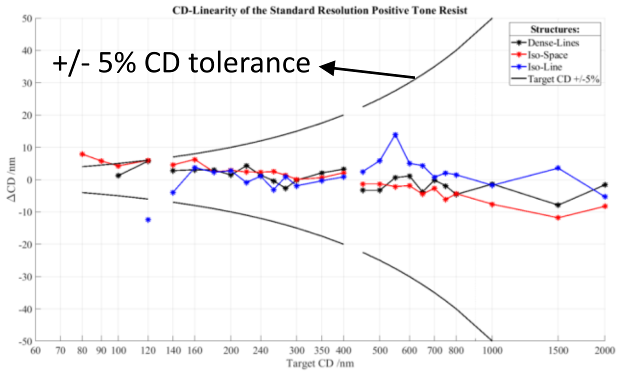
Isofocal condition is beneficial for VSB exposure, as there is least CD impact from shot-size dependent blur (CD linearity) at isofocal dose

3D Model for CAR: Results

Low-dose pCAR



Verification



Performance Characteristics:

- Resolution limit ✓
- CD-Linearity ✓
- Line edge roughness ✓
- Sidewall angle ✓
- …

VSB Exposure:

- @ isofocal condition from TRACER calibration
  - for CD linearity control
- PEC correction active
  - for CD control with density variation
- VSB writer corrections active

Summary

- Lithography requires optimal pattern transfer into the resist
- Optimizing bake from most influential to less influential parameters gives a robust process window & good lithography performance
  - with minimum experimental effort
  - any ebeam lithography benefits from resist process optimization
- Exposure at isofocal dose is particularly beneficial for VSB writers
  - shotsize-dependent blur is a VSB-writer property
  - good CD Linearity control at isofocal dose
- TRACER calibration finds isofocal condition with 3D development model
  - verified on positive and negative tonality CARs
- PEC with MC-simulated PSF controls density-dependent CD variations

Effort for getting resist and exposure conditions optimized: **Approximately one week**

Acknowledgements

We want to thank all the colleagues from GenISys and IMS CHIPS, who participated and supported the work.