Metrology For E-Beam Lithography Process Characterization

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Introduction

Most small or academic labs do not have dedicated CDSEM equipment, and are limited to manual, cursor-based measurements using an analytic SEM. These manual measurements are time-consuming, tedious, and prone to inconsistency, especially as the number of measurements grows.

Automated image analysis speeds the process, and improves quality and consistency of results. Measurements improve because the operator is no longer manually selecting edge positions, and because every linescan in the image is analyzed, rather than using a single point-to-point measurement to represent a feature size.

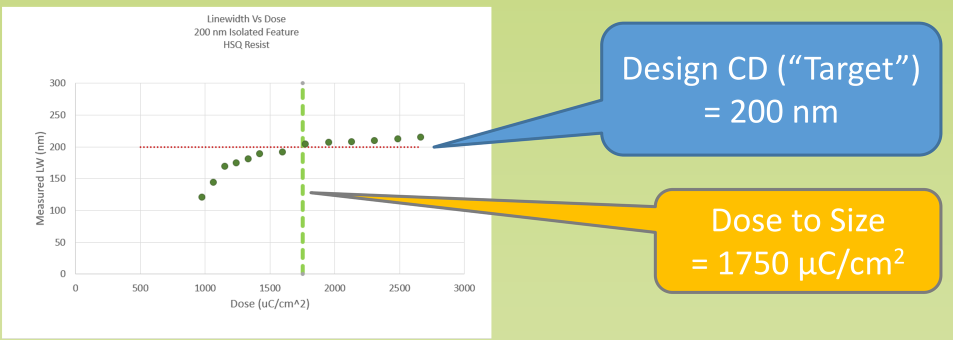
A common, vital procedure is lithographic process characterization to find operating parameters. When metrology is a limiting factor, the process chosen can be far from optimal. In process characterization, automated SEM metrology enables finding a more optimal process operating point, often with significant gains in process performance.

Process Characterization Methods

How do we choose the optimum process operating point for an electron beam lithography exposure?

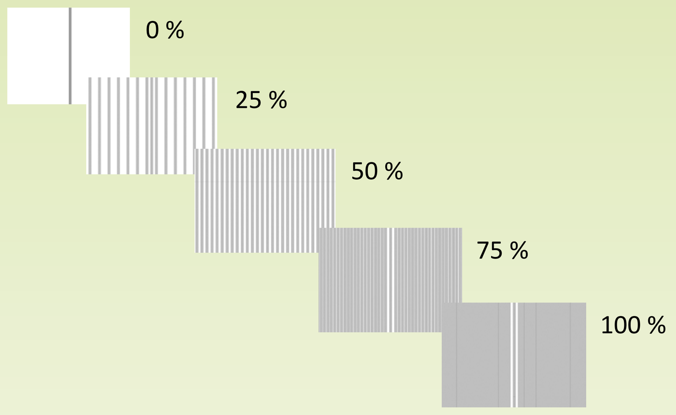
Traditional Method:

1) Expose linewidth vs dose exposure test
2) Choose dose-to-size at one pattern density
3) Make educated guesses at total process blur and pattern bias; repeat and adjust as necessary.



New Method:

1) Expose a two-factor matrix, varying dose and local pattern density
2) Measure the line CDs across this matrix
3) Fit data to determine: Exposure Base Dose, Total Process Blur, Constant Process Bias, and Density-Dependent Process Bias



This e-beam process characterization requires at least 50 SEM measurements, so automating the SEM metrology is of great value.

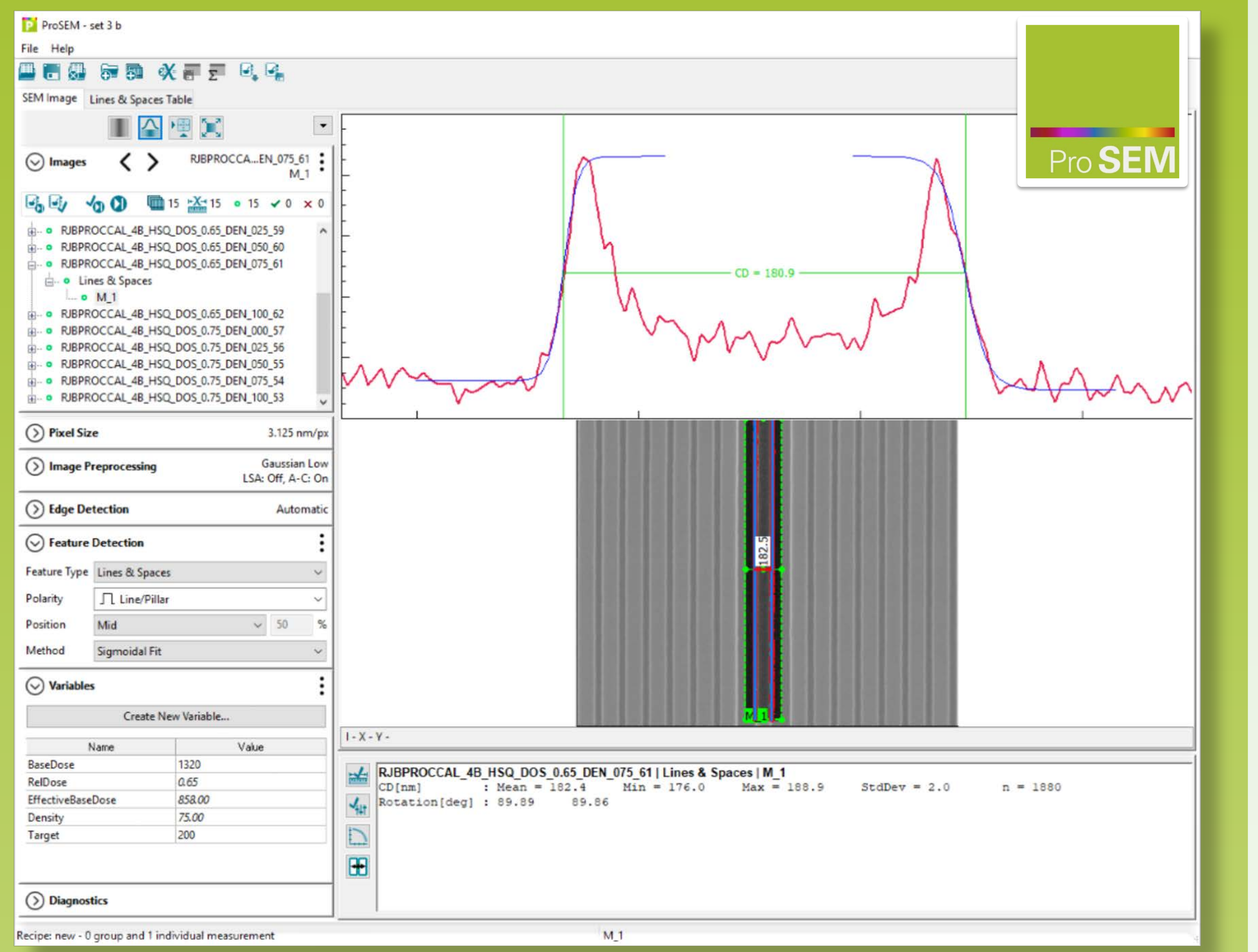
Automated SEM Image Measurement: ProSEM[1]

Feature Measurement:

- Locate edge by Canny and/or Derivative-based method
- For each line scan, fit sigmoid[2] or other function to edges
- Fit line edge by linear least-squares of edge points
- Report CD as average distance between fitted edges

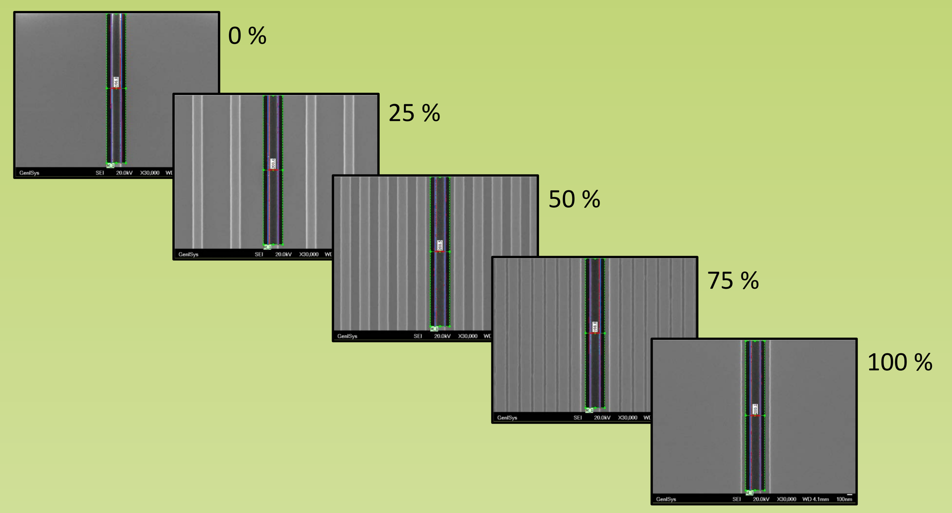
Batch Measurement:

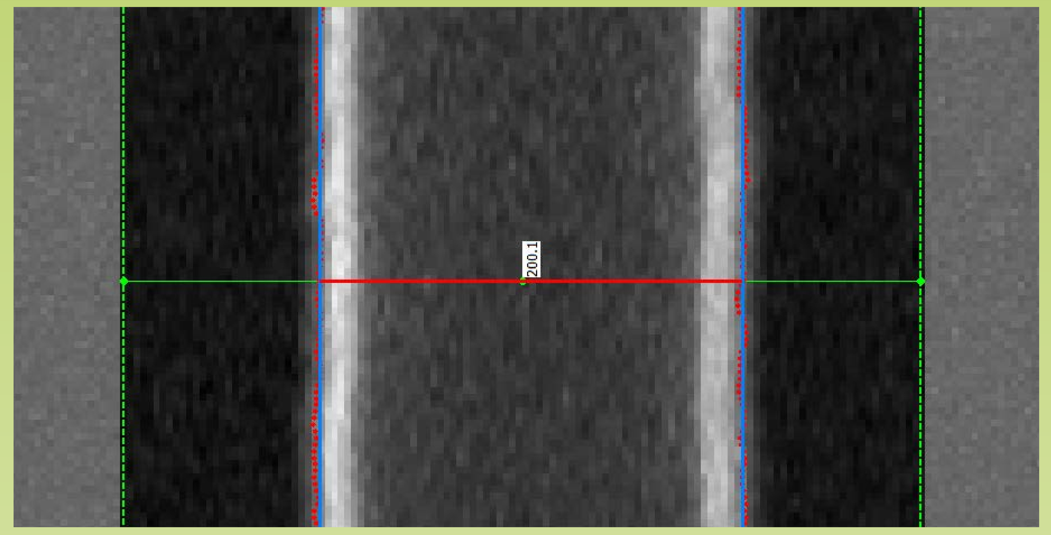
- For each image, find feature(s) to measure, using pattern matching, tolerant to:
  - Feature size variation
  - Signal level variation
  - Pattern edge quality variation, such as sidewall slope
- Measure each feature in image
- Extract exposure dose and density values from filename or image metadata
- Save data table for plotting or fitting



Example: E-Beam Resist Process Characterization

Hydrogen Silsesquioxane (HSQ) resist on Silicon-on-Insulator wafers





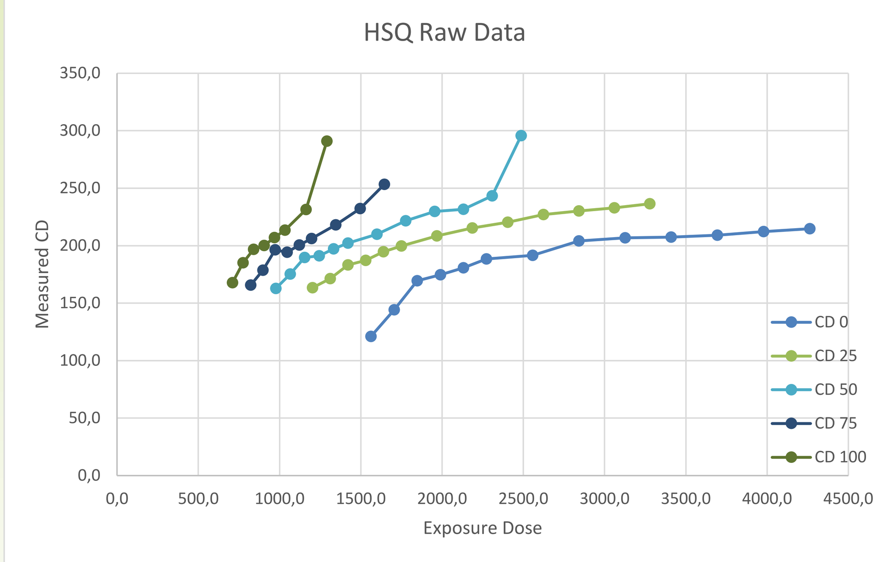
Data Fitting and Parameter Extraction using TRACER

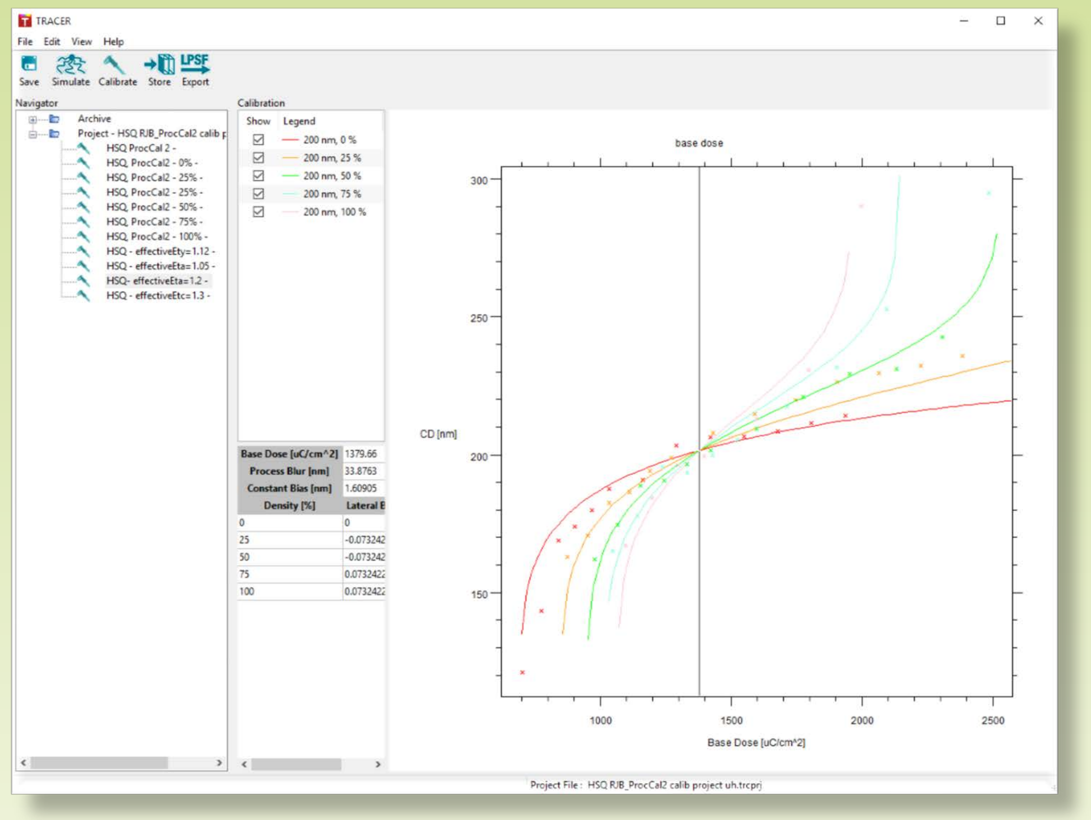
Conventional Proximity Effect Correction (PEC) accounts for dose variation from electron scattering, but not for process effects such as:

- Size Bias, from process or measurement
- Process Blur
- Finite Resist Contrast

These corrections are obtained by fitting[3,4] measured CDs using:

$$\boxed{CD = CD_0 + Bias_{const} + c_R * \left(D * Dens * \frac{\eta}{1+\eta}\right)^{\gamma} + \frac{ProcessBlur}{\sqrt{\ln(2)}} * Erf^{-1}\left(\left(\frac{D2C}{D} - Dens * \frac{\eta}{1+\eta}\right) * (1+\eta)\right)}$$



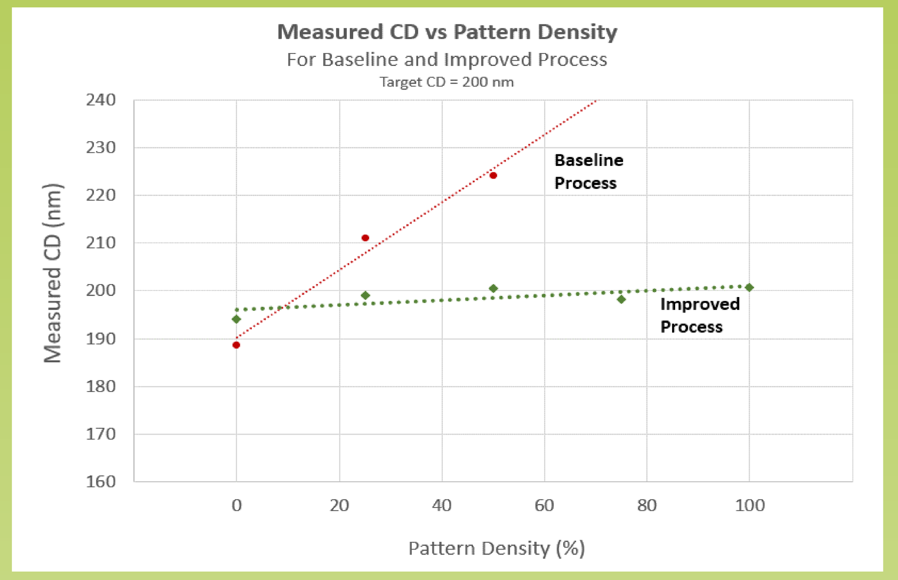


Note that linewidth-vs-dose curves at various local pattern densities converge and cross at a particular dose value. This is the e-beam analog of the iso-focal exposure condition[5,6] commonly used in photolithography, though here, more properly iso-blur condition. By operating near this point, the widest exposure process latitude can be expected.

Calibration Results

	Before Calibration *Chosen by 'Traditional Method'*	**Calibration Parameters** *Determined by TRACER fit to Measured CD Data*
Base Dose	1750 µC/cm²	1380 µC/cm²
Process Blur	50 nm	34 nm
Process Bias	none	-2 nm
Notes		Additional Mid-range Gaussian

When these calibration parameters are applied during pattern preparation, edge position and dose assignments are adjusted, and the lithographic results are significantly improved, with consistent linewidth through the full range of pattern densities from isolated to surrounded.



Conclusions

- Full calibration of an e-beam exposure process significantly improves the e-beam process targeting, by correcting for process effects beyond proximity effect correction.
- The calibration requires a number of SEM measurements, for which automated metrology software is highly valuable, providing more consistent data for parameter extraction.

References

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[2] J.S. Villarubia, A.E. Vladar, "Simulation study of the repeatability and bias in the CD-SEM", Metrology, Inspection, and Process Control for Microlithography XVII, Proc SPIE, Vol 5038 (2003)

[3] U. Hofmann, et al, "A novel method to find the best (iso-focal) process point in e-beam lithography". [White Paper] (2017)

[4] Computer program TRACER v2.6.0, GenISys, GmbH, Taufkirchen, Germany, (2018)

[5] C. Sauer and C.A. Mack, "Electron Beam Lithography Simulation for Mask Making, Part IV: Effect of Resist Contrast on Isofocal Dose", Photomask and X-Ray Mask Technology VI, Proc., SPIE, Vol 3748 (1999)

[6] G.G. Lopez, et al, "On the trends and application of pattern density dependent isofocal dose of positive resists for 100 keV electron beam lithography", J. Vacuum Science & Technology B 34, 06JAO5-13 (2018)

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