# Advances in Edge Placement Error Metrology in the Era of Stochastics

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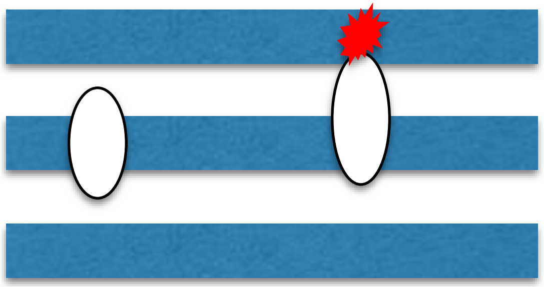
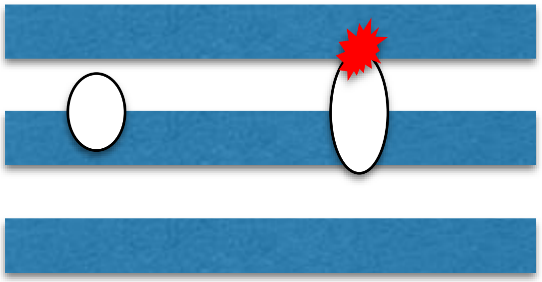
# A short history of overlay and edge placement error…

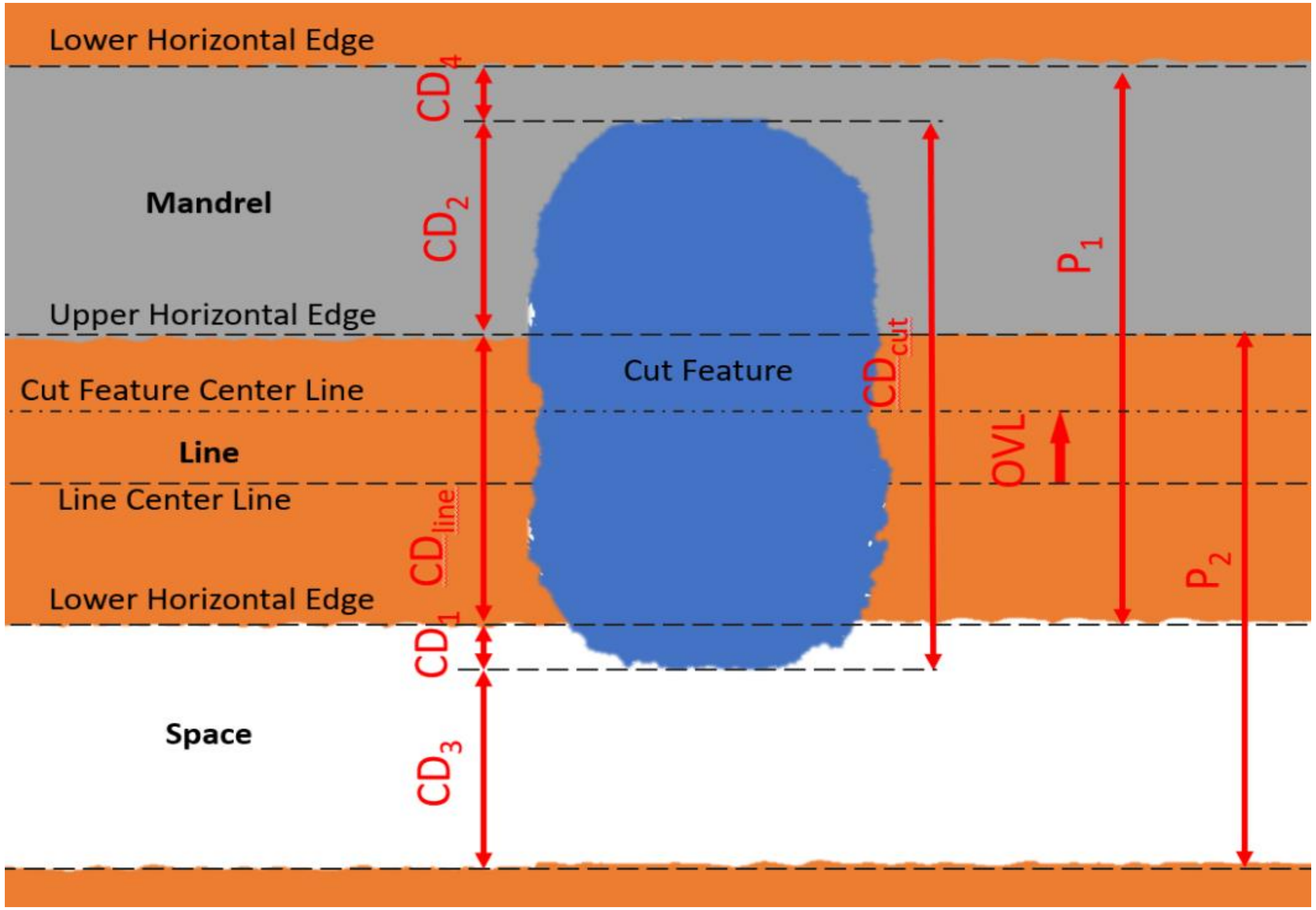
- In the beginning…
  - Overlay and CD errors were considered, and controlled, separately
- With multipatterning came the era of EPE…
  - Edge Placement Errors (EPE) combined CD errors with overlay to determine edge placement failures



- Today is the era of stochastics…
  - Stochastic variations account for more than 50% of EPE budgets
  - What is the proper way to account for, and measure, stochastic contributions to EPE and edge-related failure mechanisms?

# Prior Work: EPE Model for Complementary Lithography






Two failure mechanisms:

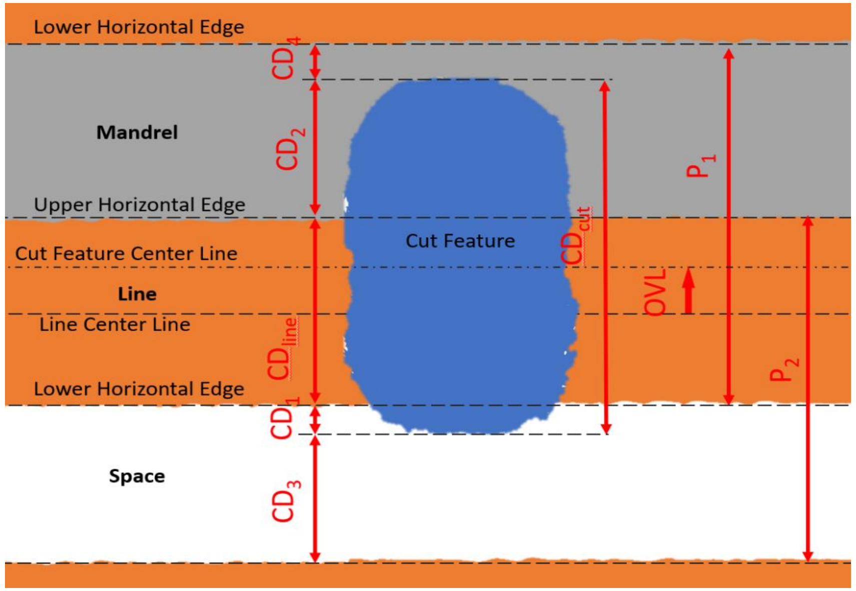
- An incomplete cut
- Cutting a neighbor feature

Chris A. Mack and Michael E. Adel "Overlay and edge placement error metrology in the era of stochastics", Proc. SPIE 12496, *Metrology, Inspection, and Process Control XXXVII*, 1249609 (2023).

# New Stochastic EPE Modeling Approach

1. Write down Geometric equations for EPE (tradition way)

$$CD_1 = \frac{CD_{cut}}{2} - \frac{CD_{line}}{2} - OVL$$




2. Take the Variance of this equation

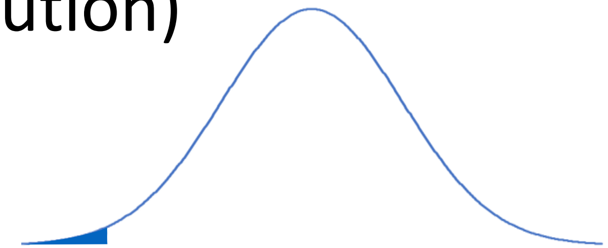
$$\sigma_{CD_1}^2 = \frac{1}{4}\left(\sigma_{CD_{cut}}^2 + \sigma_{CD_{line}}^2\right) + \sigma_{OVL}^2$$

3. Find the stochastic contributors to each term

$$\sigma_{OVL}^2 = \sigma_{Res}^2 + \sigma_{LPPE_{cut}}^2 + \sigma_{LPPE_{line}}^2$$

4. Define the failure probability (assume Gaussian distribution)

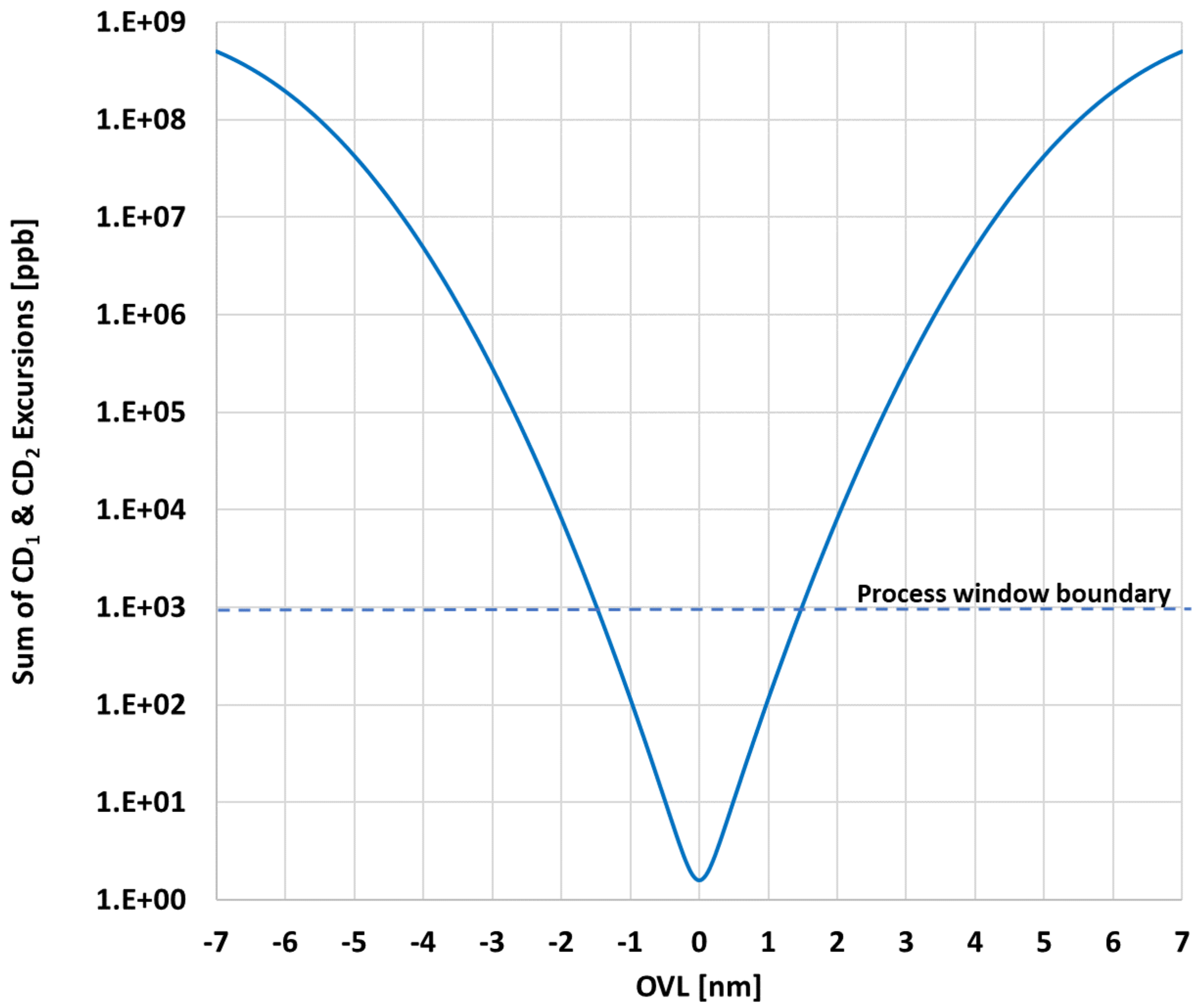
$$\text{Probability}(CD_1 < 0) \approx \frac{\sigma}{\sqrt{2\pi\mu}} e^{-\frac{\mu^2}{2\sigma^2}}$$



| Parameter name | Parameter symbol | Parameter value [nm] |
|---|---|---|
| Line CD | $CD_{line}$ | 14 |
| Space CD | $CD_{space}$ | 14 |
| Mandrel CD (same as Space CD) | $CD_{space}$ | 14 |
| Cut CD | $CD_{cut}$ | 28 |
| Overlay (varied) | OVL | -7 to +7 |
| Line global CD uniformity | $\sigma_{GCDU_{line}}$ | 0.6 |
| Line local CD uniformity (20 nm segment) | $\sigma_{LCDU_{line}}$ | 0.7 |
| Line local pattern placement error (20 nm seg) | [illegible] | 0.4 |
| [illegible] | $\sigma_{LCDU_{cut}}$ | [illegible] |
| Cut local pattern placement error | $\sigma_{LPPE_{cut}}$ | 0.5 |
| Space global CD uniformity | $\sigma_{GCDU_{space}}$ | 0.7 |
| Space local CD uniformity | $\sigma_{LCDU_{space}}$ | 0.7 |
| Mandrel global CD uniformity | $\sigma_{GCDU_{mandrel}}$ | 0.5 |
| Mandrel local CD uniformity | $\sigma_{LCDU_{mandrel}}$ | 0.5 |
| Overlay (model residuals) | $\sigma_{Res}$ | 0.8 |

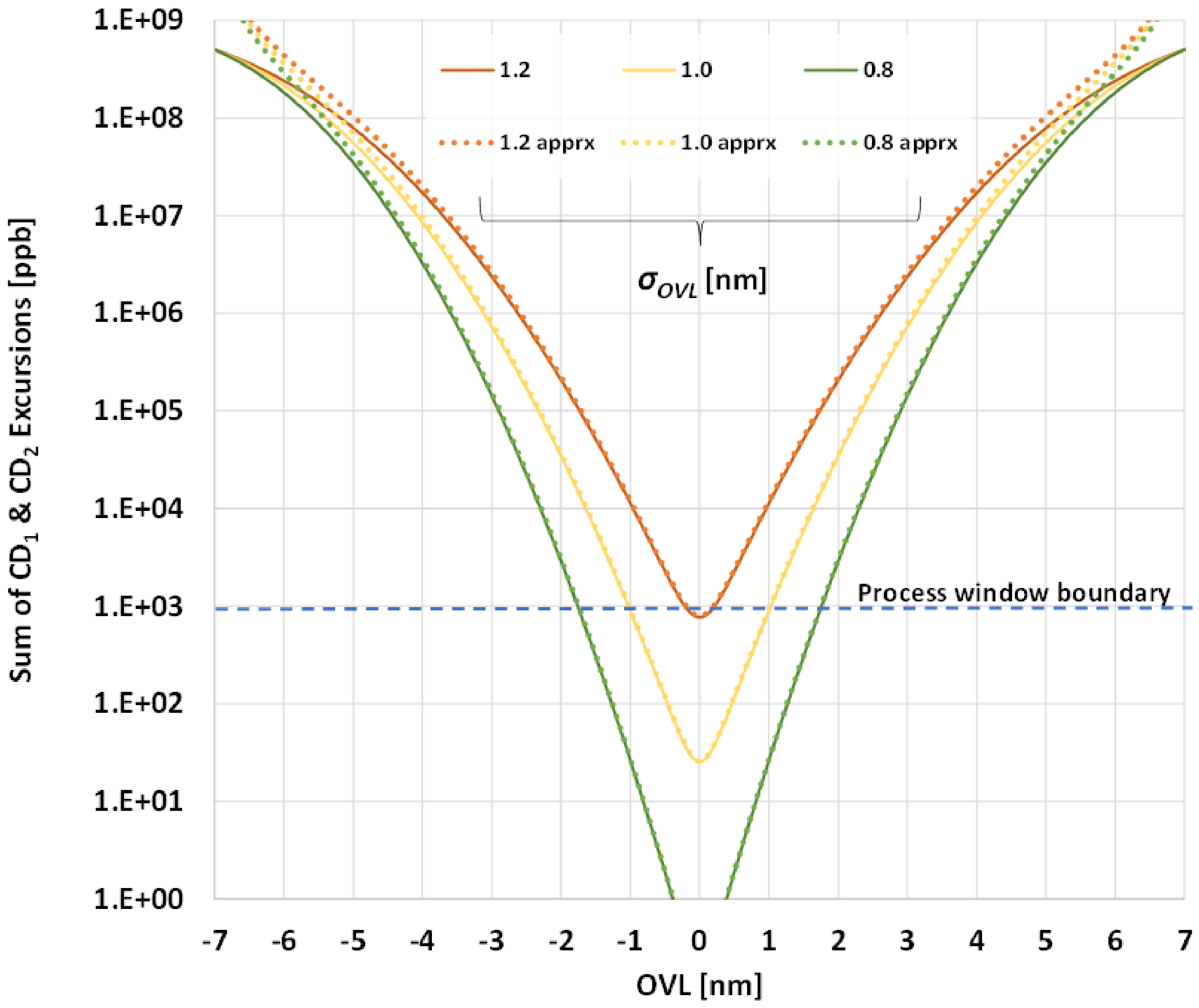
Every input to the model can be measured

# The Overlay Process Window




- "Excursion rate" = fraction of instances where either $CD_1$ or $CD_2 \leq 0$
- Assign a maximum allowed excursion rate (e.g., 1 ppm)
- The Overlay Process Window is the range of overlay that keeps the excursion rate below this threshold

# Using the Overlay Process Window




- What if $\sigma_{OVL}$ increases?
  - Caused by higher unmodeled residuals, or higher LPPE for the cut of the line segments
- Increase stochastic variation (greater LPPE) reduces the overlay process window
- Angstrom level changes in $\sigma_{OVL}$ produce nanometer level changes in the overlay process window

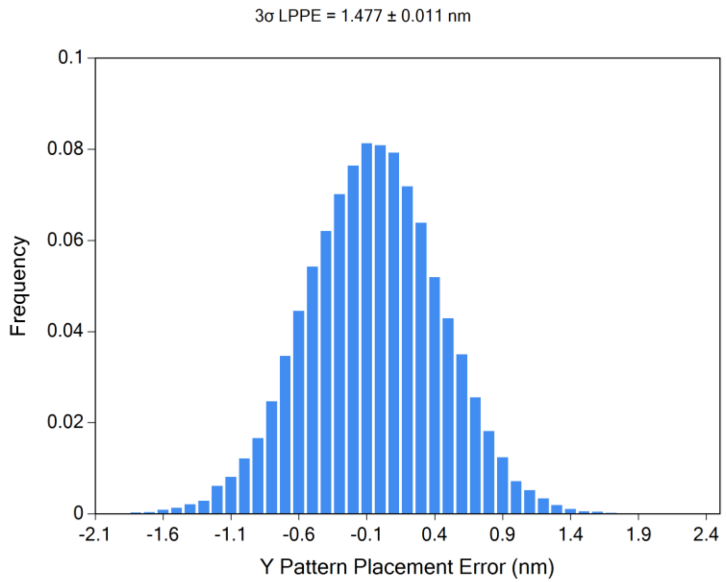
# Results Indicate High Sensitivity to Inputs

- Small variations in model inputs cause relatively large variations in the overlay process window
  - Why?
  - Can we characterize this?
- We'll use a Propagation of Uncertainty approach
  - Assume small errors and linear propagation
  - We can derive an exact expression under these assumptions
- Results will allow us to define measurement requirements for model terms (and thus sample size requirements)

# Example: Overlay Variation Term

$$\sigma_{OVL}^2 = \sigma_{OVL_{res}}^2 + \sigma_{PPE_{cut}}^2 + \sigma_{PPE_{line}}^2$$

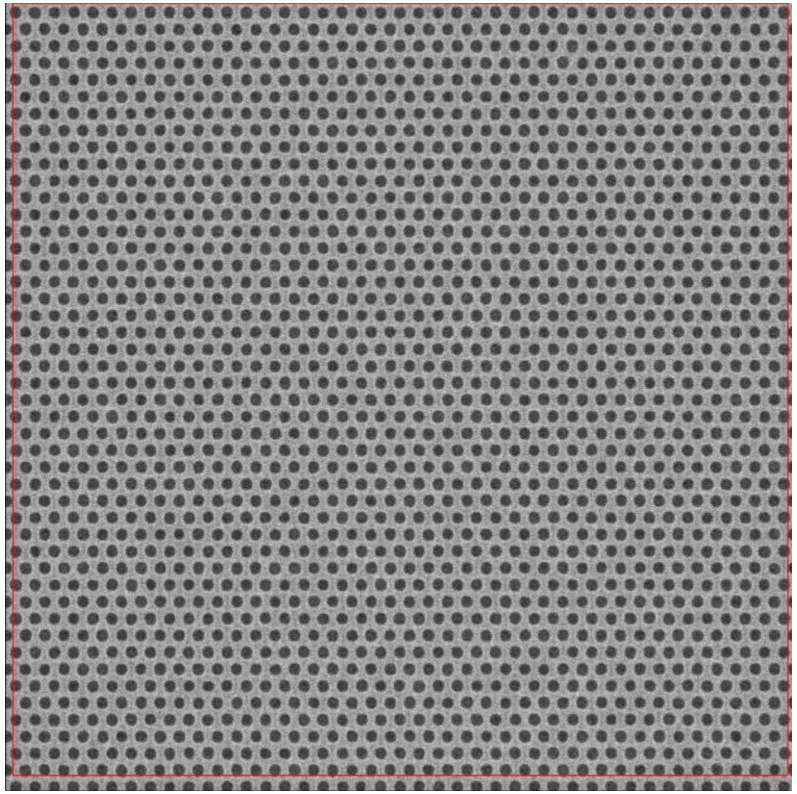
Measured terms, each with measurement uncertainty




$$SE(\sigma_{OVL}) \approx \sqrt{\left(\frac{SE(\sigma_{OVL_{res}})\sigma_{OVL_{res}}}{\sigma_{OVL}}\right)^2 + \left(\frac{SE(\sigma_{PPE_{cut}})\sigma_{PPE_{cut}}}{\sigma_{OVL}}\right)^2 + \left(\frac{SE(\sigma_{PPE_{line}})\sigma_{PPE_{line}}}{\sigma_{OVL}}\right)^2}$$

SE = Standard Error, the metrology uncertainty for that term

# Numerical Example



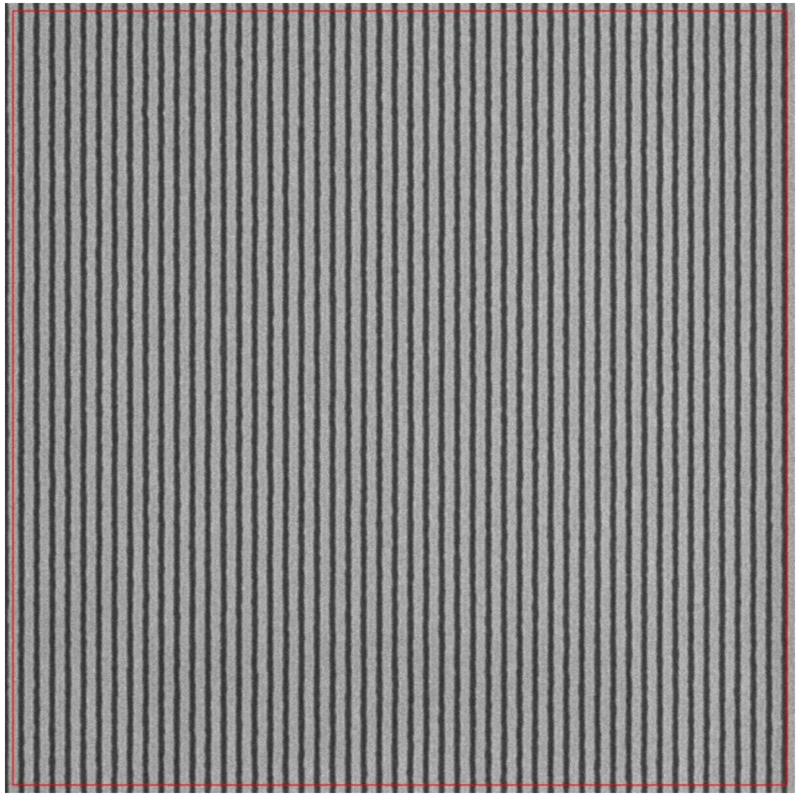
X-pitch = 40 nm
Image size = 2048x2048
Pixel size = 0.8 nm

- Each image contains about 1,777 contact holes
- Unbiased results for one image:
  - $\sigma_{CD_{cut}}$ = 0.59 nm, $SE\left(\sigma_{CD_{cut}}\right)$ = 0.011 nm
  - $\sigma_{PPE_{cut}}$ = 0.45 nm, $SE\left(\sigma_{PPE_{cut}}\right)$ = 0.008 nm
- Measurement uncertainty scales as

$$1/\sqrt{\#\ Holes}$$

Results from paper #12750-28, “Improvements in the measurement of local critical dimension uniformity for holes and pillars”

# Numerical Example



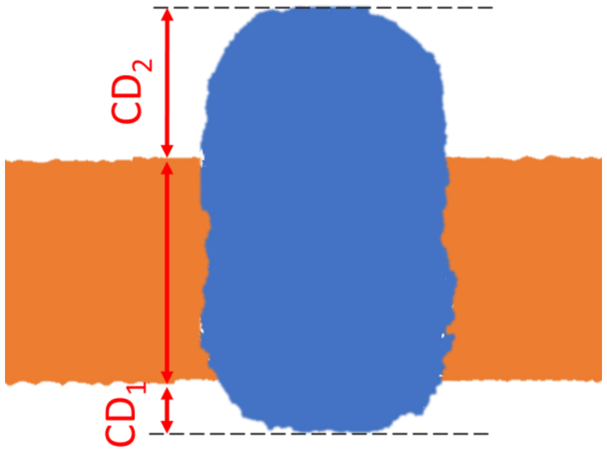
Pitch = 32 nm
Image size = 2048x2048
Pixel size = 0.8 nm

- Each image contains about 49 lines
- Unbiased results for one image (segment length = 32 nm):
  - $\sigma_{CD_{line}}$ = 0.50 nm, $SE\left(\sigma_{CD_{line}}\right)$ = 0.008 nm
  - $\sigma_{PPE_{line}}$ = 0.29 nm, $SE\left(\sigma_{PPE_{line}}\right)$ = 0.005 nm
- Measurement uncertainty scales as

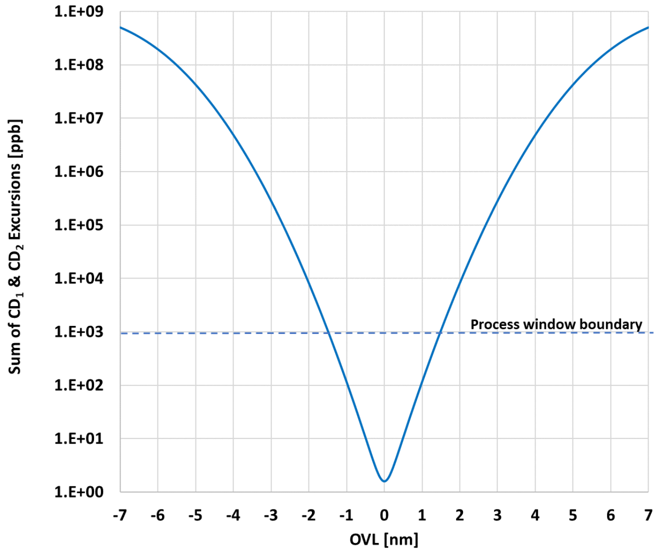
$$1/\sqrt{\#\ Lines}$$

Chris A. Mack, Frieda Van Roey, and Gian F. Lorusso, “Unbiased Roughness Measurements: Subtracting out SEM Effects, part 3”, Proc. SPIE 10959, *Metrology, Inspection, and Process Control for Microlithography XXXIII*, 109590P (2019).

# Propagation to the OPW




- All individual terms propagate to an uncertainty in $\sigma_{CD_1}$ and $\sigma_{CD_2}$
- Uncertainty in $\sigma_{CD_1}$ and $\sigma_{CD_2}$ propagates to uncertainty in the Overlay Process Window based on the slope of the OPW at the failure threshold




$$\Delta\text{OPW} = -2 * \left(\mu_{CD_1}/\sigma_{CD_1}\right) * \text{SE}\left(\sigma_{CD_1}\right)$$

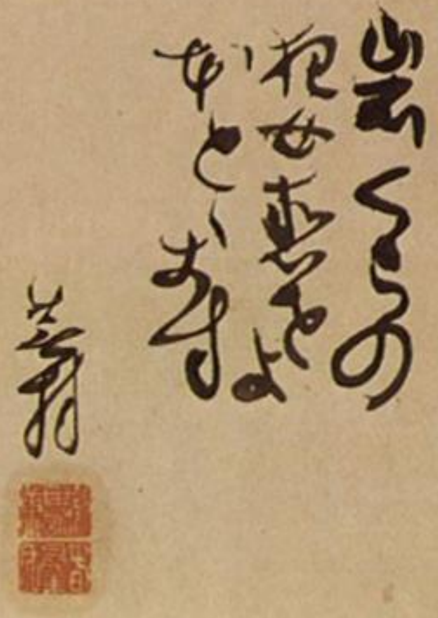
For a failure rate threshold of 1 ppm, $2 * \left(\mu_{CD_1}/\sigma_{CD_1}\right)$ = 9.5

For a failure rate threshold of 1 ppb, $2 * \left(\mu_{CD_1}/\sigma_{CD_1}\right)$ = 12

# Conclusions

- Existing approximate methods for incorporating stochastics into EPE budgets are no longer good enough
  - Rigorous analysis of any given situation allows local (stochastic) + systematic errors to be combined to predict failure mechanisms
- The overlay process window shows how changes in stochastic variations affect the range of allowed overlay errors
  - A similar process window exists for mean CD variations as well
- Propagation of Uncertainty approach translates measurement uncertainty into uncertainty in overlay process window predictions
  - Accurate stochastics metrology is a necessary enabler for overlay control

Edges are random
We can still understand them
Just not the old way



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# Thank You

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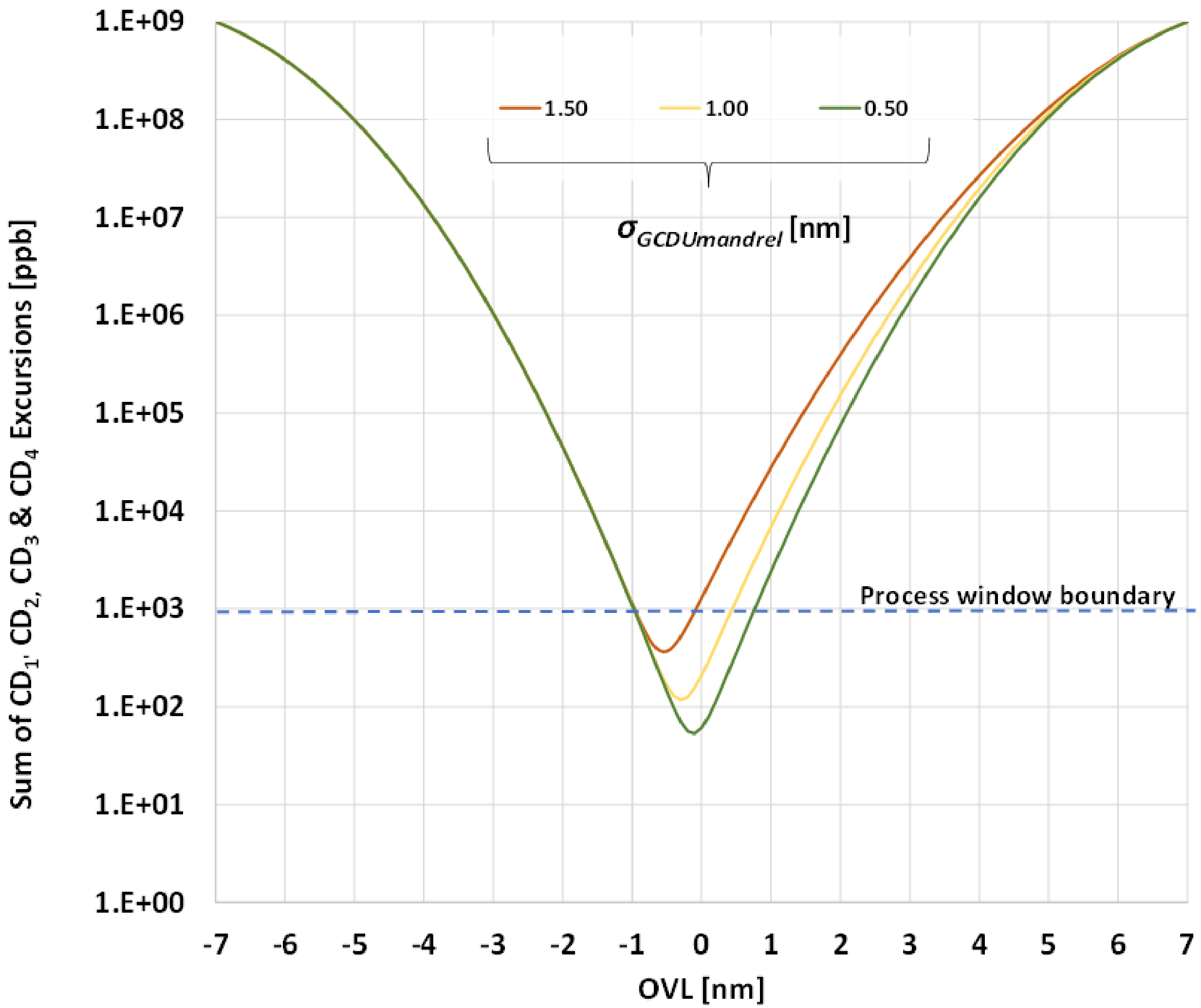
# Backup




- Overlay process window for the case including all excursion types CD1, CD2, CD3, & CD4
- All parameters as shown in table 1, with the exception of $\sigma_{OVL}$ = 0.88 nm.