More on Stochastics and the Phenomenon of Line-Edge Roughness

FRACTILIA

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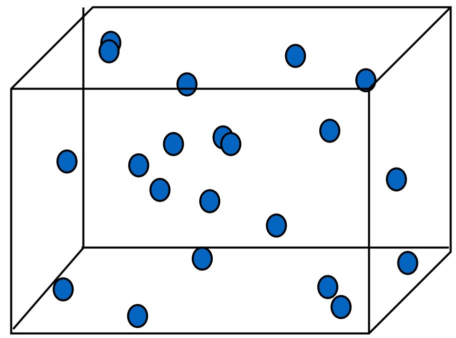
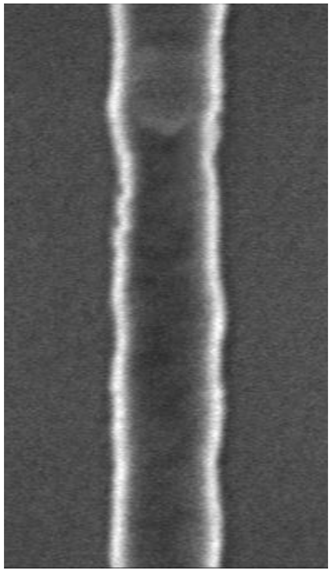
Conclusions

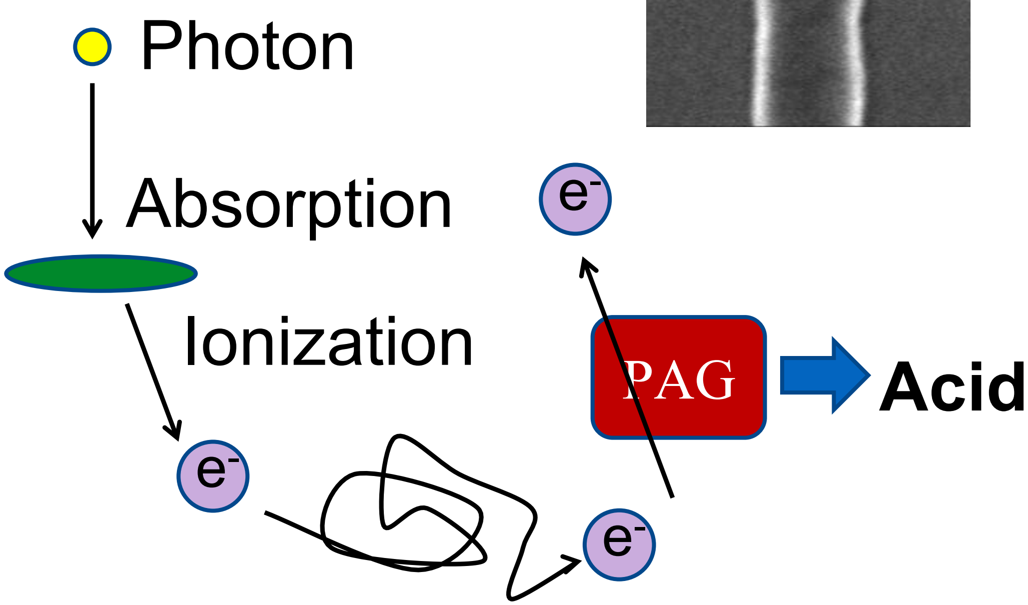
- We need more than just 3σ to understand roughness
  - We need the power spectral density (PSD) to understand the relationship between LWR and LCDU
- Using biased roughness can be very misleading
  - We need to measure the unbiased roughness
- After litho, resist blur = correlation length
- There is an optimum resist blur for stochastics
- New simple model predicts the optimum resist blur and the scaling of minimum LER

Randomness in Lithography

- Photon count
- PAG positions
- Absorption/acid generation
- Polymer chain length
- Blocking position
- Reaction-diffusion
- Dissolution



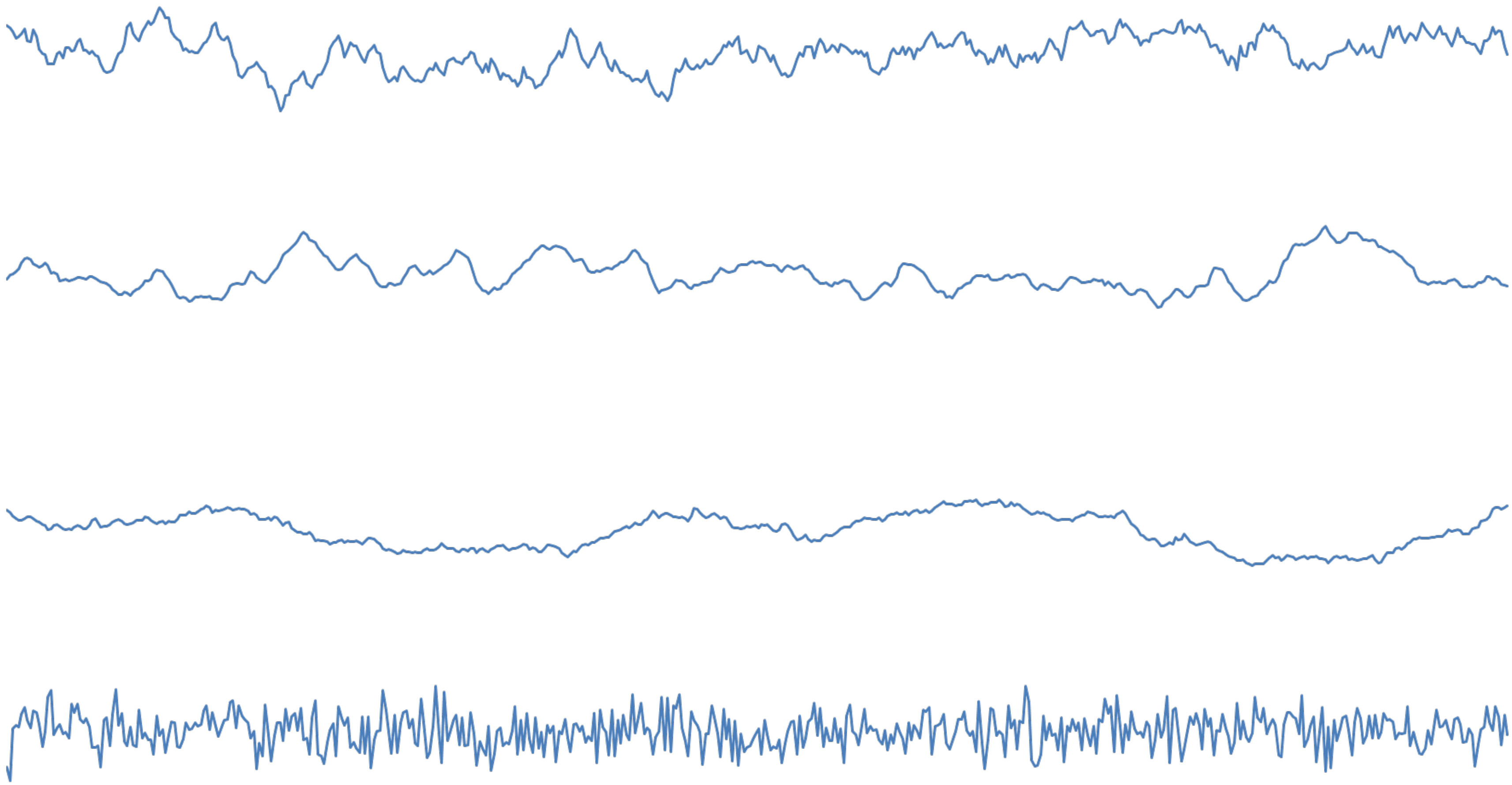




The Importance of Correlations

- **White noise**: uncorrelated, each random event is independent
  - Photon shot noise, absorption, chemical concentration, acid generation
  - Produces a flat power spectral density (PSD)
- **Correlating mechanisms**: random events that are not independent
  - Secondary electron generation, acid generation, reaction-diffusion, development front propagation
  - Lowers (smooths) the PSD on length scales below the correlation length (i.e., high frequency roughness)

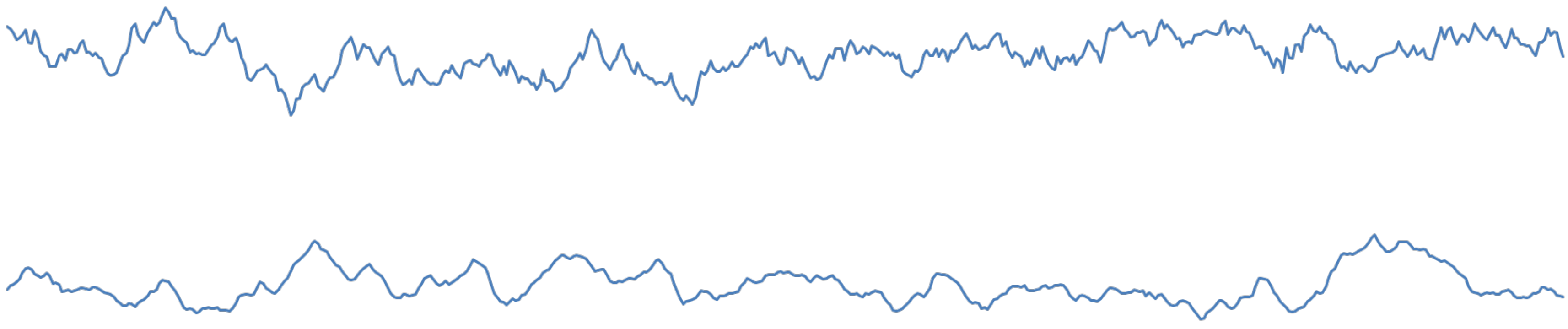
Are these edges different?



All have the same 3σ roughness!

$\xi = 10\ \Delta x$
$H = 0.5$

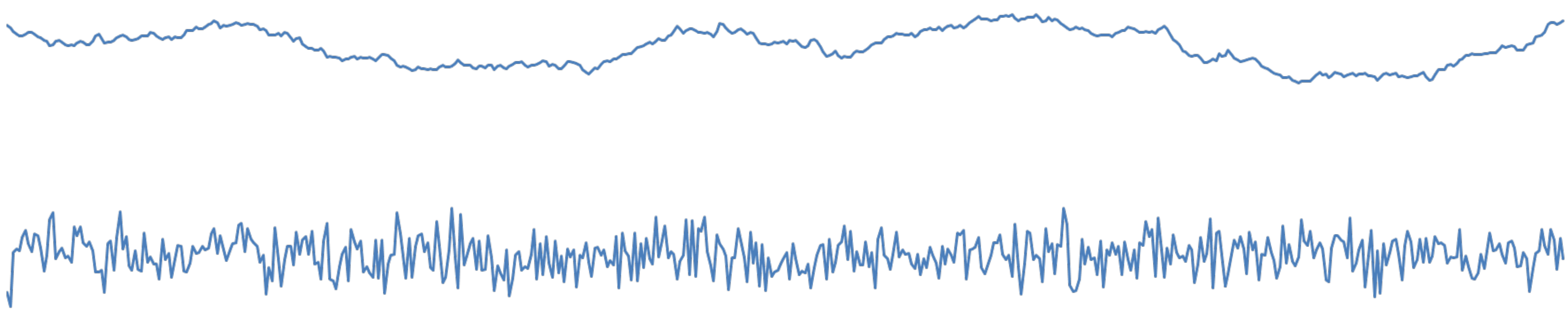
$\xi = 10\ \Delta x$
$H = 1.0$



Knowing the roughness standard deviation is <u>not good enough</u>

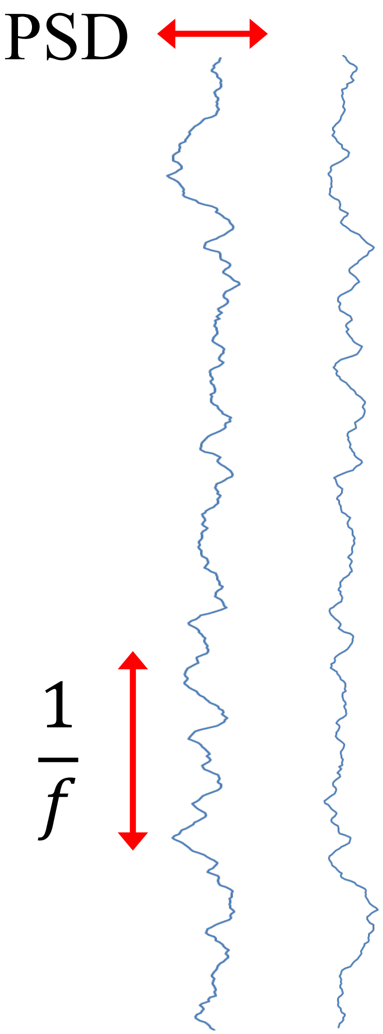
$\xi = 100\ \Delta x$
$H = 0.5$

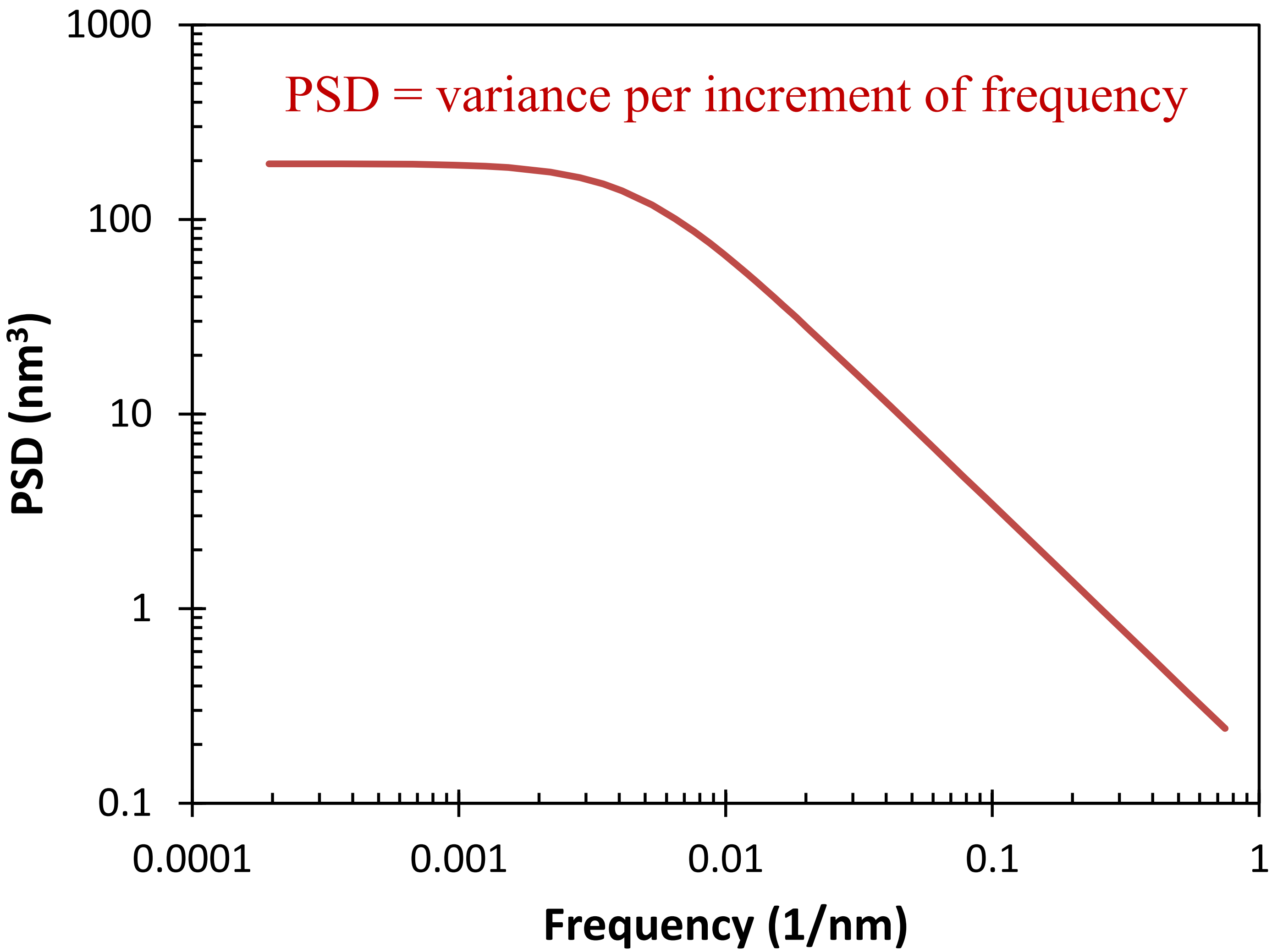
$\xi = 0.1\ \Delta x$
$H = 0.5$



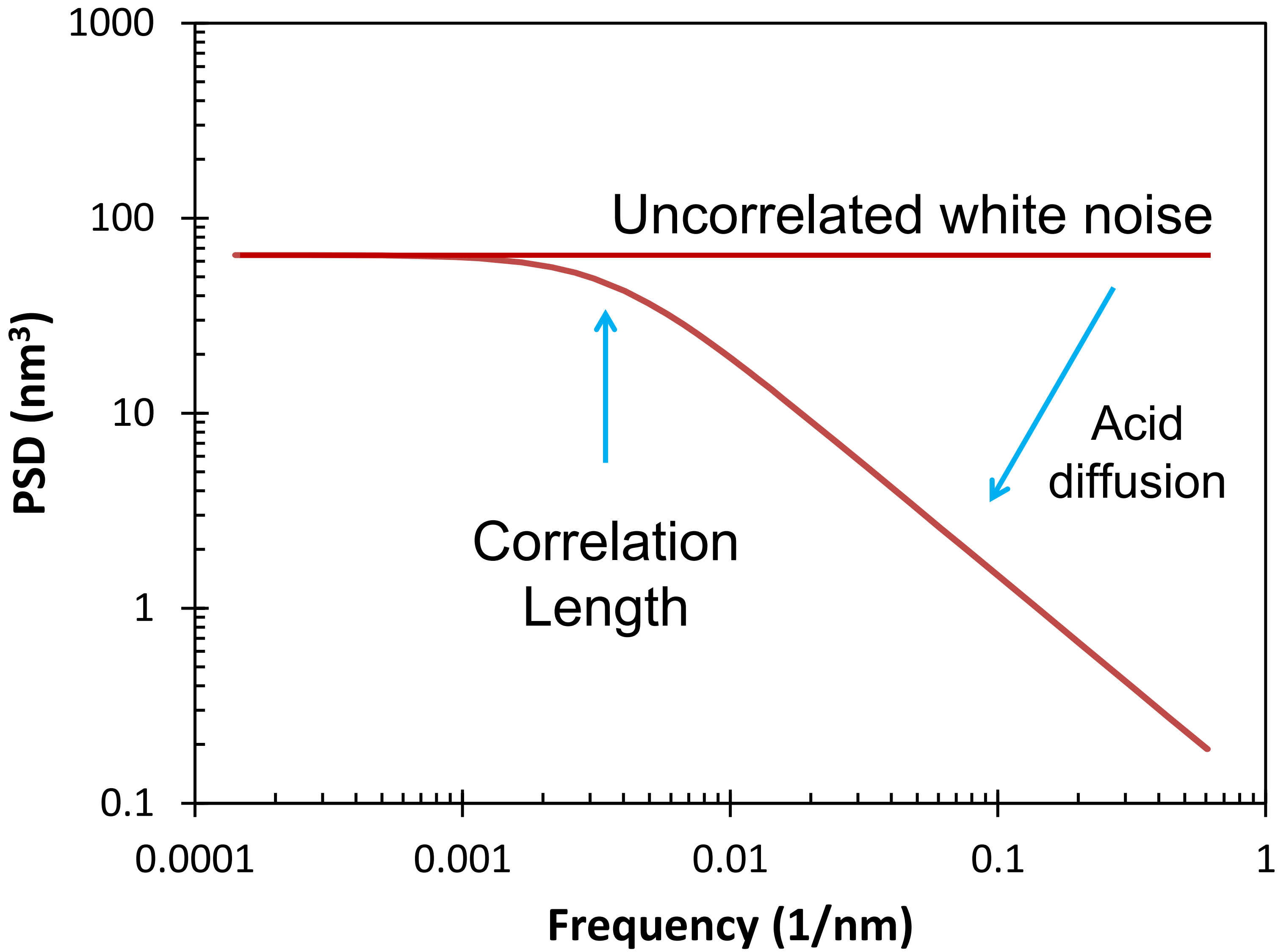
$L = 512\ \Delta x,\ \sigma = \text{fixed}$

The Power Spectral Density

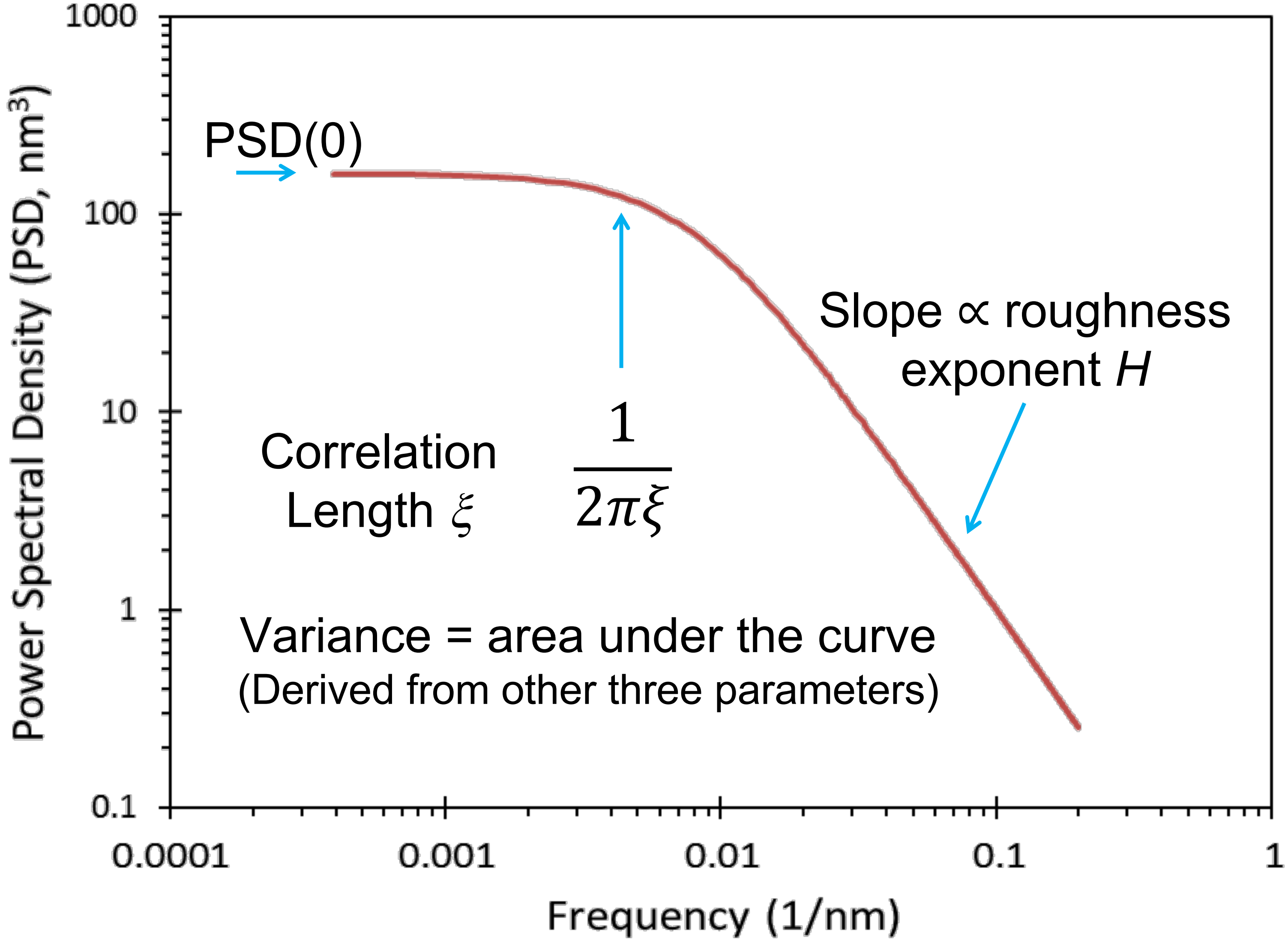




What Gives the PSD its Shape?

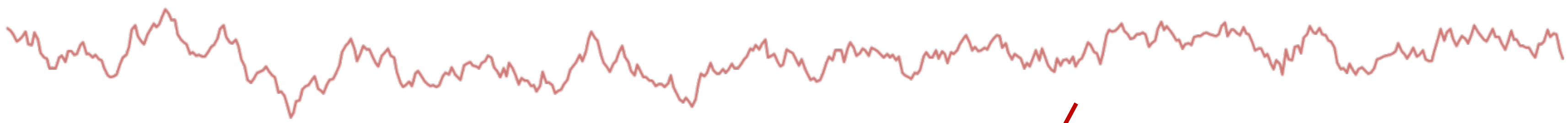


The Power Spectral Density

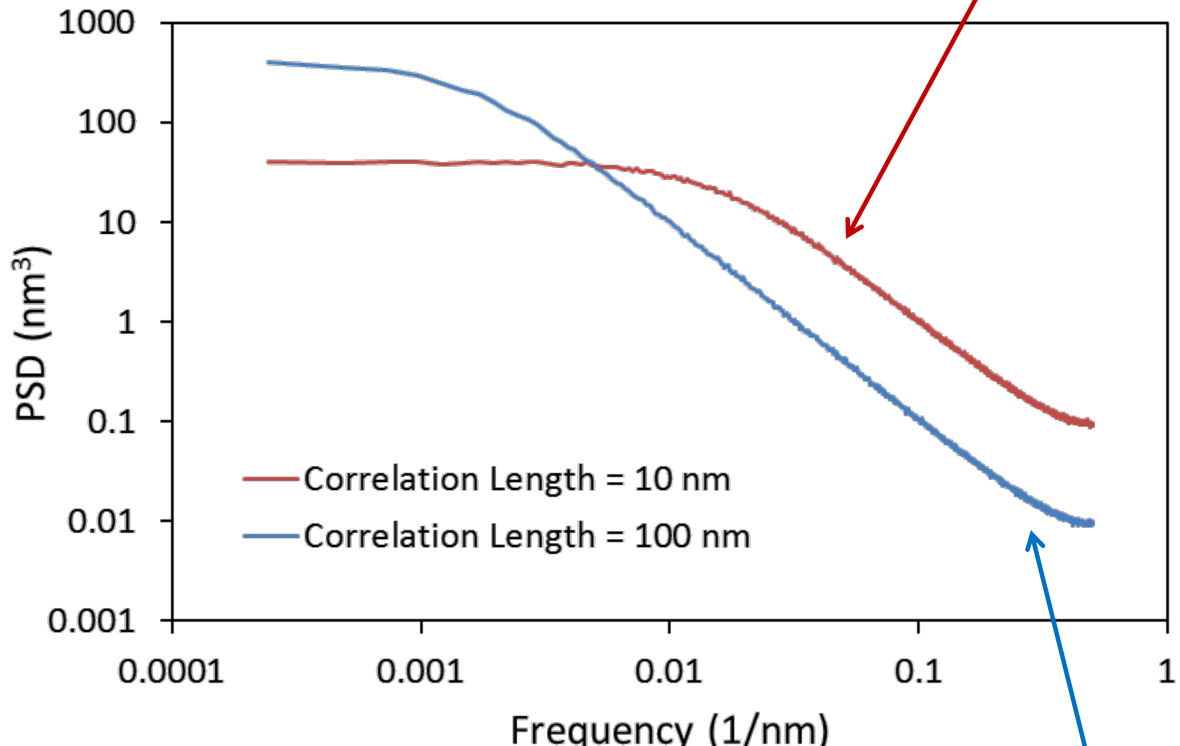


The Same 3σ, but Different PSDs

$\xi = 10\ \Delta x$
$H = 0.5$



These PSDs will have different device feature impact



$\xi = 100\ \Delta x$
$H = 0.5$

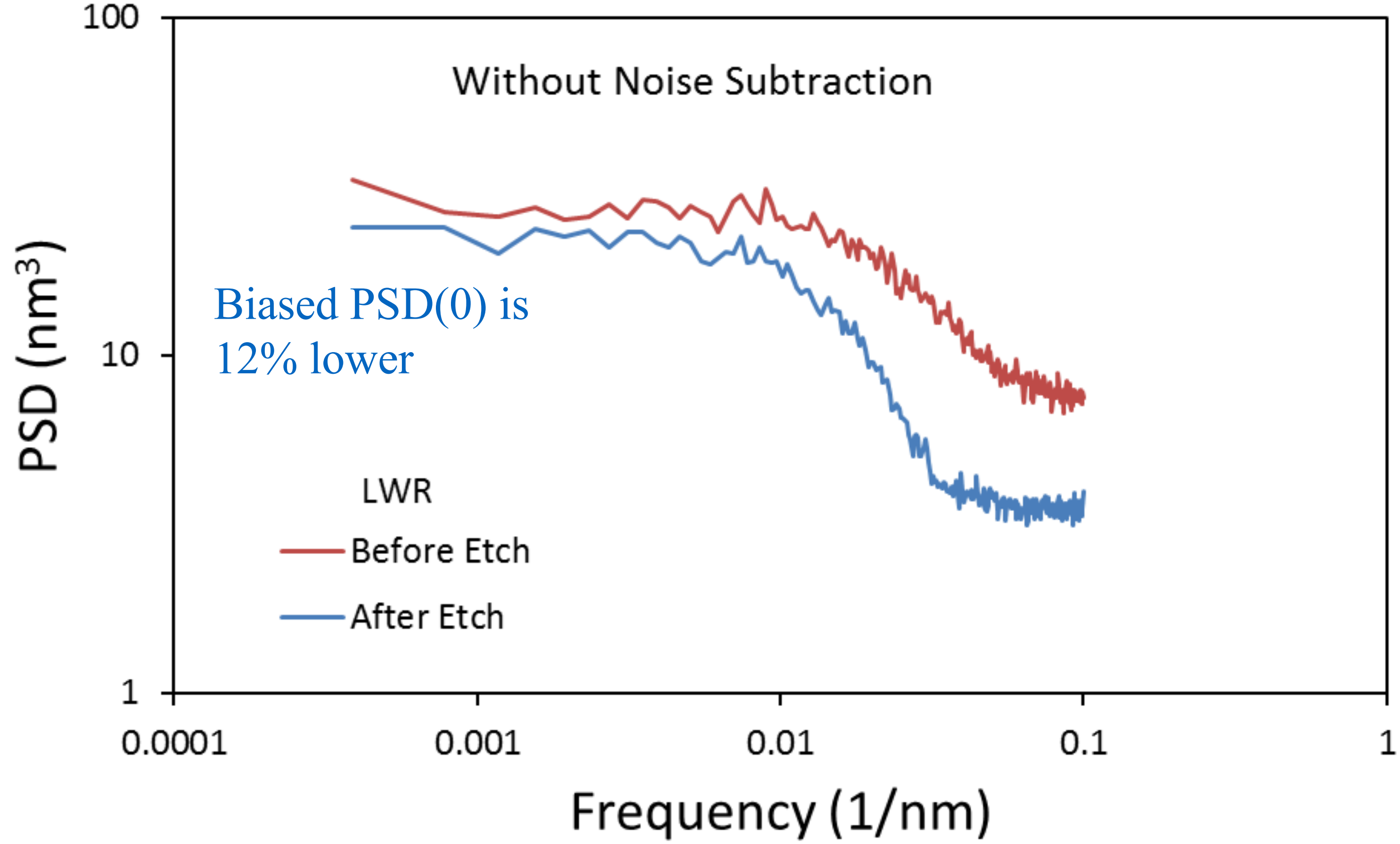
Example 1: Does etch reduce roughness?

- Experiment: Measure roughness before and after etch
  - 3s roughness (for long lines) goes down
  - What happens to device features?
- We need to look at unbiased PSDs to understand the impact of etch on roughness
  - Does PSD(0) change?
  - How much does etch increase correlation length?

Before and After Etch: a biased view

Biased LWR Before Etch: 4.9 nm
Biased LWR After Etch: 3.6 nm

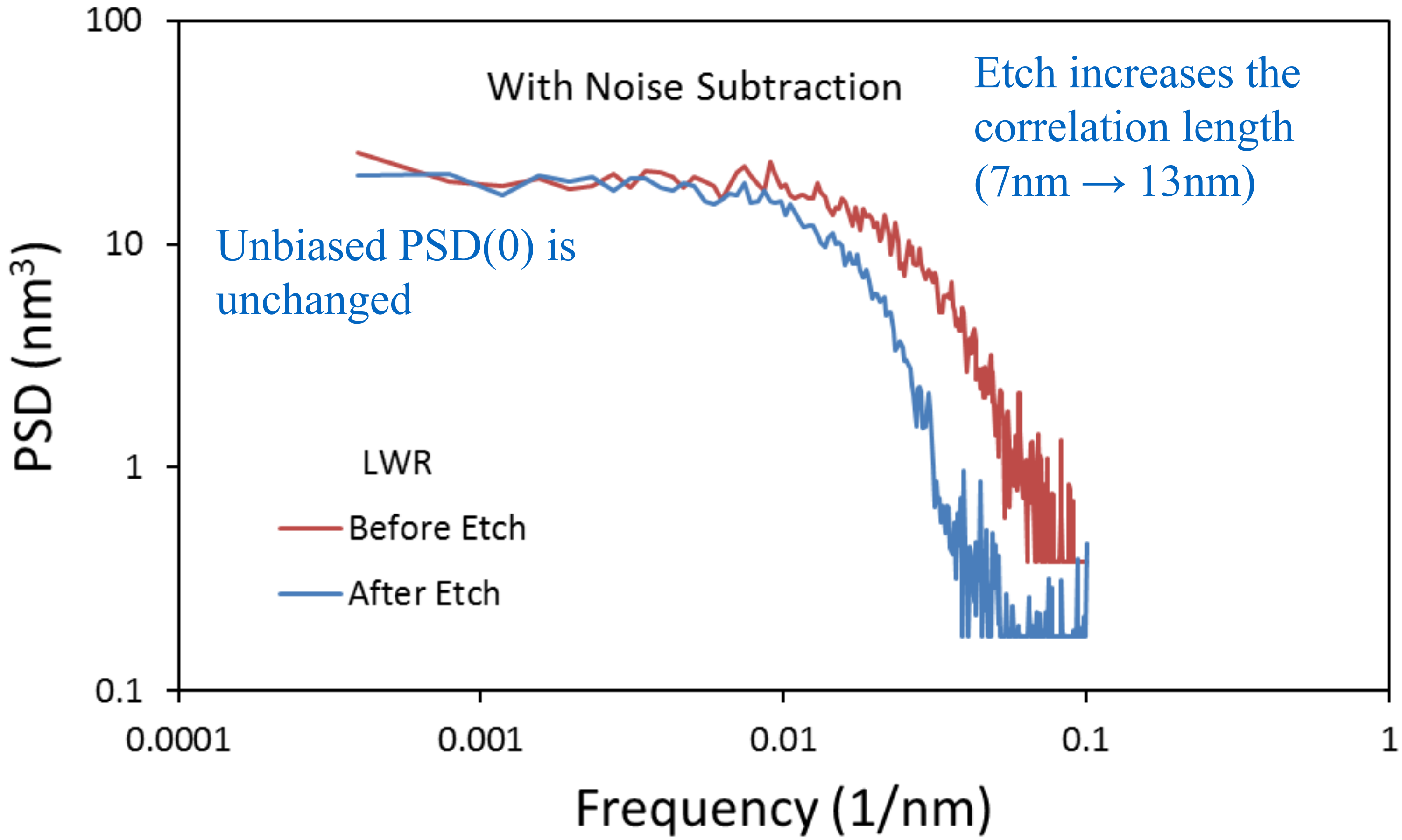
27% reduction



Before and After Etch: an unbiased view

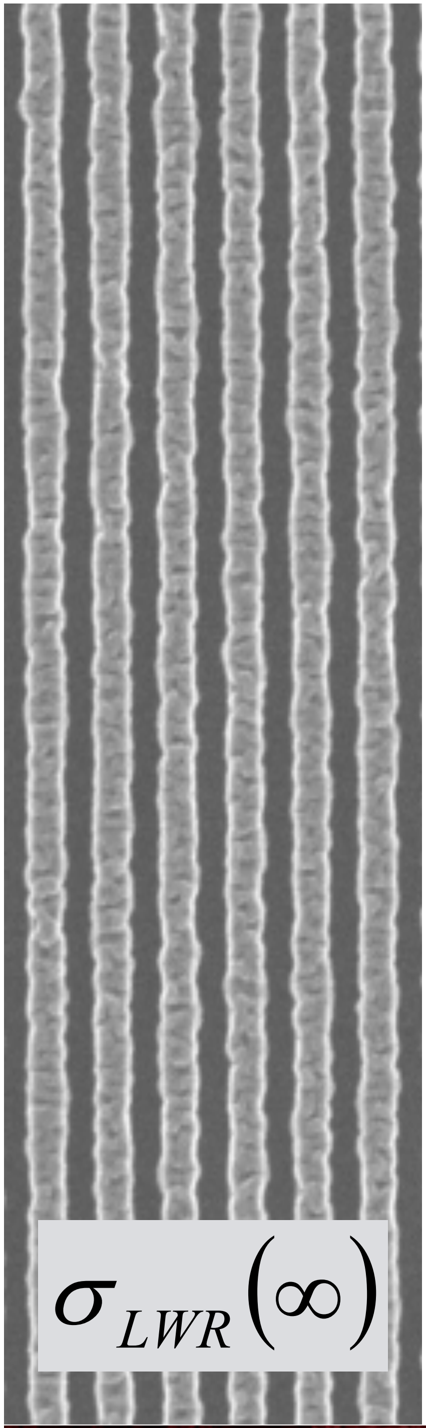
Unbiased LWR Before Etch: 3.5 nm
Unbiased LWR After Etch: 2.6 nm

26% reduction



Does Etch Reduce Roughness?

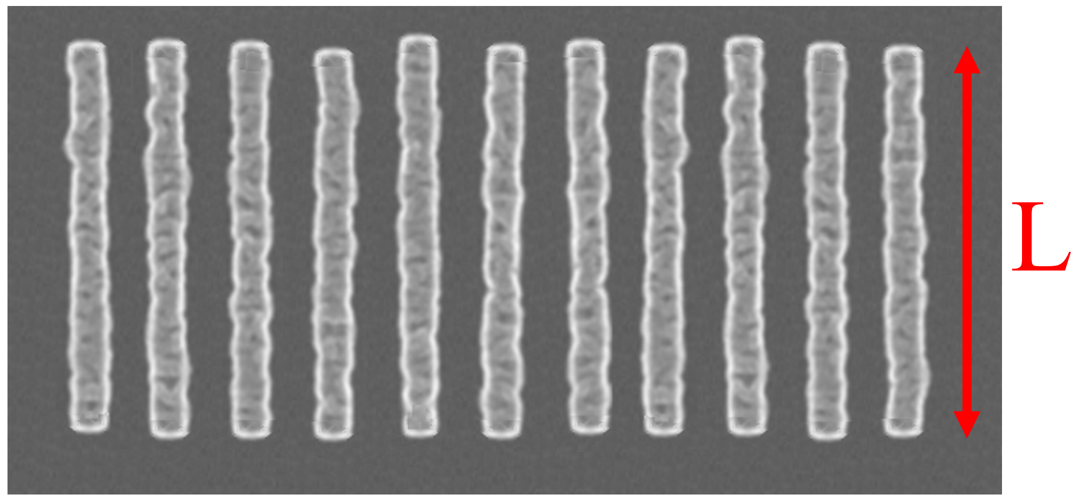
- Biased measurement, without noise subtraction, gives a false picture since after etch SEM images generally have lower noise
- Only unbiased PSD measurement (after noise subtraction) gives you the right picture
  - In this example, etch increased the correlation length, but did not lower PSD(0)
  - Within-feature roughness will decrease due to etch, but LCDU will remain the same



$$\sigma_{LWR}(\infty)$$

Finite-Length Features

$$\sigma_{LWR}(L)$$ Within-feature roughness



LCDU: Feature-to-feature variation of mean CD (local CDU)

$$\sigma_{CDU}(L)$$

Conservation of Roughness

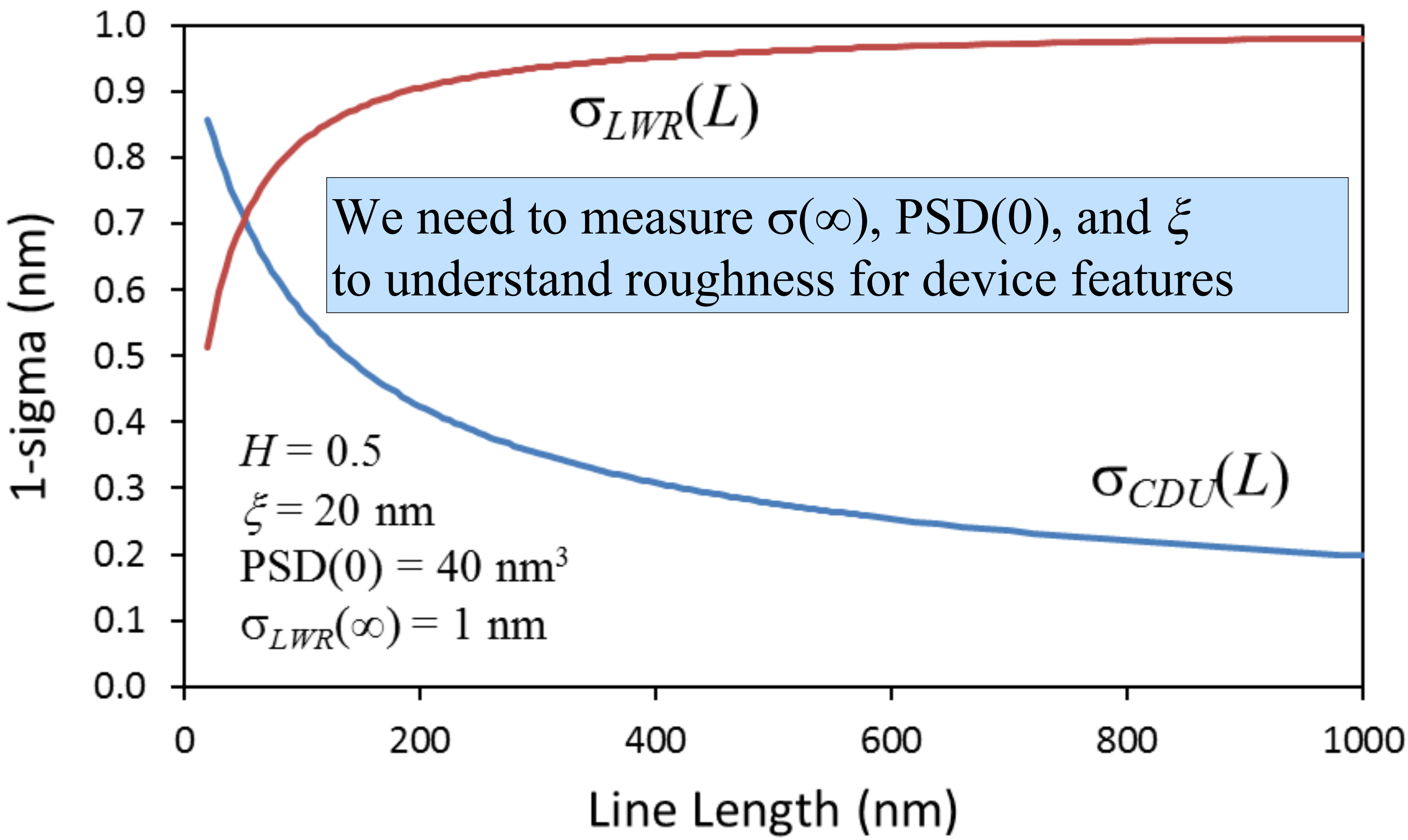
- For all features of the same CD and pitch, for any length *L*,

$$\sigma^2_{CDU}\left(L\right)+\sigma^2_{LWR}\left(L\right)=\sigma^2_{LWR}\left(\infty\right)$$

- Different line lengths partition the total roughness into within-feature and feature-to-feature variation

$$\sigma^2_{CDU}\left(L\right)\approx\frac{PSD(0)}{L}\left[1-\frac{\xi}{L}\right] \qquad \sigma^2_{LWR}\left(\infty\right)\approx PSD(0)/\left[\left(2H+1\right)\xi\right]$$

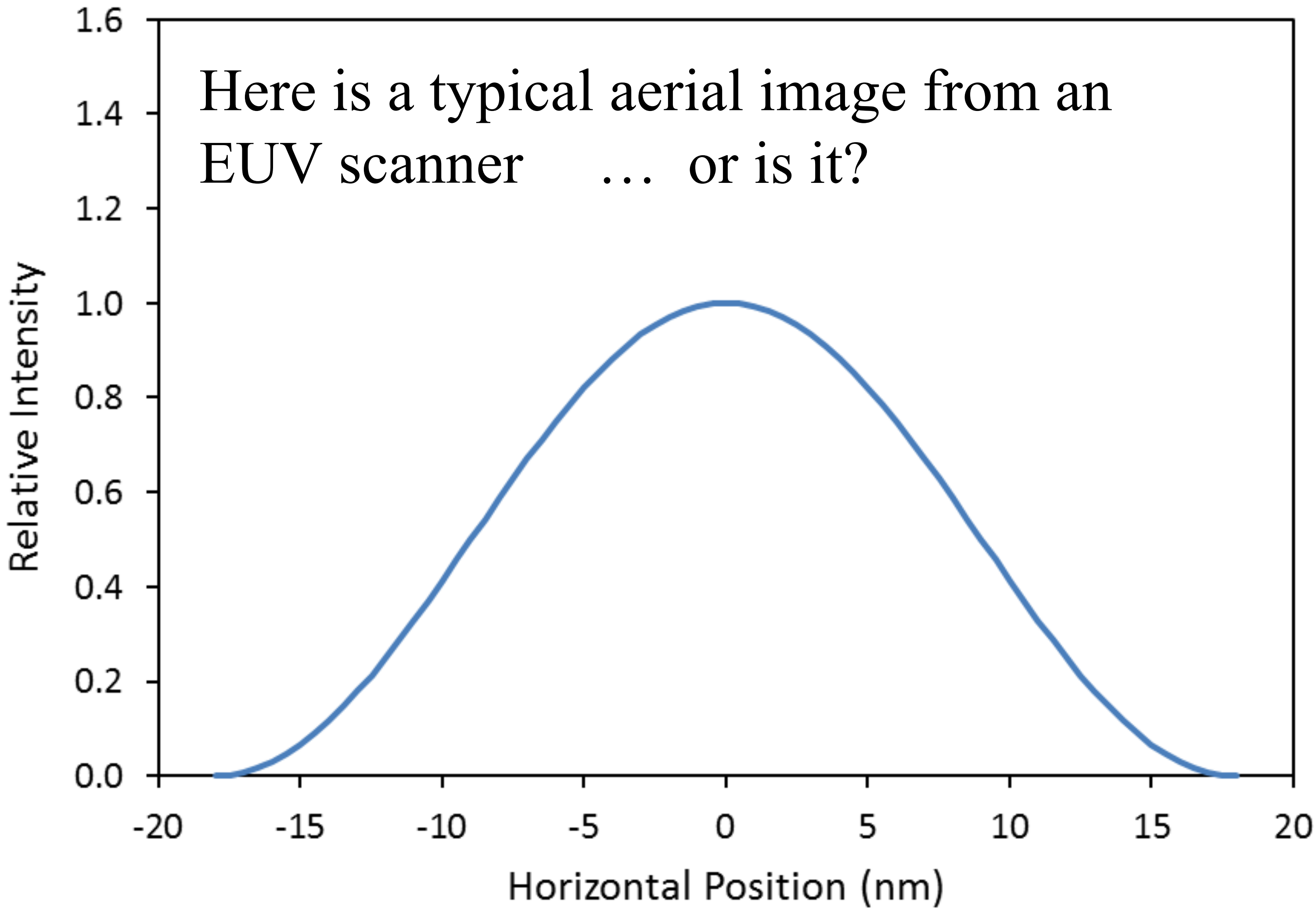
Conservation of Roughness



Measuring Roughness is Hard

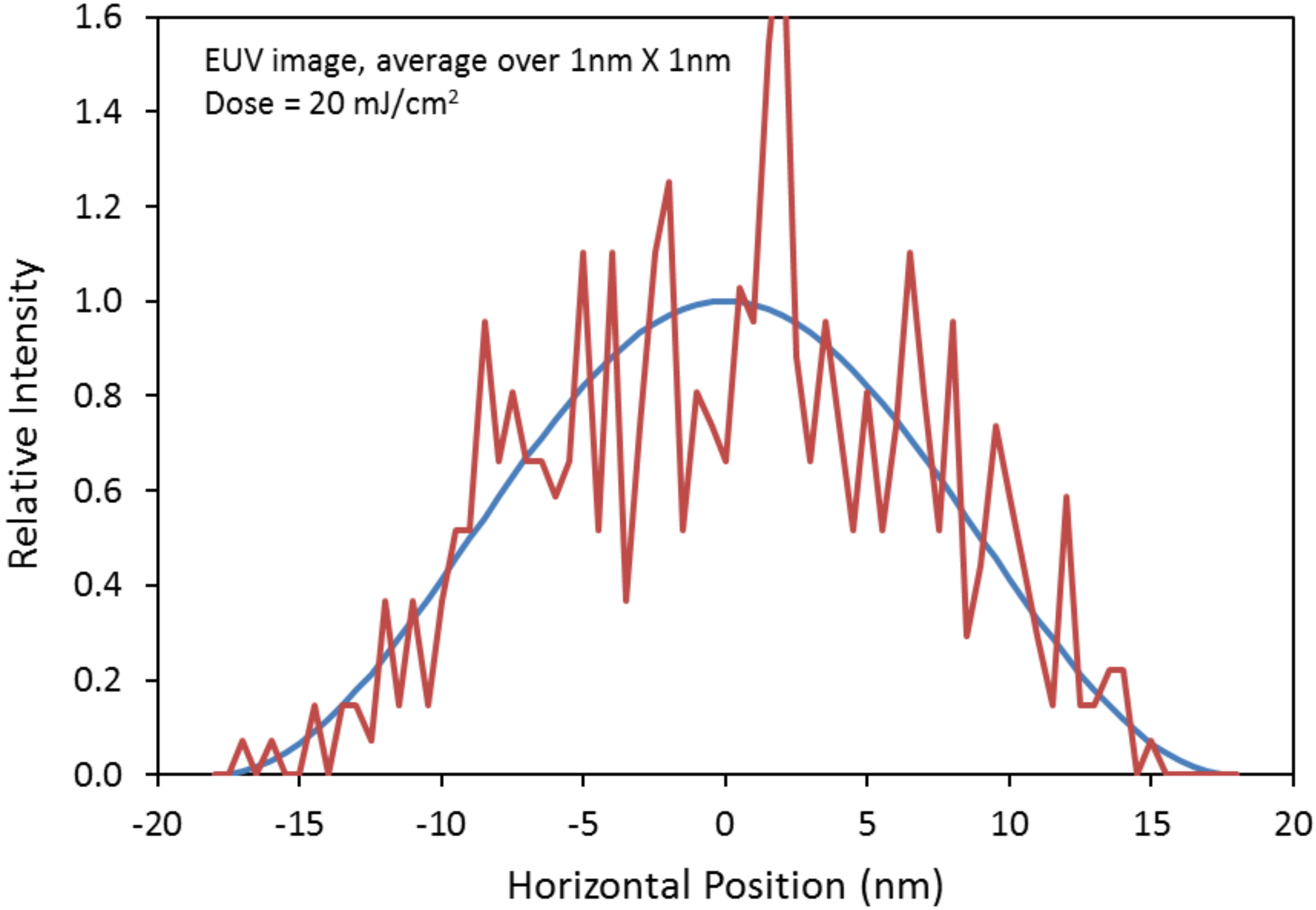
- We need to measure the PSD parameters to understand how roughness impacts device features (LWR and LCDU)
- SEM images contain both random and systematic errors that bias our results
  - Random noise in the image produces white noise
  - Systematic field variations (intensity, distortion) increase the apparent low-frequency roughness
- Conclusions based on biased roughness measurements are often wrong

What is the EUV Image?



18nm HP

What is the EUV Image?



Line-Edge Roughness (Simple Model)

- Consider a small deviation in resist development rate (ΔR). The resulting change in resist edge position (x) will be approximately

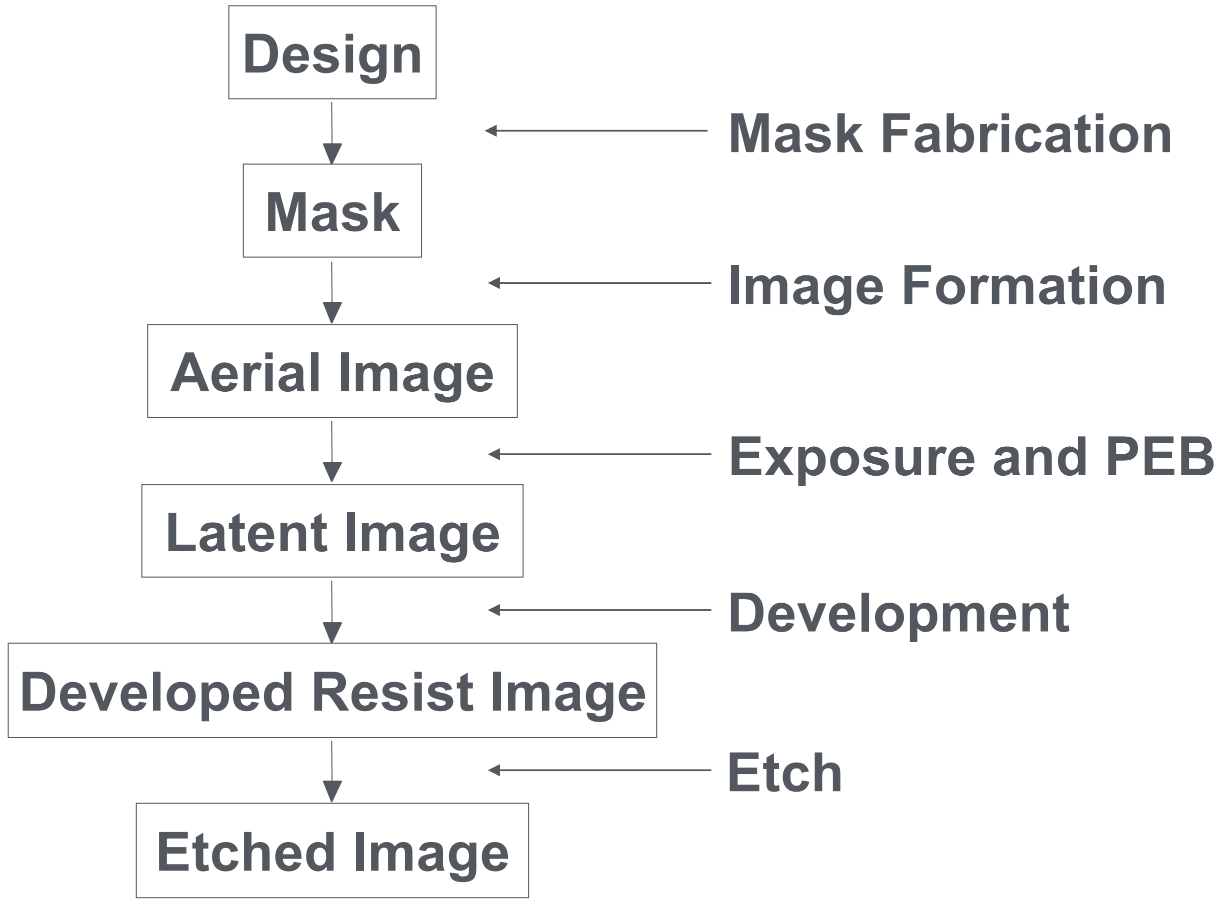
$$\Delta x = \frac{dx}{dR}\Delta R$$

- For some random variation in development rate σ_R, the resulting LER is

$$\sigma_{LER} = \frac{\sigma_R}{dR/dx}$$

Lithography Information Transfer

- Lithography can be thought of as a sequential transfer of information



Consider Exposure through Development

- The only source of information is the aerial image
  - Subsequent process steps do not add information
  - It is possible to add noise (increase σ) and lose information (decrease gradient), but the signal to noise can never improve

$$\sigma_{LER} = \frac{\sigma_R}{dR/dx} \geq \frac{\sigma_m}{dm/dx} \geq \frac{\sigma_h}{dh/dx} \geq \frac{\sigma_{I_{abs}}}{dI_{abs}/dx}$$

- A fundamental limit of LER is the last term in this sequence (you can't do any better than the information in the image)

What is the LER limit?

- The distribution of the number of absorbed photons (N_{abs}) is Poisson

$$\sigma_{N_{abs}} = \sqrt{N_{abs}}$$

- The gradient of absorbed photons is determined by the image log-slope

$$ILS = \frac{d \ln I}{dx} = \frac{1}{N_{abs}} \frac{dN_{abs}}{dx}$$

What is the LER limit?

- The best possible LER is then

$$Best\ Case\ \sigma_{LER} = \frac{\sigma_{I_{abs}}}{dI_{abs}/dx} = \frac{1}{ILS\sqrt{N_{abs}}}$$

- How many photons are absorbed? It depends on the volume V you are looking at:

At the feature edge: $N_{abs} = \alpha VE$

α = resist absorption coefficient
E = dose (#photons/area) incident on the volume

What is the Correct Volume to Average Over?

- Two suppositions about the ambit volume V:
- First,

$$V = \xi^3 \qquad \text{where } \xi = \text{max(polymer size, resist blur)}$$

- Second, after litho: resist blur = correlation length
  - Correlation length comes from measurement of the roughness power spectral density (PSD)

Complication: Blur lowers ILS

- Effective ILS is a function of resist blur

Diffusion:

$$\frac{\partial \ln I_{eff}}{\partial x} \approx \frac{\partial \ln I}{\partial x}\left(e^{-2(\pi\xi/CD)^2}\right)$$

Reaction-Diffusion:

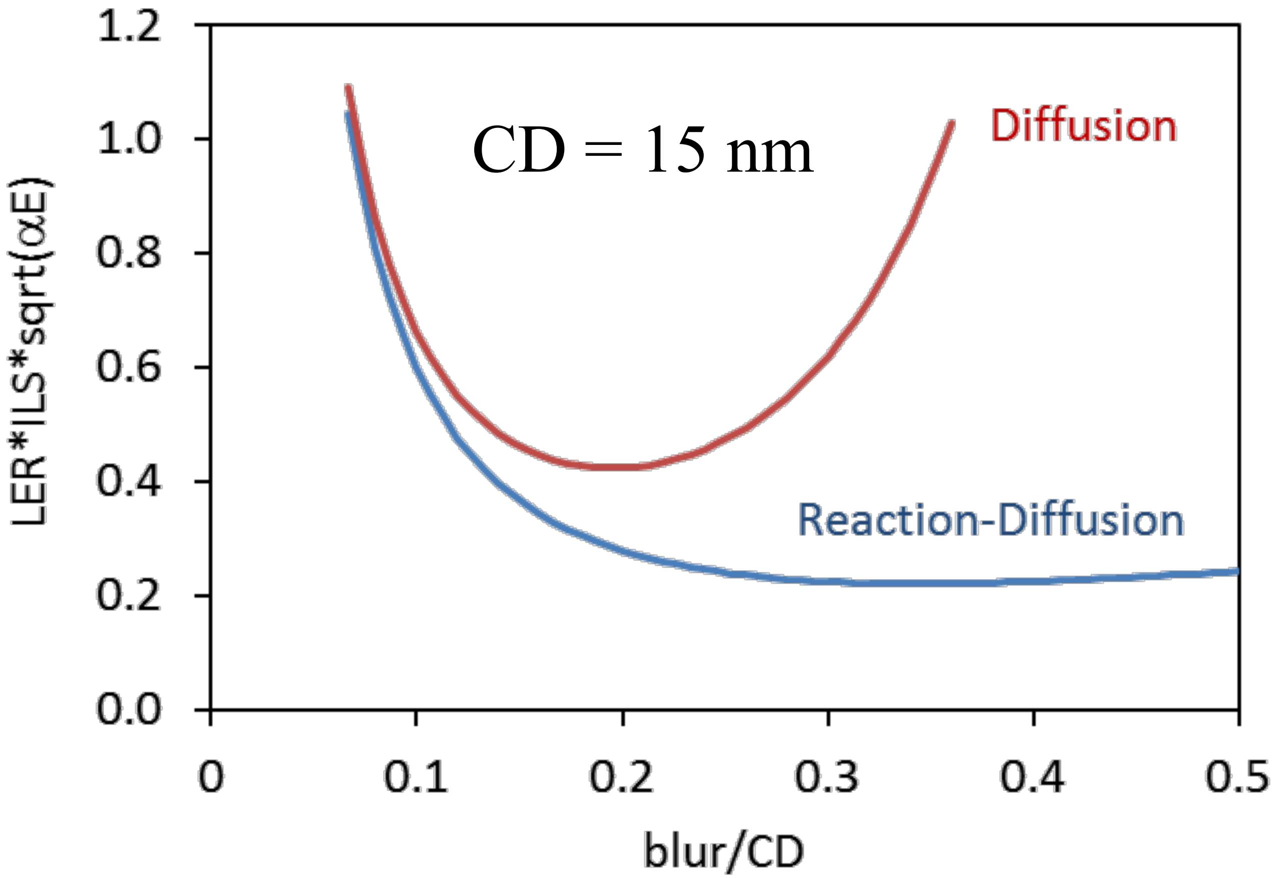
$$\frac{\partial \ln I_{eff}}{\partial x} \approx \frac{\partial \ln I}{\partial x}\left(\frac{1-e^{-2(\pi\xi/CD)^2}}{2(\pi\xi/CD)^2}\right)$$

where ξ = diffusion length and CD = half-pitch

From: Chris A. Mack, *Fundamental Principles of Optical Lithography*, (Wiley: 2007).

Impact of Blur on ILS and LER

$$\textit{Best Case } \sigma_{LER} = \frac{1}{ILS_{eff}\sqrt{\alpha E \xi^3}}$$



Optimum Blur:

Diffusion:
$\xi_{opt} \approx CD/5$

Reaction-Diffusion:
$\xi_{opt} \approx CD/3$

Simple Model: Scaling Relationship

- Using the optimum resist blur,

$$\min \sigma_{LER} \propto \frac{1}{NILS\sqrt{\alpha\, ECD}}$$

- This is a mathematical version of the RLS trade-off
- We can always make it worse!

Conclusions

- We need more than just 3σ to understand roughness
  - We need the power spectral density (PSD) to understand the relationship between LWR and LCDU
- Measuring biased roughness can be very misleading
  - We need the unbiased roughness
- After litho, resist blur = correlation length
- There is an optimum resist blur for stochastics
- New simple model predicts the optimum resist blur and the scaling of minimum LER

Thank You

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