Line-Edge Roughness and the Ultimate Limits of Lithography

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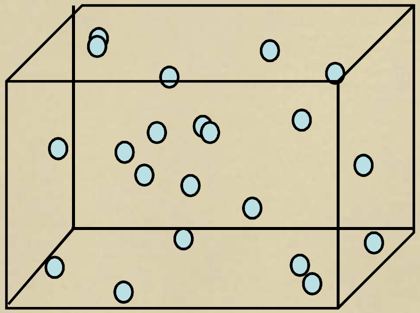
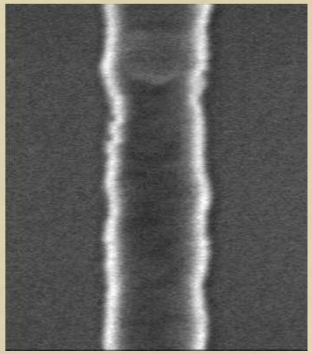
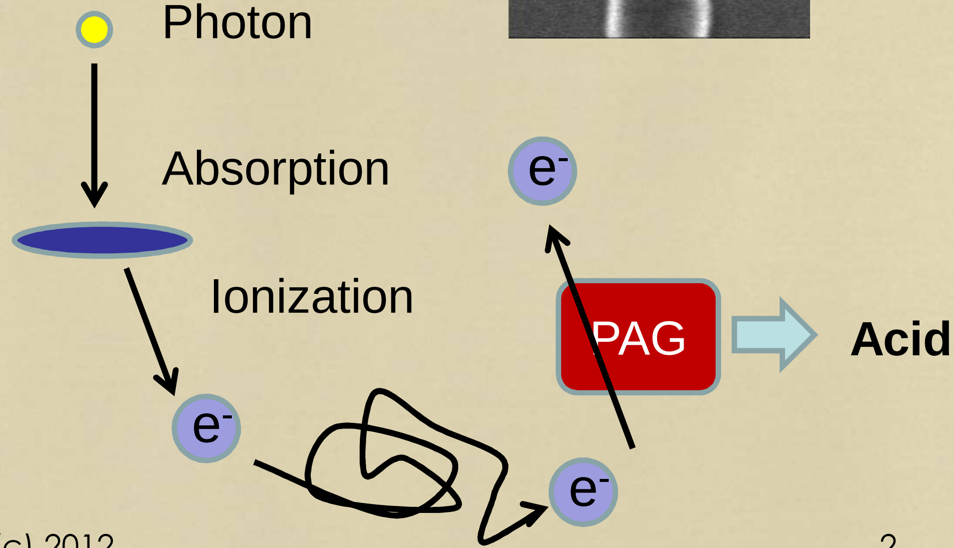
Randomness in Lithography

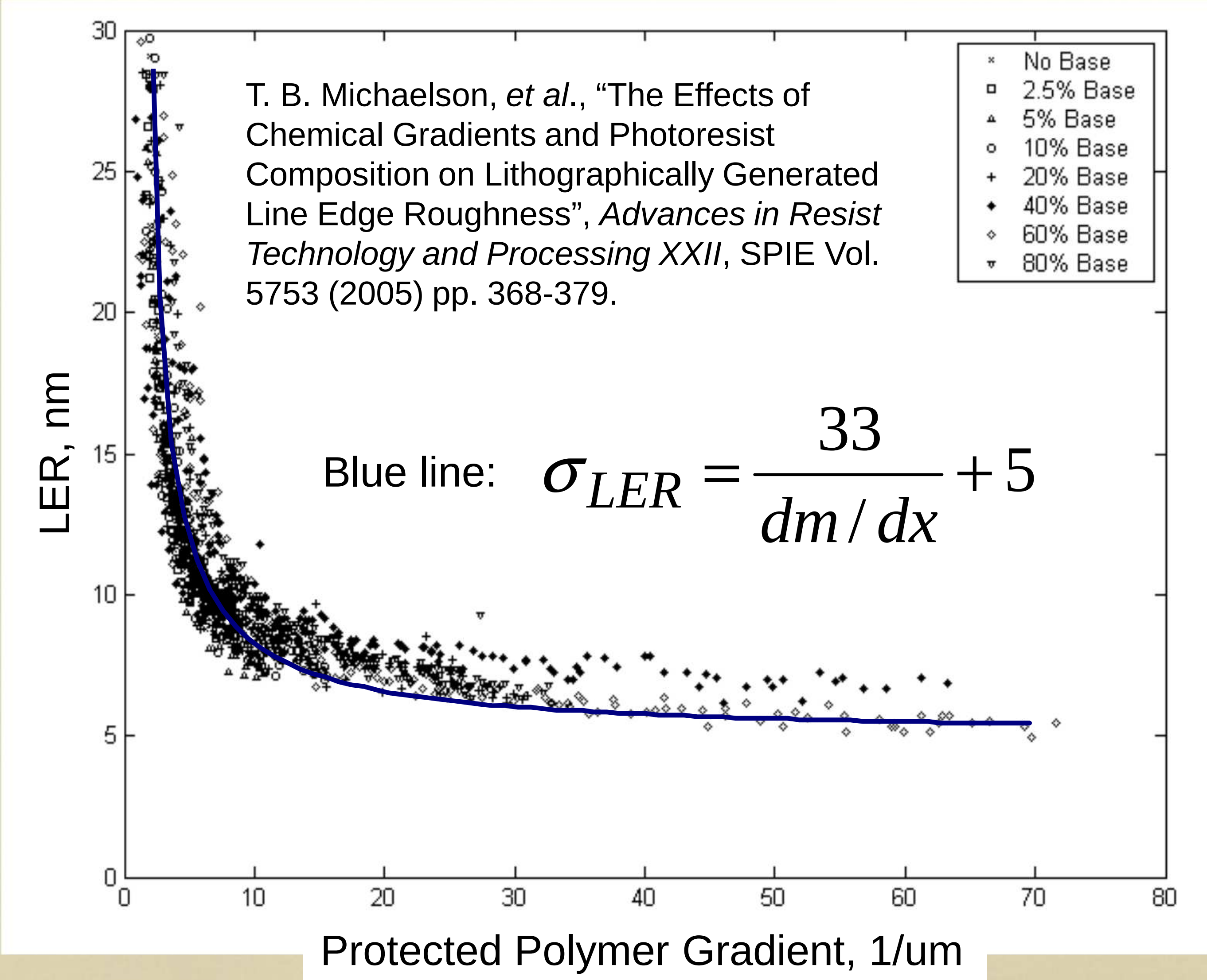
- Photon count
- PAG positions
- Absorption/acid generation
- Polymer chain length
- Blocking position
- Reaction-diffusion
- Dissolution







Impact of Gradient on LER



T. B. Michaelson, *et al*., “The Effects of Chemical Gradients and Photoresist Composition on Lithographically Generated Line Edge Roughness”, *Advances in Resist Technology and Processing XXII*, SPIE Vol. 5753 (2005) pp. 368-379.

Blue line: $$\sigma_{LER} = \frac{33}{dm/dx} + 5$$

Line-Edge Roughness (Simple Model)

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

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

- For some variation in development rate σ_R,

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

Line-Edge Roughness
(A Simple Model)

- Add the finite size of a resist molecule, σ_0

$$\sigma_{LER} = \frac{\sigma_m}{dm/dx} + \sigma_0$$

- What affects the three terms of this model?
  - Molecular size
  - Acid diffusion length
  - Dose
  - Image NILS
  - Others…

Stochastic View of Exposure + Reaction-Diffusion

- Uncertainty in deblocked polymer concentration:

$$\left(\frac{\sigma_m}{\langle m\rangle}\right)^2 = \frac{1}{\langle n_{0-blocked}\rangle\langle m\rangle} + \left(K_{amp}t_{PEB}\right)^2\left(\frac{2a}{\sigma_D}\right)^2\left(\frac{\langle h\rangle}{\langle n_{0-PAG}\rangle} + \frac{\left[\left(1-\langle h\rangle\right)\ln\left(1-\langle h\rangle\right)\right]^2}{\langle n_{photon}\rangle}\right)$$

Deblocking reaction

Reaction-diffusion

PAG concentration, exposure

Photon shot noise

Effect of Polymer Size

- As polymer size increases ($\uparrow$):

$$\sigma_{LER} = \frac{\sigma_m \downarrow}{dm/dx} + \sigma_0 \uparrow$$

- Solubility of the polymer is a function of the total number of deprotection events associated with that polymer
- These events are averaged over the volume of one polymer
- There is an optimum polymer size

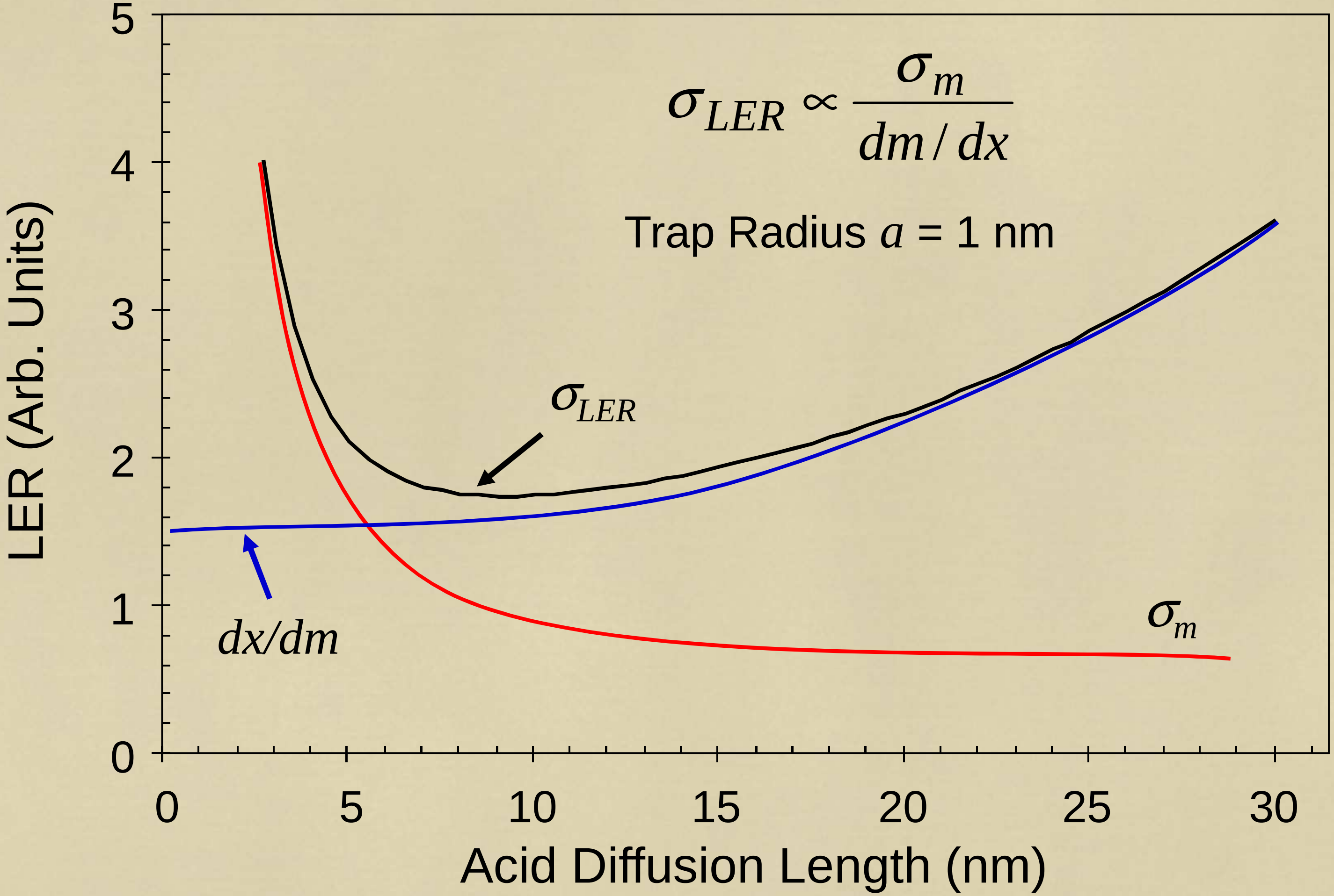
Effect of Diffusion

- As diffusion length increases ($\uparrow$):

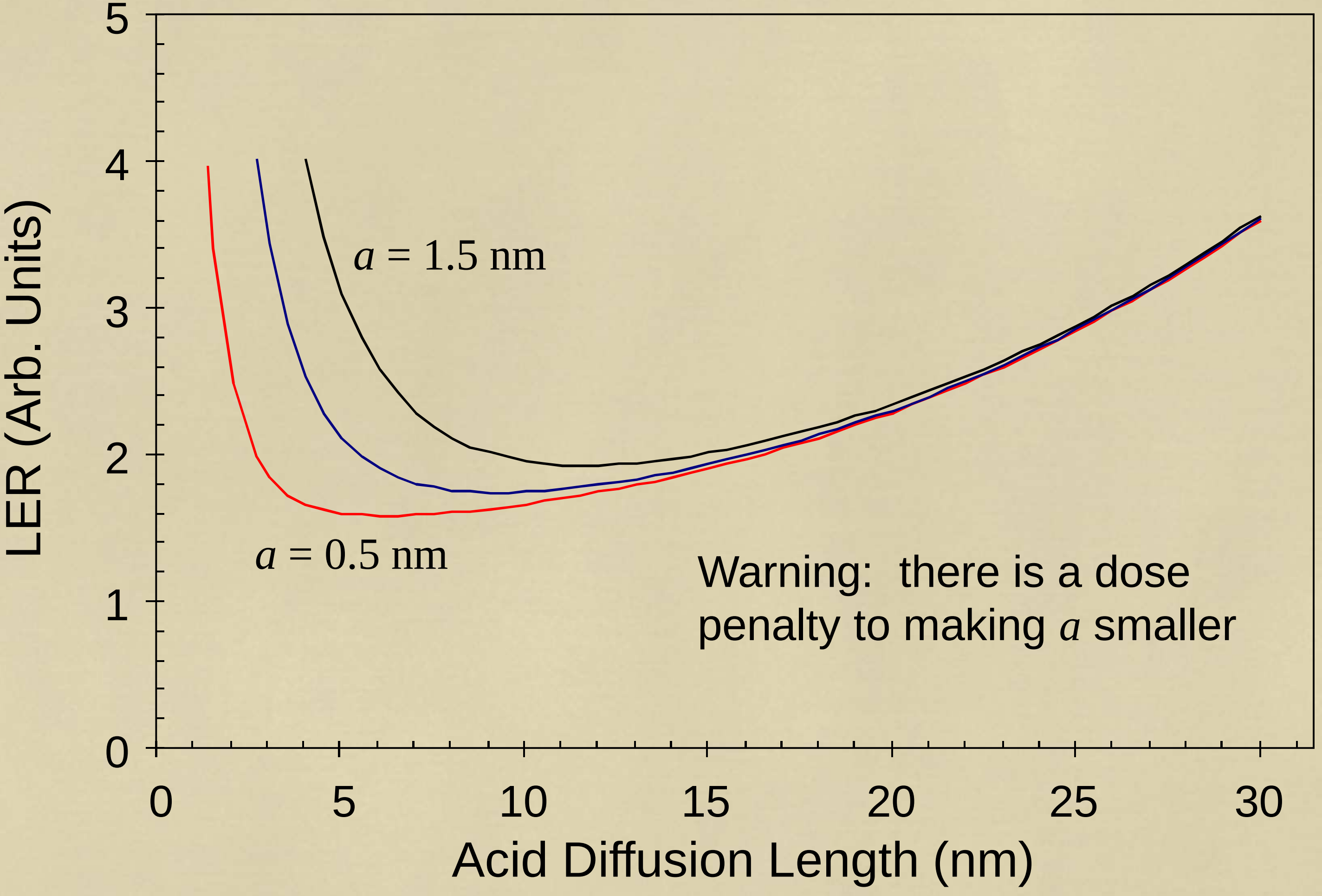
$$\sigma_{LER} = \frac{\sigma_m}{dm/dx} + \sigma_0$$

- Smoothing is caused by the diffusion of a catalyst
- This catalyst diffusion also leads to correlation
- Diffusion also smears away the image

Line-Edge Roughness and Acid Diffusion



Line-Edge Roughness and Acid Diffusion



Effect of Dose

- As dose increases (↑):

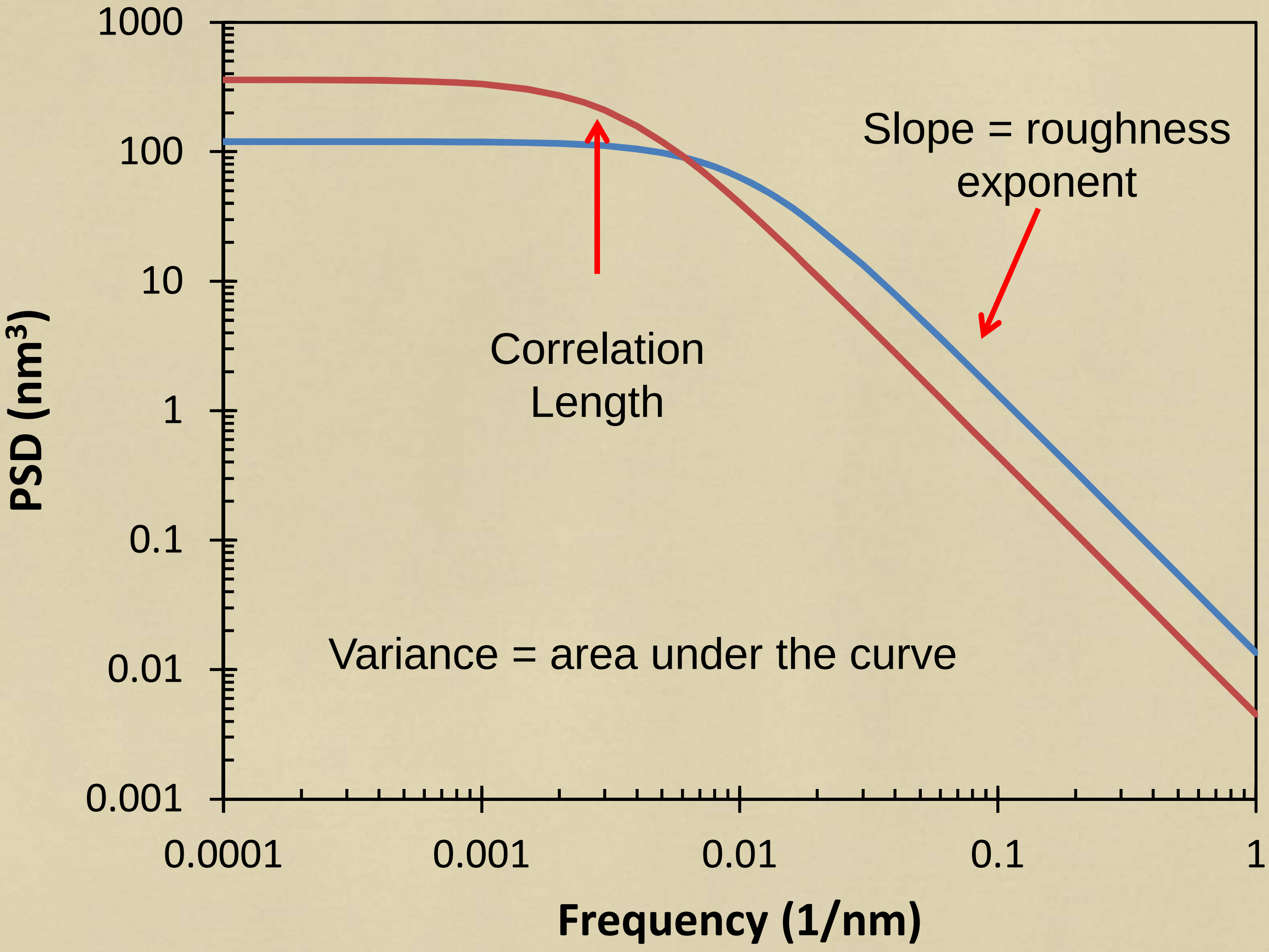
$$\sigma_{LER} = \frac{\sigma_m \downarrow}{dm/dx \uparrow} + \sigma_0$$

- Increasing dose improves the chemical gradient (to a point)
- Increasing dose reduces uncertainty (to a point)
- Diminishing returns for higher dose (in fact, there is an optimum), but we are a long ways away from that for EUV

Optimizing LER

- There is an optimum polymer size
  - Current materials are probably close to optimum
- There is an optimum diffusion length
  - Current materials probably diffuse too much
  - Optimum diffusion length scales with feature size
  - There is a dose penalty for lower diffusivity
- There is an optimum dose
  - The best dose is probably higher than what we now use (definitely true for EUV)
- Looking only at σ_{LER} is not enough

Which PSD is Better?

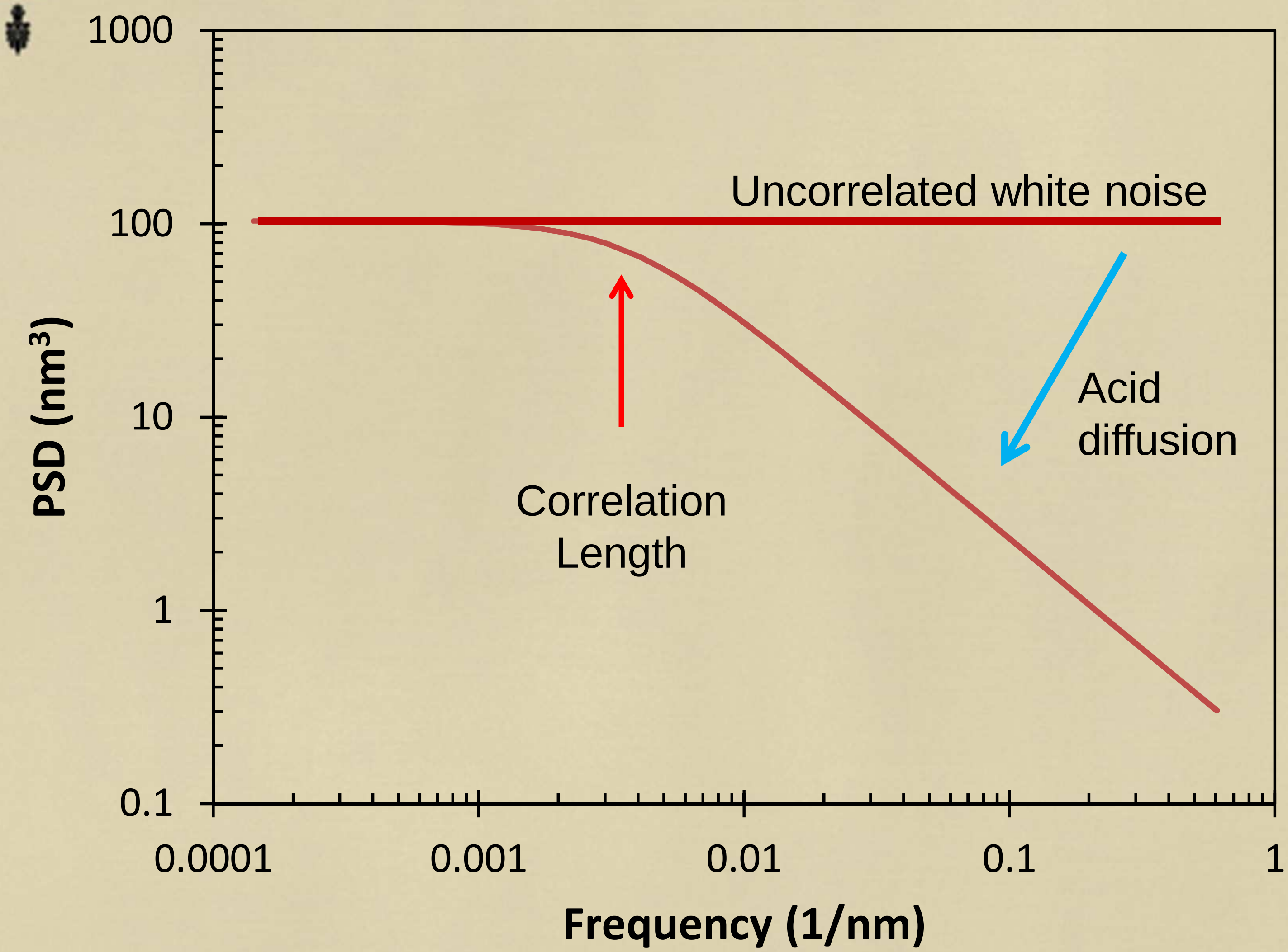


What Affects the PSD

- Roughness Standard Deviation
  - Dose, concentrations, acid diffusion length, polymer volume
- Correlation Length
  - 1-2 times the acid diffusion length
- Roughness Exponent
  - Probably equal to 0.5

How can I lower the low frequency LER?

What Gives the PSD its Shape?



Magic Rinse

- Can we smooth away the LER post-processing?
- Low frequency LER is like a CD error
- Any smoothing technique that can reduce the low frequency LER must do so by changing the CD
- How does the magic rinse know which CD is the correct one?
- The only thing that LER post-processing can help with is high-frequency LER
  - Is this more than just cosmetic?

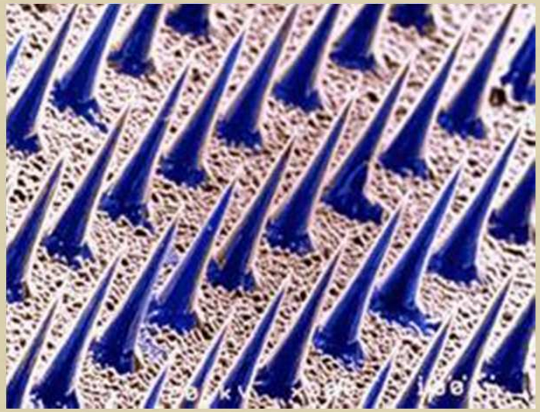
What Can Be Done?

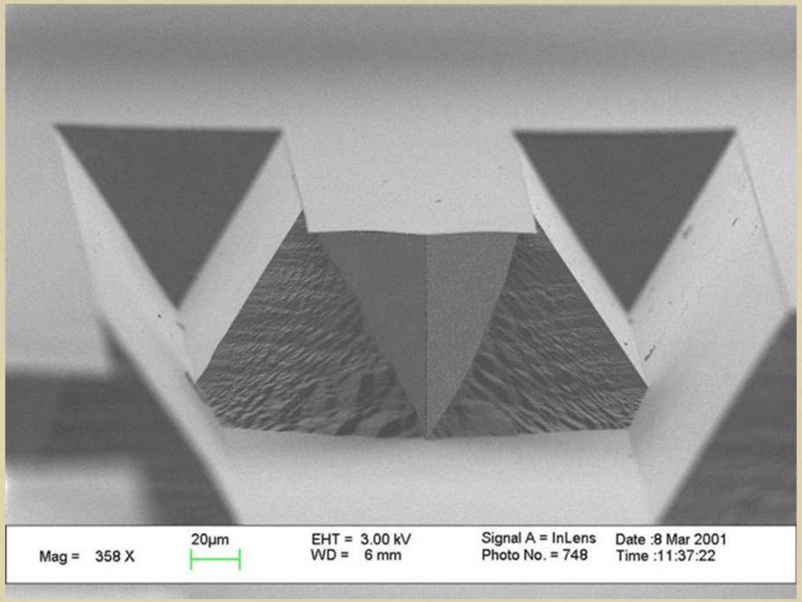
- Low frequency LER comes from all the sources of shot noise:
  - Photon counts, PAG counts, acid counts, protecting group counts, deprotection event counts, dissolution events
- This low frequency uncertainty cannot be smoothed away
  - The only approach is to reduce the source of uncertainty
  - We need a new paradigm

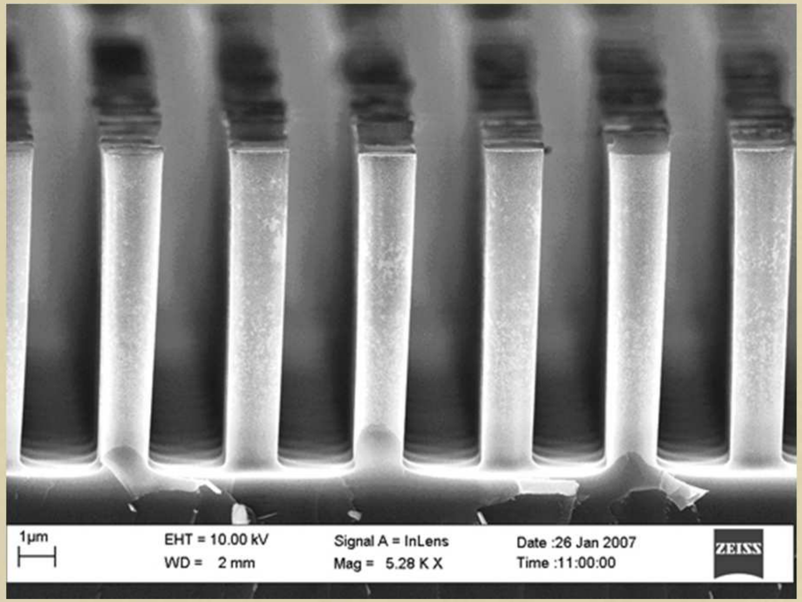
What Can Be Done?

- Reducing photon uncertainty
  - Use of fundamentally different photon statistics (I don’t know what this might look like)
  - Use more photons
- Reducing chemical uncertainty
  - Random molecular positioning can be improved by higher densities, but we can only go so far
  - We must break out of the random position paradigm

KOH Etching of Silicon Crystal Planes

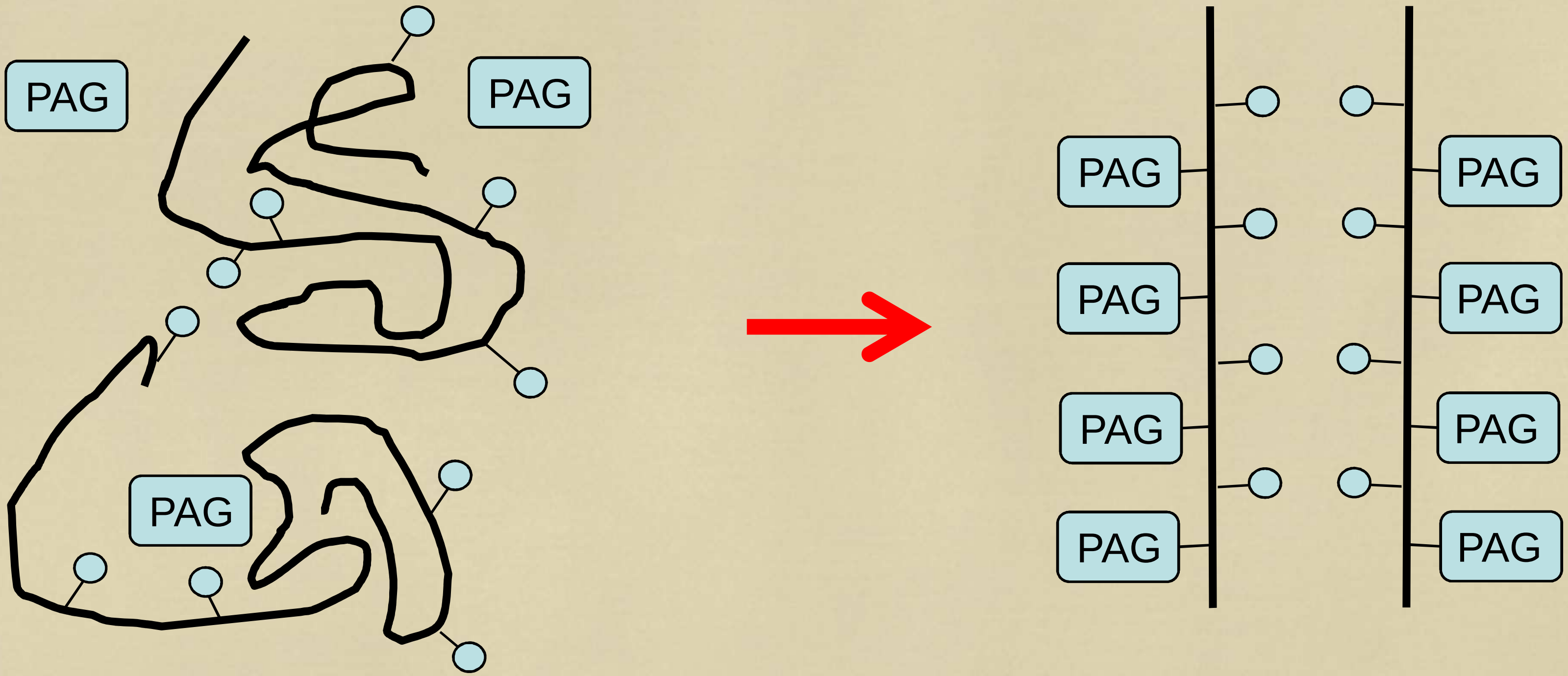






Proposal for the Low-LER Resist

- Block Copolymer (or Crystal) Photoresist



Conclusions

- LER is the ultimate limiter to resolution in optical lithography
- We still need to learn more about how LER works, but we know enough (I think) to draw conclusions
  - We can't optimize out way out of the current LER performance gap
  - LER post-processing (aka magic rinse) can never fix low-frequency LER
  - We must break the randomness paradigm if we want to push down to the 1x-nm level
  - We need more photons and a non-random resist