Stochastic Approach to Modeling Line Edge Roughness in Photolithography

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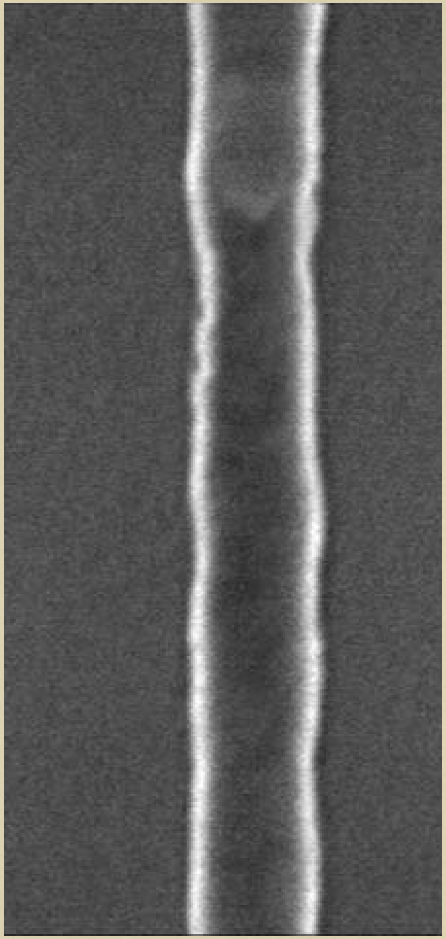
Outline:
There's a lot going on in LER

- Photon and acid shot noise
- Reaction-diffusion kinetics
- Development and dynamical scaling
- Overall model for LER
- What's missing – future work

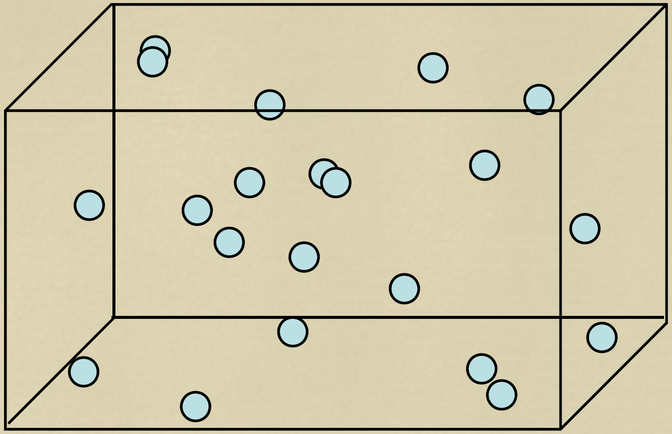


Continuum Approximation

- The real world is discrete (photons, atoms, etc.), but most macroscopic models (e.g., litho simulation) make the *continuum approximation*
  - Matter and energy are described with continuous mathematical functions
  - Ex: aerial image intensity, acid concentration after exposure, resist dissolution
- What are the implications of making the continuum approximation?
  - Line-edge roughness cannot be predicted

Continuum Approximation Example: Chemical Concentration

- Concentration: The number of atoms or molecules of a certain type per unit volume
  - By necessity, an average over a volume
- What is the meaning of H(x,y,z) – the concentration of acid at a specific point in space?



Stochastic View of Chemical Concentration

- Model atom/molecule as a point located at its center of mass
- Consider a volume V – is the molecule in the volume or not?
  - This is a binary proposition, governed by the binomial distribution: $P(n)$ = probability of finding n molecules in V
  - The binomial probability distribution can be well approximated by a Poisson distribution with average concentration C

$$P(n) = \frac{(CV)^n}{n!} e^{-CV} \qquad \langle n \rangle = CV \qquad {\sigma_n}^2 = CV$$

$$\frac{\sigma_n}{\langle n \rangle} = \frac{1}{\sqrt{\langle n \rangle}} = \frac{1}{\sqrt{CV}}$$

Stochastic View of Chemical Concentration

- Example: for a typical 193nm resist formulation, $G_0 N_A$ = 0.042 /nm^3 (G_0 = the initial concentration of PAG, N_A = Avogadro's number)

For V = (3 nm)^3	$\langle n \rangle = 1.13$	$\sigma_n / \langle n \rangle = 94\%$
For V = (6 nm)^3	$\langle n \rangle = 9$	$\sigma_n / \langle n \rangle = 33\%$
For V = (10 nm)^3	$\langle n \rangle = 42$	$\sigma_n / \langle n \rangle = 15\%$

Photon Shot Noise
(Also a Poisson Distribution)

- Example: for a typical 193nm resist with 10 mJ/cm^2 dose to clear,

For A = (1 nm)^2 $\langle n \rangle = 97$ $\sigma_n / \langle n \rangle = 10\%$

For A = (10 nm)^2 $\langle n \rangle = 9700$ $\sigma_n / \langle n \rangle = 1\%$

- Example: for an EUV resist with 5 mJ/cm^2 dose to clear,

For A = (1 nm)^2 $\langle n \rangle = 3$ $\sigma_n / \langle n \rangle = 58\%$

For A = (10 nm)^2 $\langle n \rangle = 300$ $\sigma_n / \langle n \rangle = 6\%$

EUV Resists

- High energy EUV photons (92 eV) produce secondary electrons, which then travel ~few nanometers to expose PAG
  - How far is an important unanswered question
  - Quantum efficiency can be greater than 1
- Simple approach to account for this blur is to convolve aerial image with the secondary electron position probability density function
  - Result is a decrease in image log-slope (ILS)

Stochastic View of Exposure Reaction

- Including photon shot noise, acid uncertainty is

$$\sigma_h^2 = \frac{\langle h \rangle}{\langle n_{0-PAG} \rangle} + \frac{\left[\left(1-\langle h \rangle\right)\ln\left(1-\langle h \rangle\right)\right]^2}{\langle n_{photon} \rangle}$$

- When h = 0, σ_h = 0. When h = 1, max $\sigma_h^2 = \frac{1}{\langle n_{0-PAG} \rangle}$
- Max value of $\left[\left(1-\langle h \rangle\right)\ln\left(1-\langle h \rangle\right)\right]^2 = 0.135$
- The pure photon shot noise contribution is very small, even for EUV

Reaction-Diffusion

$$h_{eff}(x) = \frac{1}{t_{PEB}} \int_0^{t_{PEB}} h(x, t=0) \otimes DPSF \, dt$$

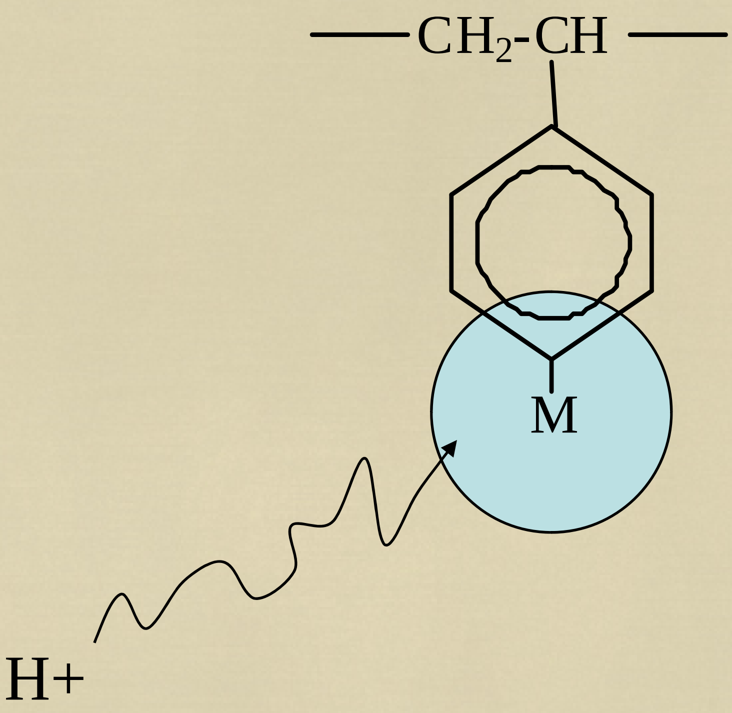
Relative concentration of blocked polymer sites →

$$m(\mathrm{x}) = e^{-K_{amp} t_{PEB} h_{eff}(x)}$$

Deblocking responds to the time-average of the acid latent image

Stochastic View of Reaction-Diffusion

- Is reaction-diffusion different from just diffusion? Yes, if the reaction is catalyzed by the diffusing species.



von Smoluchowski Trap:

Reaction can occur once acid approaches the blocking group within its capture radius, *a*.

$$Rate \propto a$$

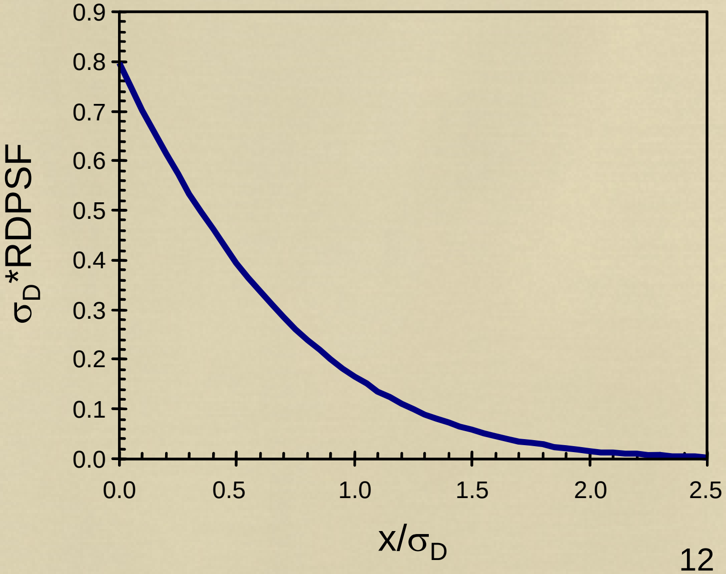
Stochastic View of Reaction-Diffusion

- If an acid passes through the capture zone and a reaction doesn't occur, that acid is more likely to pass through that zone again because it is close by (correlation)
- Probability of reaction is governed by the time average of the acid concentration as it diffuses around

$$h_{eff}(x) = \frac{1}{t_{PEB}} \int_0^{t_{PEB}} h(x, t=0) \otimes DPSF\, dt$$

$$RDPSF = \frac{1}{t_{PEB}} \int_0^{t_{PEB}} DPSF\, dt$$

(Reaction-Diffusion Point Spread Function)



Stochastic View of Reaction-Diffusion

- Deriving the statistics of reaction-diffusion is hard! For the details, please see: Chris A. Mack, Fundamental Principles of Optical Lithography: The Science of Microfabrication, John Wiley & Sons, (London: 2007).

$$\left\langle h_{eff} \right\rangle = \left\langle h \right\rangle \otimes RDPSF$$

Derivation of this is approximate – more work is needed →

$$\sigma_{h_{eff}} \approx \left(\frac{2a}{\sigma_D} \right) \sigma_h$$

Stochastic View of Deprotection

- Statistical uncertainty in the blocked polymer site concentration comes from the Poisson distribution of the initial blocked sites, plus the stochastics of deblocking

$$\sigma_m^2 \approx \frac{\langle m \rangle}{\langle n_{0-blocked} \rangle} + \langle m \rangle^2 \left(K_{amp} t_{PEB} \sigma_{h_{eff}} \right)^2 = \frac{\langle m \rangle}{\langle n_{0-blocked} \rangle} + \left(\langle m \rangle \ln \langle m \rangle \right)^2 \left(\frac{\sigma_{h_{eff}}}{\langle h_{eff} \rangle} \right)^2$$

- Combining with our previous expressions for σ_{heff} and σ_h gives the final result

Stochastic View of Exposure + Reaction-Diffusion

- Final expression for the uncertainty in deblocked polymer concentration:

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

Deblocking reaction → $\frac{1}{\langle n_{0-blocked}\rangle\langle m\rangle}$

Reaction-diffusion → $\left(K_{amp}t_{PEB}\right)^2\left(\frac{2a}{\sigma_D}\right)^2$

Acid concentration, exposure → $\frac{\langle h\rangle}{\langle n_{0-PAG}\rangle}$

Photon shot noise → $\frac{\left[\left(1-\langle h\rangle\right)\ln\left(1-\langle h\rangle\right)\right]^2}{\langle n\rangle}$

Correlation and Acid-Catalyzed Reaction-Diffusion

- As one acid diffuses and catalyzes several deprotection reactions, those deprotections are correlated

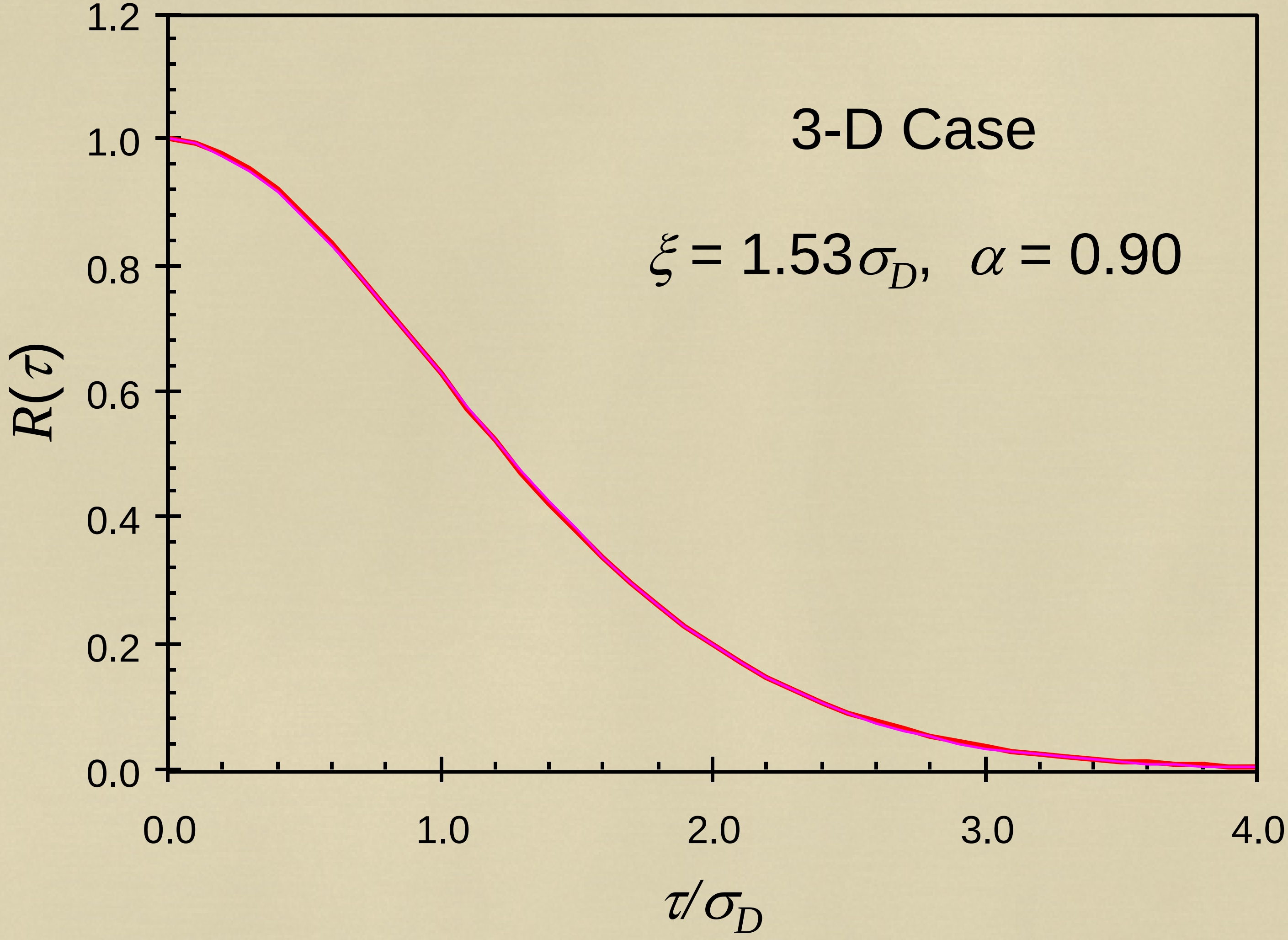
Correlation Function →

$$R(\tau) = \frac{RDPSF \otimes RDPSF}{\iiint_{\infty} \left(RDPSF \right)^2}$$

- Perform integrations numerically, examine the results
- Results can be almost perfectly fit with the standard exponential correlation function:

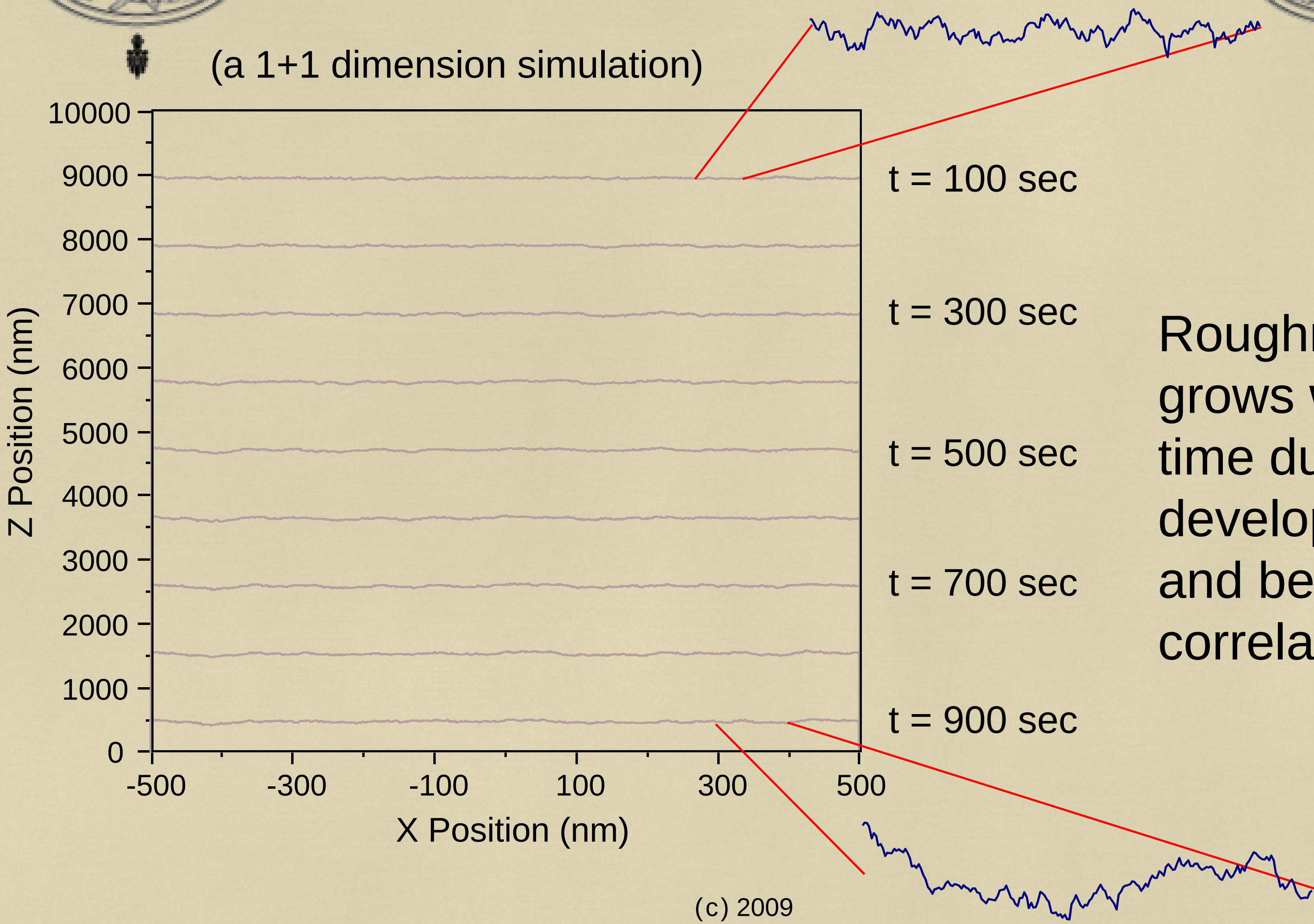
$$R(\tau) = e^{-\left(\left| \tau \right| / \xi \right)^{2\alpha}}$$

Correlation and Acid-Catalyzed Reaction-Diffusion



Development and Dynamical Scaling

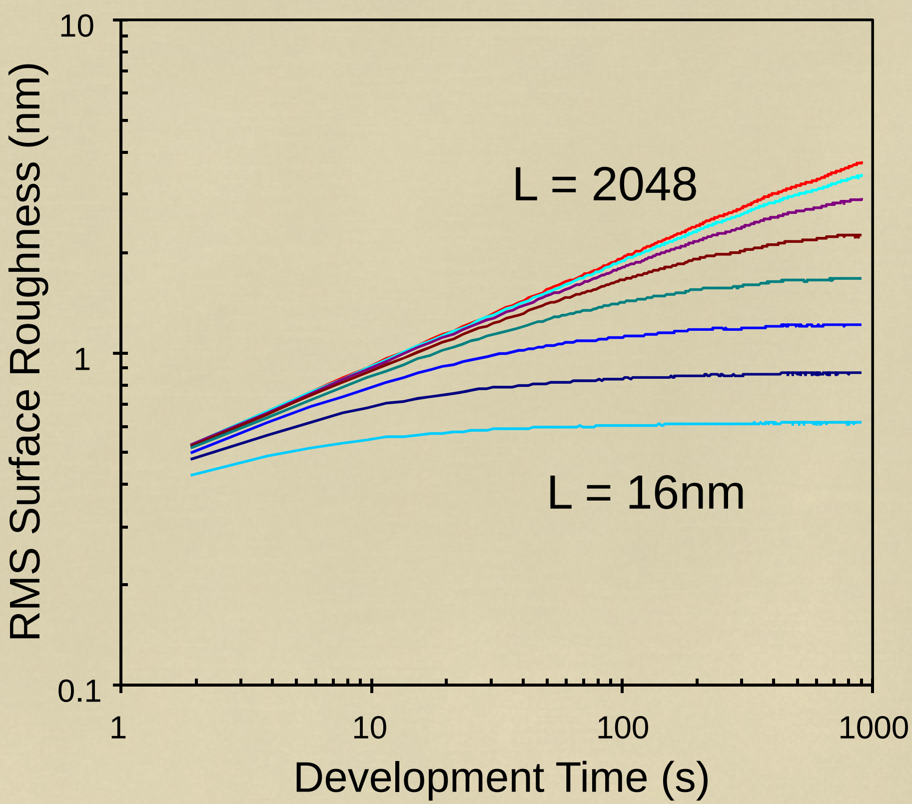
(a 1+1 dimension simulation)

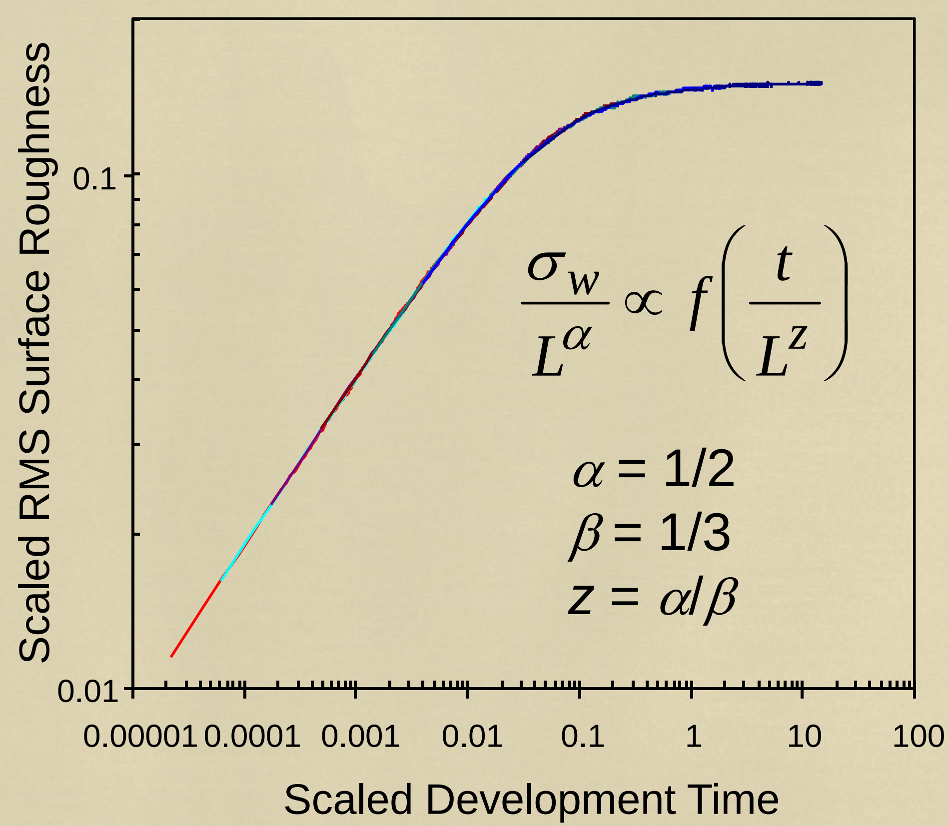


Roughness grows with time during development, and becomes correlated

Dynamical Scaling (1+1)

$$\langle r \rangle = 10\, nm/s, \quad \sigma_r = 2\, nm/s$$





Data collapses to a single curve for the right values of the scaling exponents

Line-Edge Roughness (Tying it all Together)

- 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,

$$\sigma_{LER} = \frac{\sigma_R}{dR/dx} = \left(\frac{\sigma_R}{R}\right)\left(\frac{d\ln R}{dx}\right)^{-1}$$

Line-Edge Roughness (Tying it all Together)

- The Lithographic Imaging Equation

$$\frac{d\ln R}{dx} = \gamma \frac{d\ln I}{dx} = \gamma (ILS)$$

- Thus,

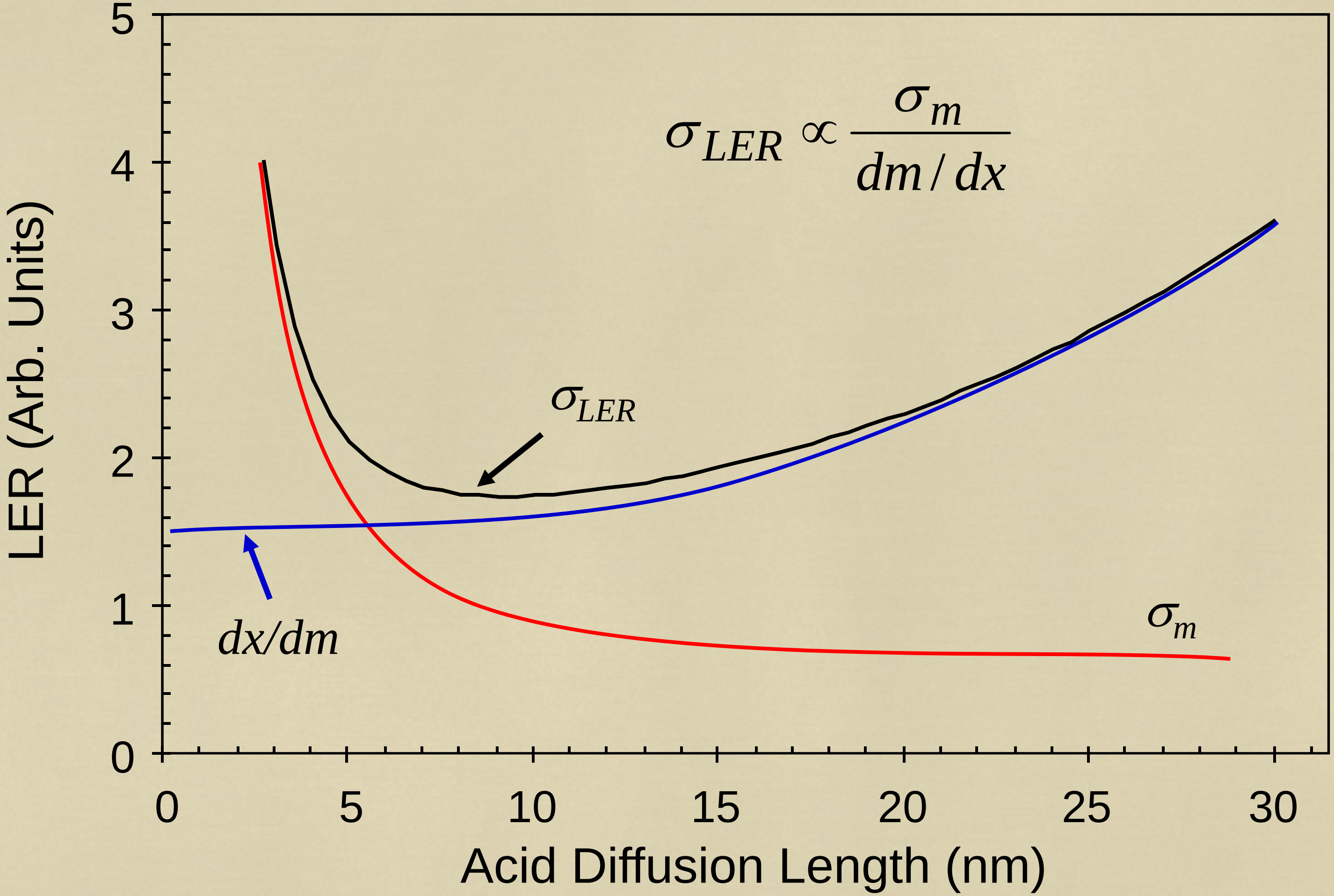
$$\sigma_{LER} = \left(\frac{\sigma_R}{R}\right)\left(\frac{1}{\gamma\, ILS}\right) \quad \text{or} \quad \frac{\sigma_{LER}}{CD} = \left(\frac{\sigma_R}{R}\right)\left(\frac{1}{\gamma\, NILS}\right)$$

Note: γ is not a bulk resist property, but the value at the line edge (see Chapter 9 of Fundamental Principles of Optical Lithography)

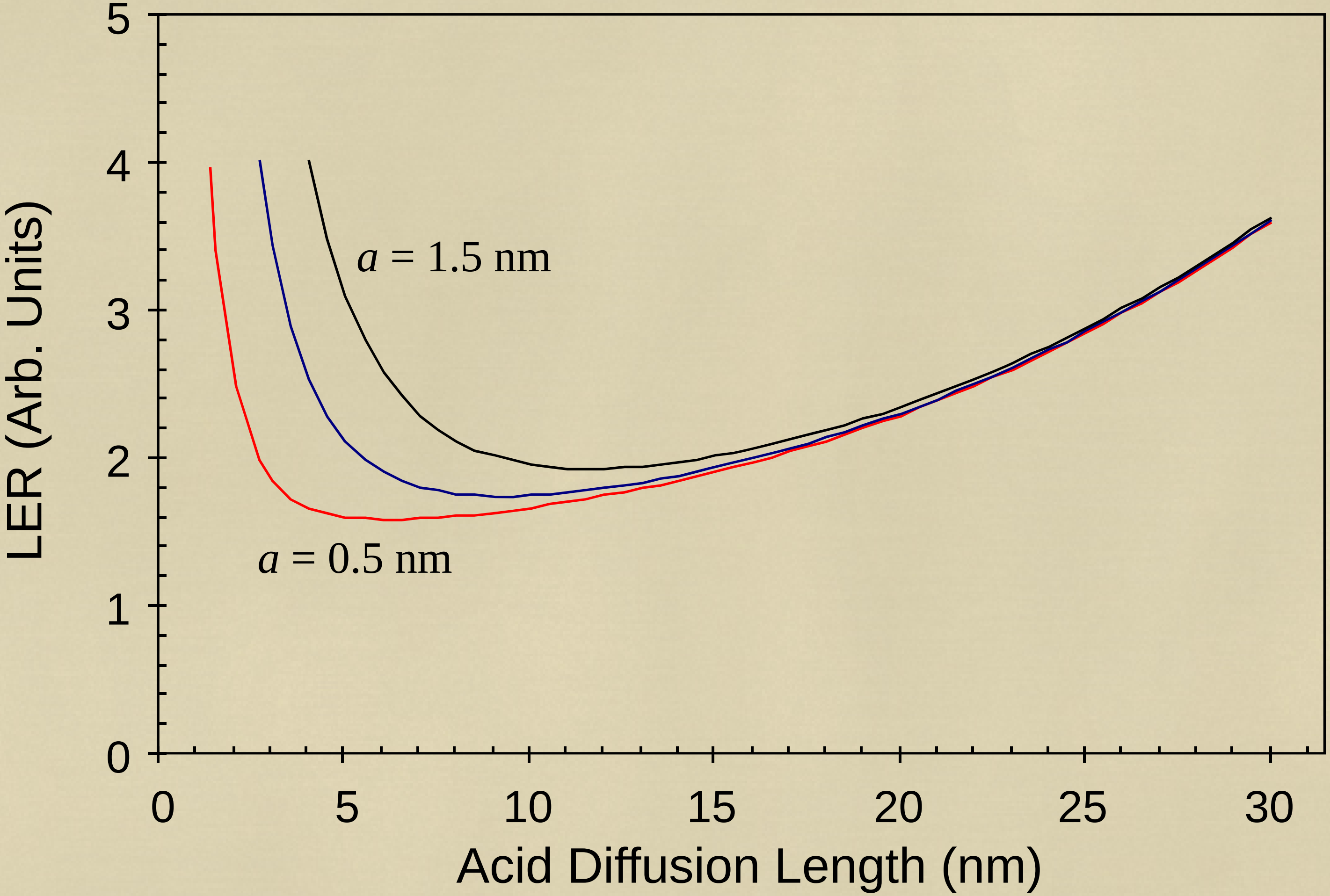
Line-Edge Roughness (Tying it all Together)

- How to improve LER:
  - Increase *ILS*
  - Increase γ
  - Decrease σ_R/R
- These terms sometimes work against each other
- The product $\gamma NILS$ controls exposure latitude for a given feature, and thus lithographers already work to maximize this term

Line-Edge Roughness and Acid Diffusion



Line-Edge Roughness and Acid Diffusion



Future Work (What's Missing)

- Base quencher has been ignored (by me) to date
  - Quencher will always be at lower concentrations than acid, adding an extra term to the final uncertainty in blocked polymer that could be significant
  - Quencher can dramatically improve the latent image gradient, thus quencher concentration and diffusion will be important levers for optimizing LER (there has to be an optimum quencher concentration)
- Development rate uncertainty
  - Examine impact of correlations of development rate noise
  - How does a development rate gradient affect things?
  - What happens as the dissolution rate becomes very slow – will we move into the directed percolation depinning (DPD) universality class?