Lithographically Generated Line Edge Roughness in Photoresist

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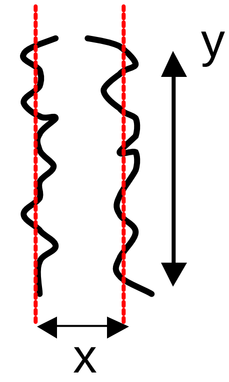
Outline

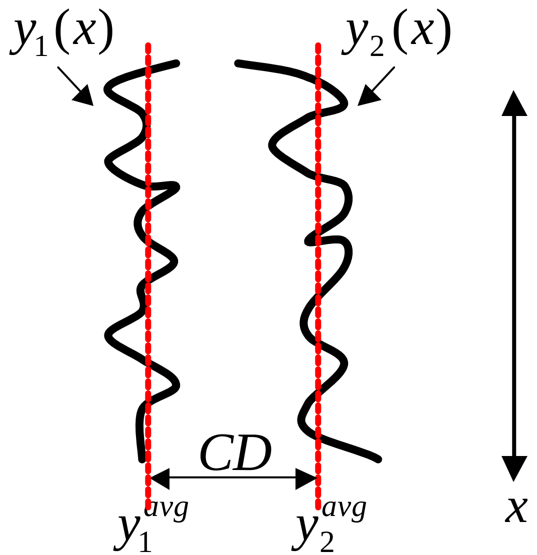
- A few remarks why LER is bad
- At least 5 major factors contributing to LER in photoresist
  - The quality of the aerial image
  - The edge roughness of the photomask absorber
  - Photon statistics
  - Chemical transformations that occur during image formation
  - The physical chemistry of the resist surface
- Outlook
  - What solutions to the LER problem are available?
  - What role do etch engineers play?

Why LER is Bad, Bad, Bad



- CD Control and Device Performance
  - → Across chip linewidth variation (ACLV)!
    - LER is CD control at relevant frequencies (we have the tendency to think of LER with respect toward the limit as $y \to 0$, but CD control as $y \to \infty$)
  - → The industry has more than 20 years of data that tells us leakage is reduced by making gate dimensions more uniform across the chip and yield goes up when reducing variations across the wafer
  - → Simulation data (and some limited experimental data) show that device fluctuations get much, much worse when LER is large
  - → Better CD control = less leakage = low power = $$$

Line Edge Roughness Measurement



$$CD = \left| y_1^{avg} - y_2^{avg} \right|$$

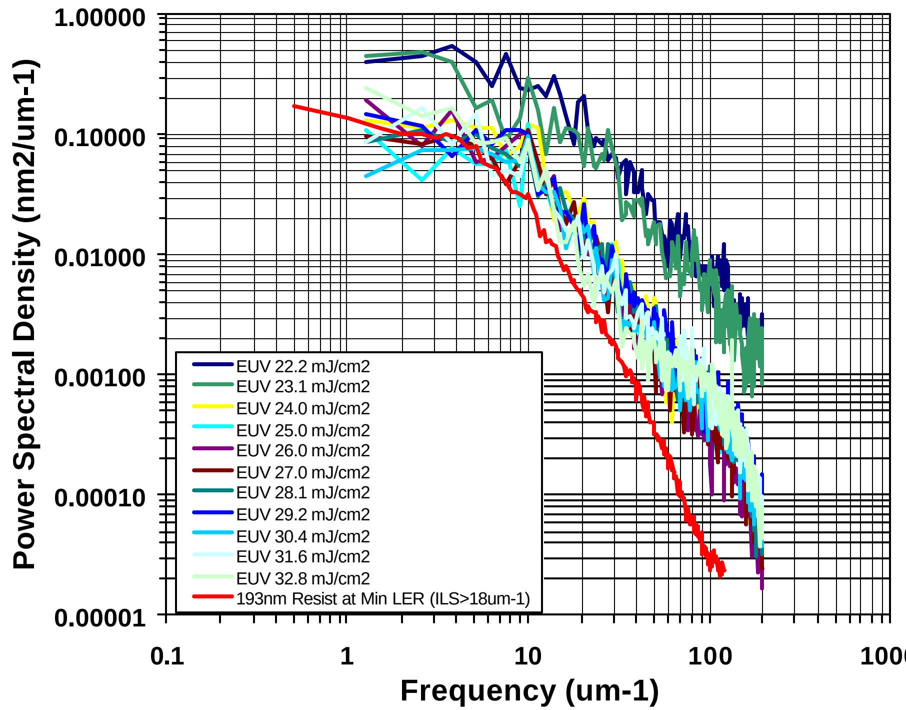
$$3s\ \ LWR = 3\sqrt{\frac{\sum_i \left\{ \left| y_1(x_i) - y_2(x_i) \right| - CD \right\}^2}{N-2}}$$

$$3s\ \ LER = 3\sqrt{\frac{\sum_i \left(y_1(x_i) - y_1^{avg} \right)^2}{N-1}}$$

$$Y(f) = \int_{x_0}^{x_f} \left(y_1(x) - y_1^{avg} \right) e^{-2pifx}\, dt$$

$$\mathrm{PSD_{LER}} = \frac{2\left|Y(f)\right|^2}{x_f - x_0}$$

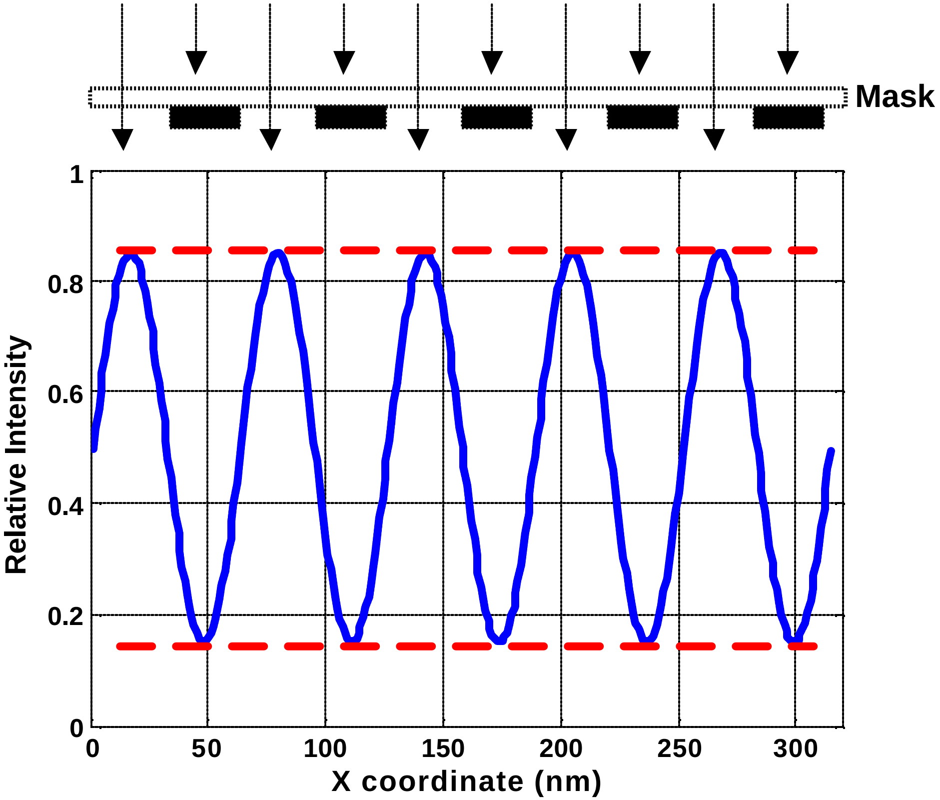
$$3s\ \ LER = 3 \times \sqrt{2\int \mathrm{PSD_{LER}}(f)\, df}$$



Quality of the Aerial Image

- The aerial image is the intensity distribution of light from the exposure tool incident upon the wafer
  - → It defines the theoretical locations of exposed and unexposed material

- Think of an aerial image as modulation
  - → Very little in the exposure is completely dark or completely bright
  - → It becomes more difficult to generate high contrast aerial images as features get smaller (decreasing pitch)



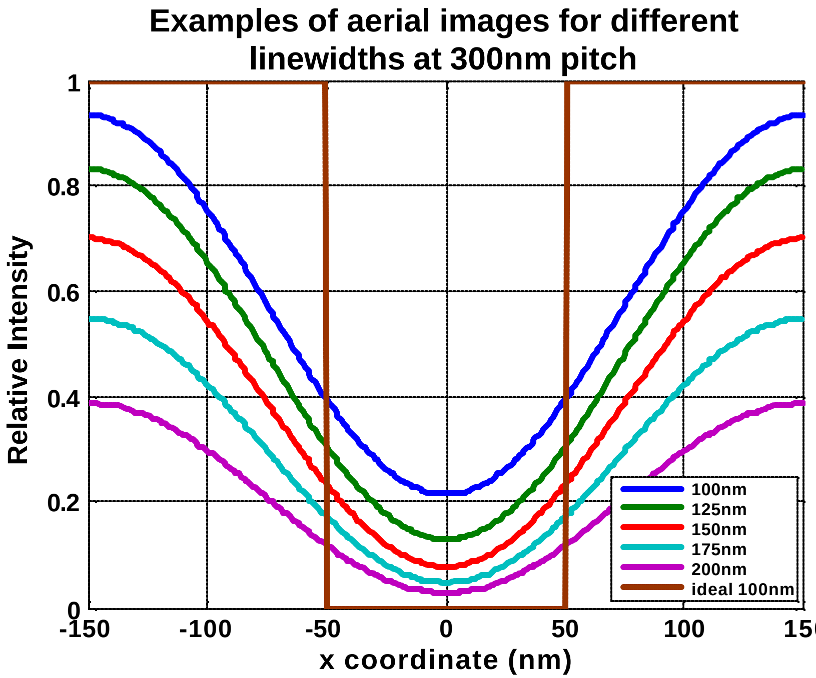
Quality of the Aerial Image

- The "steepness" of the aerial image at the edge of the patterned feature plays a large role on resist pattern quality
- The closer an aerial image is to a step function in intensity, the better

  → CD control improves with increasing "steepness" of the aerial image because the resist CD at the pattern edge is less sensitive to local fluctuations in dose

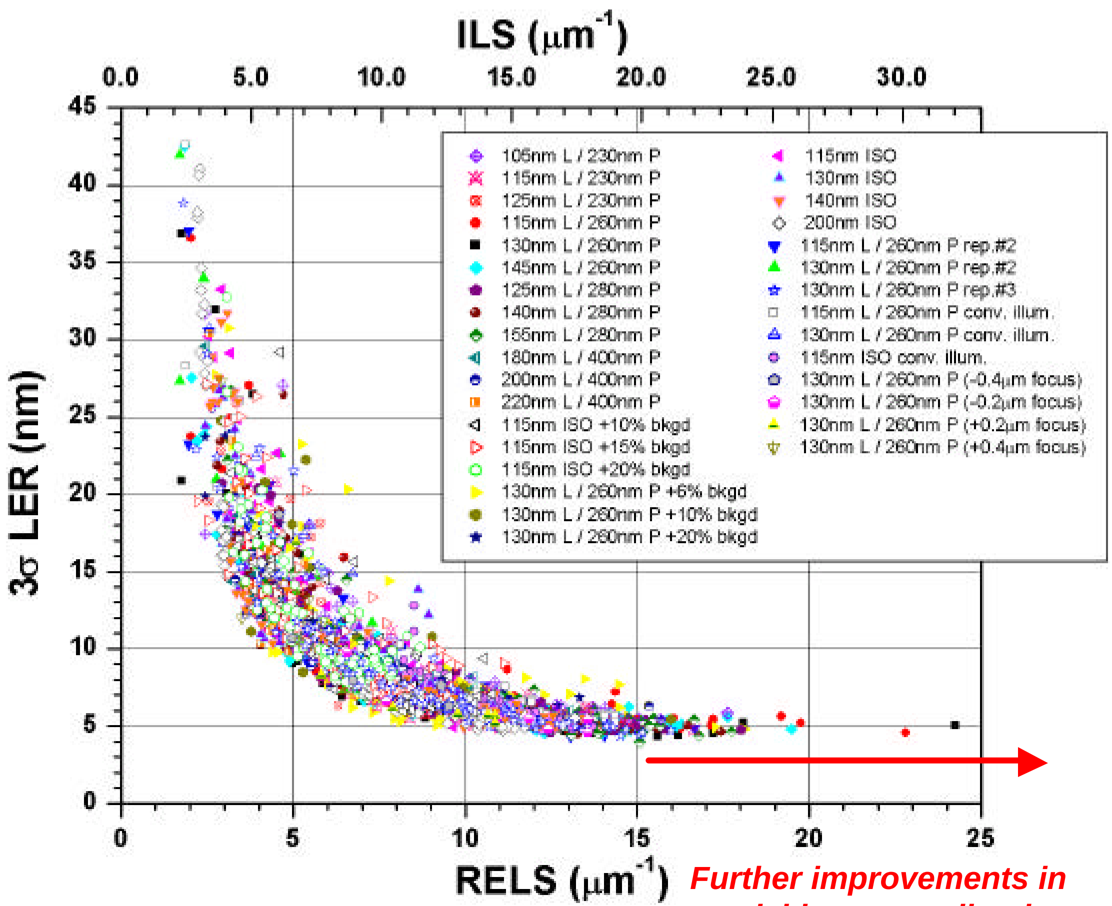
- The aerial image parameter that quantifies profile "steepness" is the image-log-slope (ILS)

$$ILS = \left(\frac{1}{I(x_0)} \left. \frac{\partial I(x)}{\partial x} \right|_{x_0} \right)$$



Quality of the Aerial Image

- The most significant contributor to LER is the quality of the aerial image
  - → Pitch, illumination, line width, flare, fading, etc.
- LER is a minimum as the image-log-slope (ILS) of the aerial image is a maximum
- As the ILS approaches infinity, the magnitude of LER reaches a non-zero constant
  - → In this regime we begin to see the effects of polymer physics



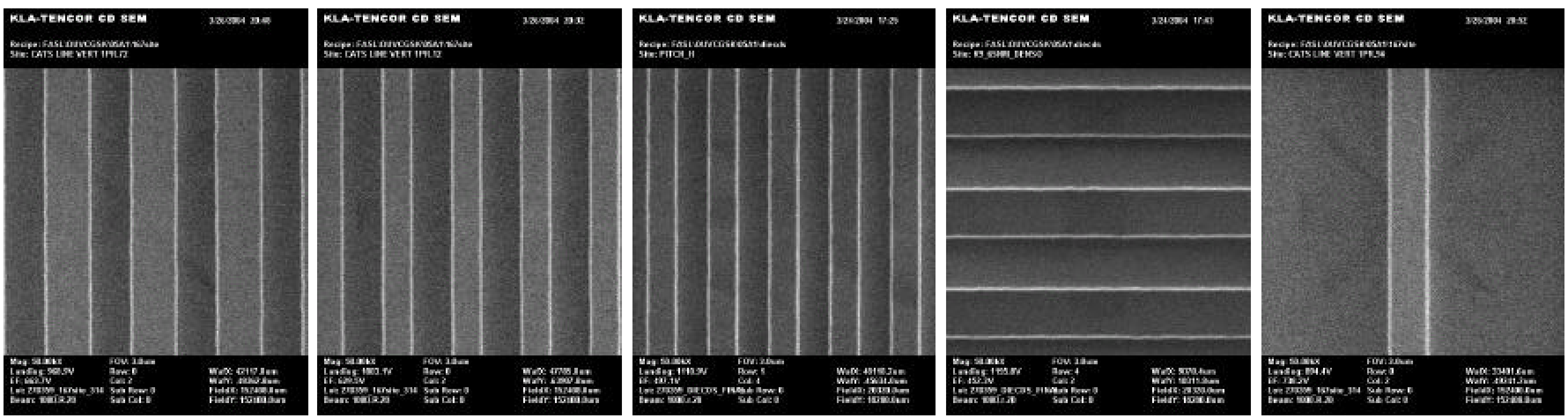
Further improvements in aerial image quality do not reduce LER further

*A.R Pawloski et al., Proc. SPIE, vol. 5376, 2004

Mask Absorber Roughness

- Since the photomask is made using lithography and photoresists, it also has some magnitude of LER
- Can mask absorber roughness transfer to the wafer as resist LER?

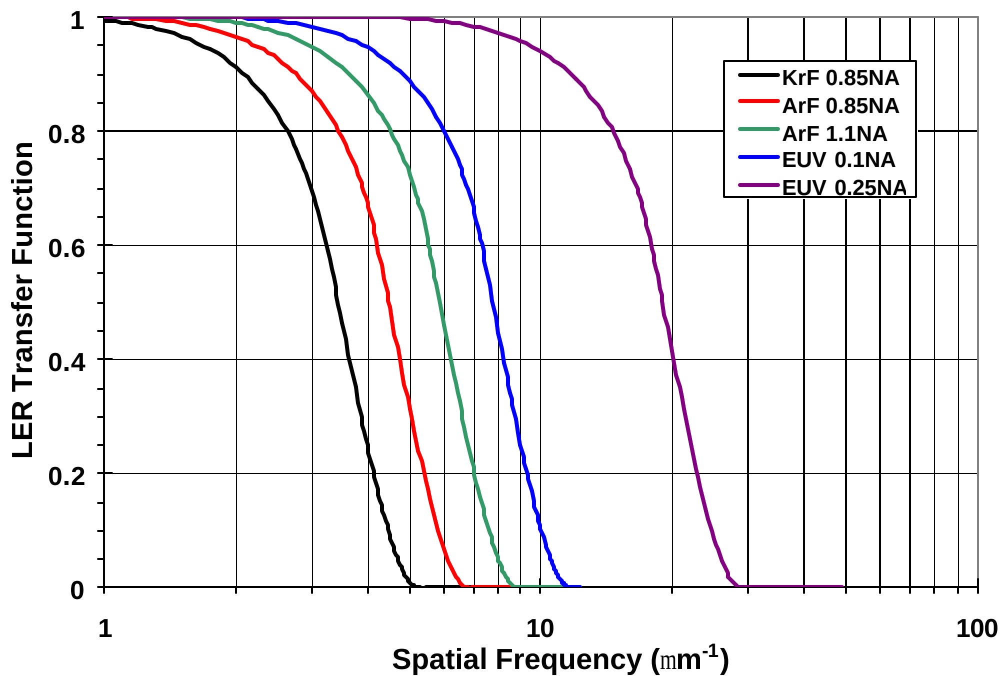
CD SEM images illustrating typical line quality for absorber lines from binary mask fabrication



Mask Absorber Roughness

- The LER transfer function from the mask absorber to the resist was derived by Naulleau and Gallatin (*Appl Opt*, vol. 42, pp. 3390-7, 2003) for EUV imaging
- Following these procedures, the LER transfer function was calculated for a variety of exposure tools from KrF through EUV
- As the resolving power of the optical system improves (moving to higher NA and shorter wavelength) more mask LER is transferred to the wafer leading to resist LER

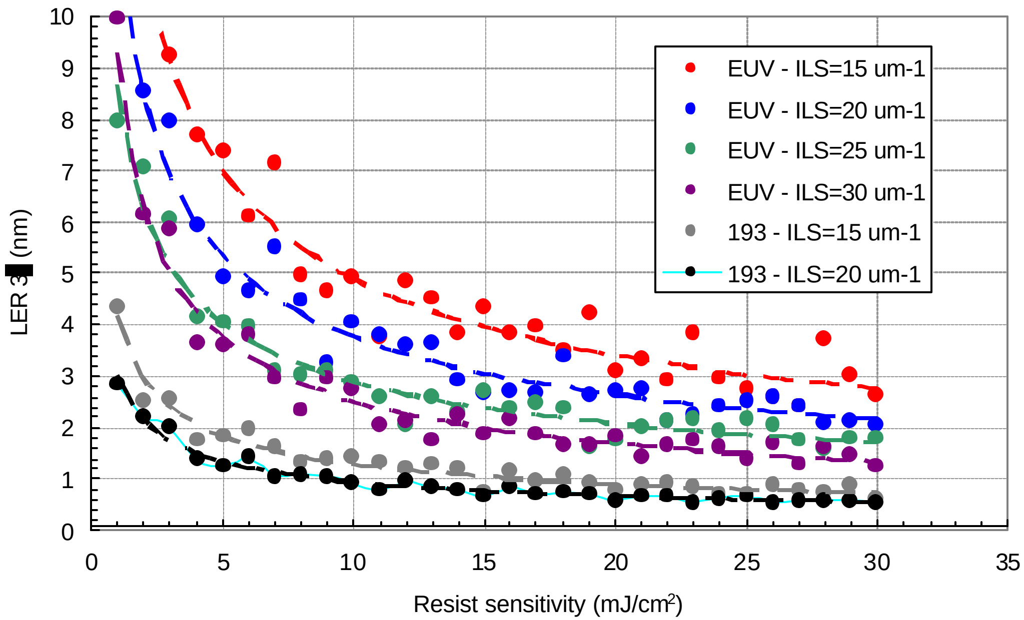
  → Low frequency roughness in resist
- Negligible contributions for most optical lithography processes and masks



Photon Statistics

- Decreasing the exposure wavelength, the exposure dose, or the quality of the aerial image increases the probability that photon statistics (shot noise) contribute to LER
- At EUV, shot noise could contribute to increasing the magnitude of LER for fast resists (fewer, higher energy photons at EUV)
- For optical lithography, shot noise effects are small, if at all present, and likely are overshadowed by other contributions to resist LER

  → However, photon statistics beget photoacid molecule statistics!



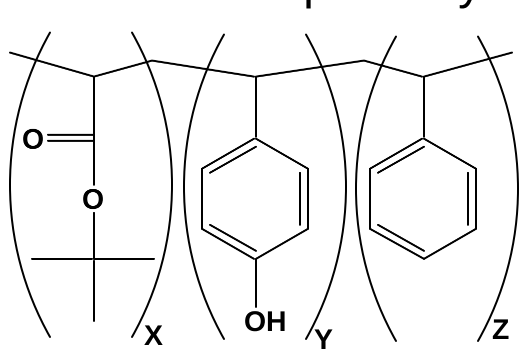
Results from stochastic simulation assuming Poisson statistics to describe the arrival of photons at the resist.

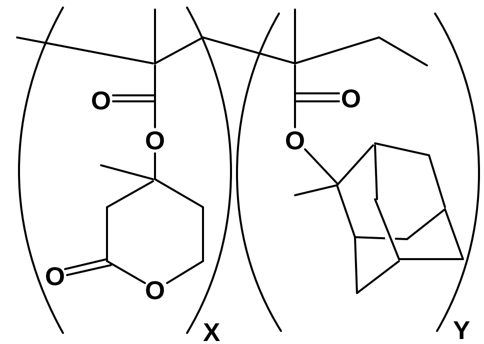
The resist contribution is simulated using a 40nm gaussian blur to describe photoacid diffusion

The Chemical Composition of Resist

- The resist film is made up mostly of polymer

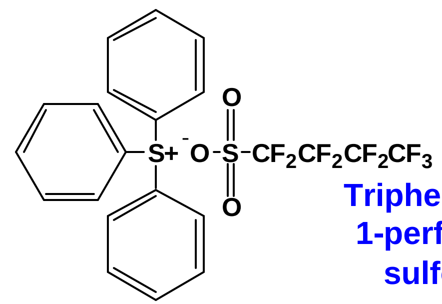
Phenolic polymers typical of 248nm resists





Methacrylate polymers typical of 193nm resists

- A photo-acid generator produces photoacid catalyst upon exposure



Triphenylsulfonium 1-perfluorobutane sulfonate PAG

- A quencher (base) provides profile control, environmental stability and lower LER

$H_3C(CH_2)_7-N(-(CH_2)_7CH_3)-(CH_2)_7CH_3$

Trioctylamine base

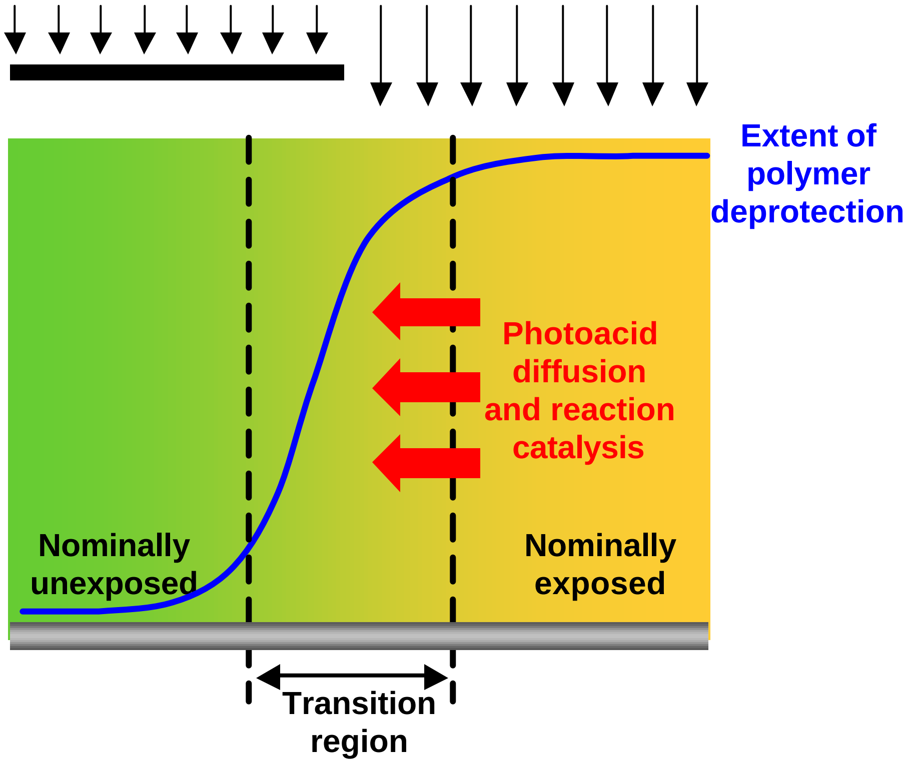
- Other additives, like dissolution inhibitors and surfactants are added to improve dissolution behavior and contrast

???

Uncle Joe's secret sauce, wing of bat, pixie dust, etc.

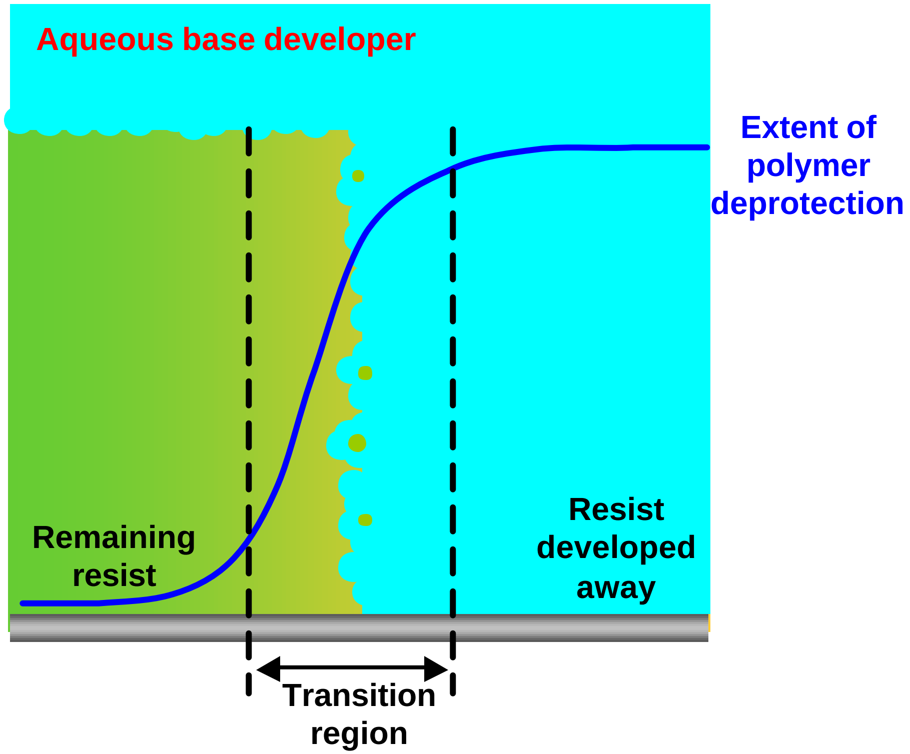
Latent Image Formation at the Pattern Edge

- Photogenerated acid catalyzes the removal of blocking groups from the polymer backbone, converting to hydrophilic, base soluble functional groups (acids and alcohols)
- Reaction catalysis is coupled with thermal diffusion during the post-exposure bake (PEB)
- Photoacid statistics and gradients are important
- The final distribution of reaction products at the end of the PEB defines latent roughness prior to development
  - → Which polymer chains dissolve and which remain



Resist Dissolution at the Pattern Edge

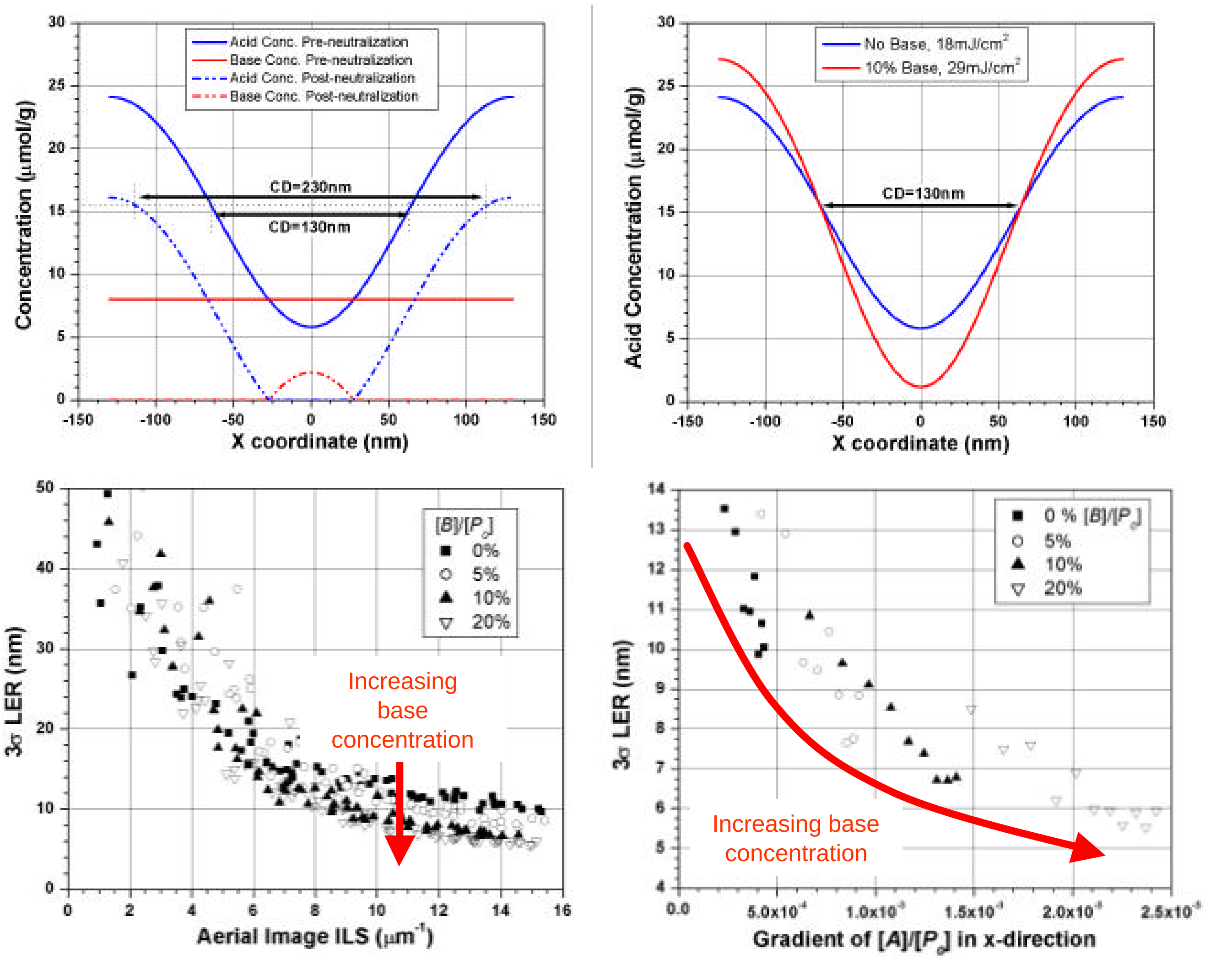
- During development, polymer chains dissolve into solution
- The dissolution mechanism for resist is also based on chemical reaction (acidic functional groups are converted to ions allowing solubility in aqueous base while remaining insoluble in water)
- Do polymer chains dissolve individually, or do they come out at aggregates, possibly contributing to roughness?
- How do the thermodynamics of the resist-developer interface contribute to roughness formation?
- Are these chemical mechanisms limited to high frequency roughness, or are there cooperative, low frequency effects?



The Photoacid Gradient at the Pattern Edge

Ex: The action of adding base to reduce LER

Adding base to the resist formulation increases the gradient in photoacid concentration at the edge of the resist



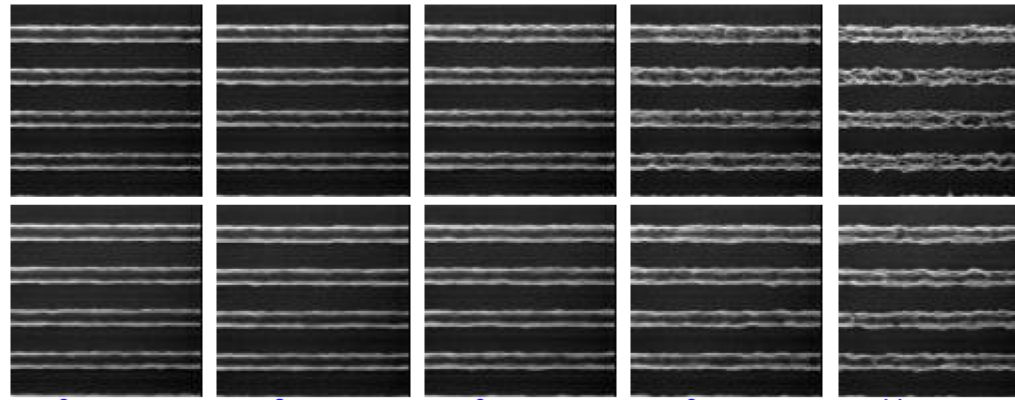
*A.R. Pawloski *et al.*, Arch Interface Conf. Proceedings, Tempe, AZ 2004

Physical Chemistry of the Resist Surface

- LER can be altered by the physical chemistry of the surface of the resist in contact with developer or a rinse liquid
- Polymer molecules at the surface of the resist adapt conformations to minimize the energy of interaction across the resist/developer or resist/rinse liquid interface
- If methods are found to control this thermodynamic interaction, it may be possible to reduce mid and high frequency roughness

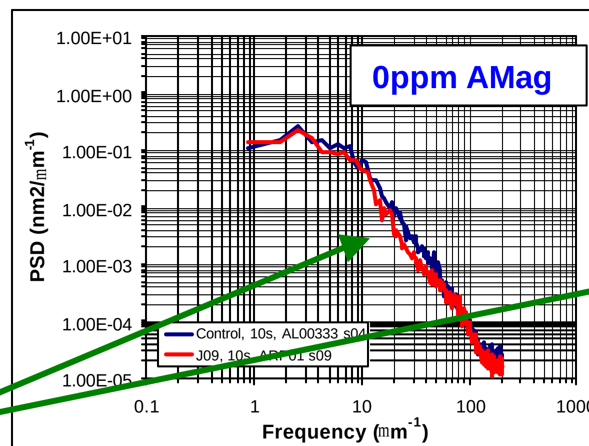
Resist after DI water rinse

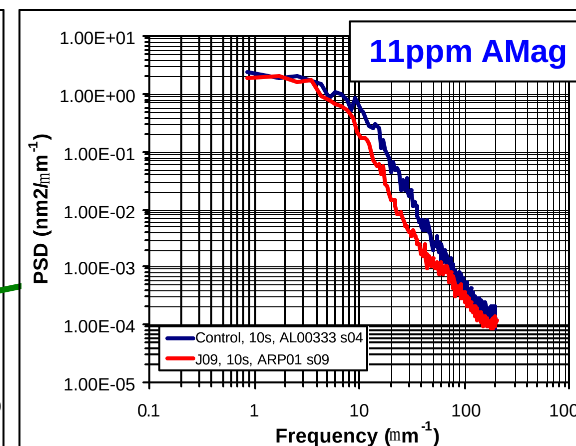
Resist after surface conditioning rinse (Air Products)



0 ppm 3 ppm 6 ppm 9 ppm 11 ppm

Increased Fading (decreasing aerial image quality) →

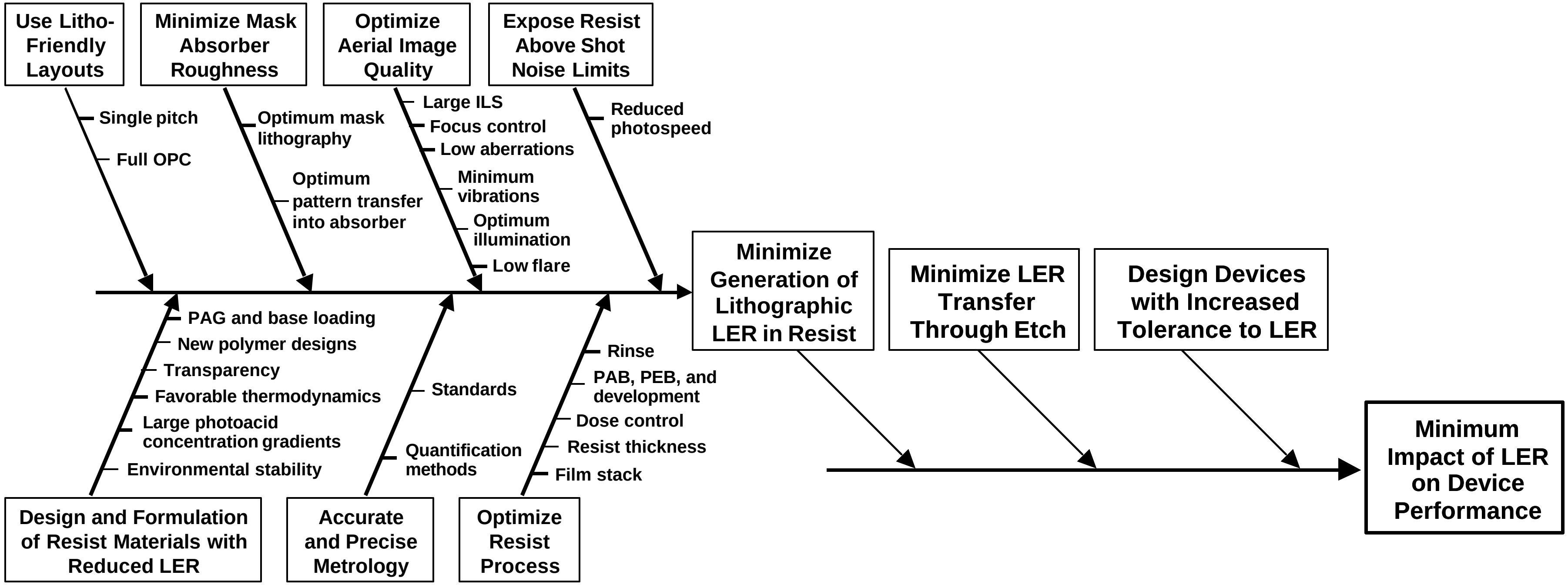




Reduction in LER!

Strategies for LER Reduction

- Minimization of LER requires a holistic approach
- Critical performance needed from suppliers, designers, and process



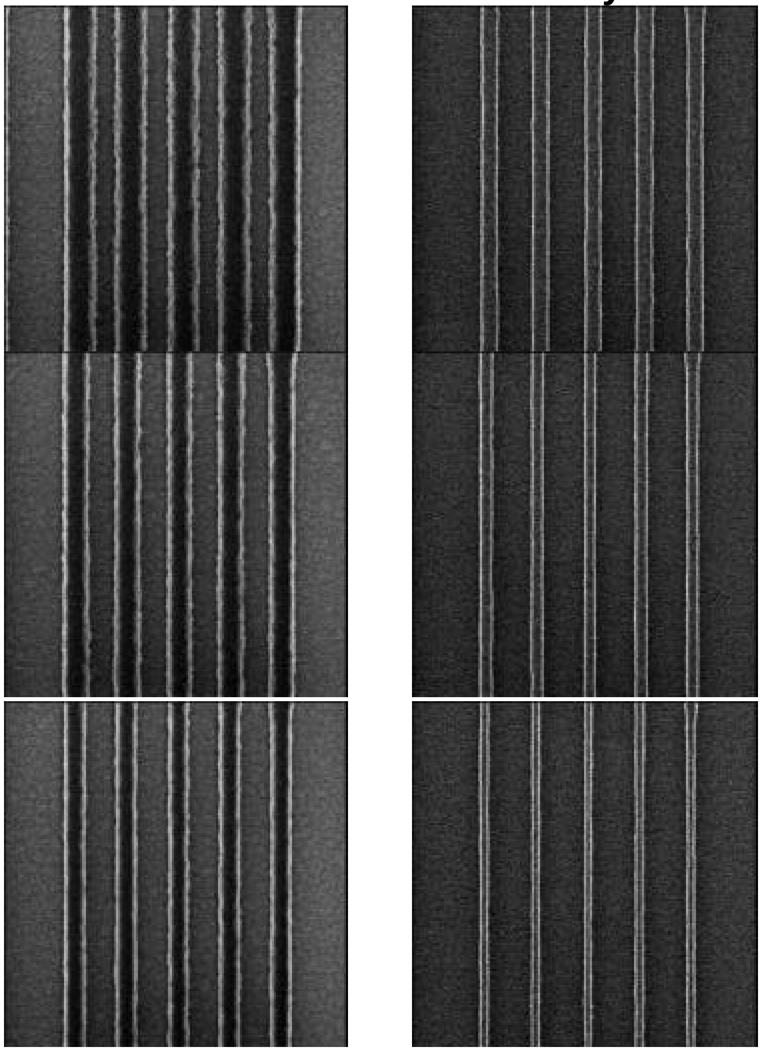
Pre- and Post- Etch LER

Resist Poly

14 mJ/cm2

16 mJ/cm2

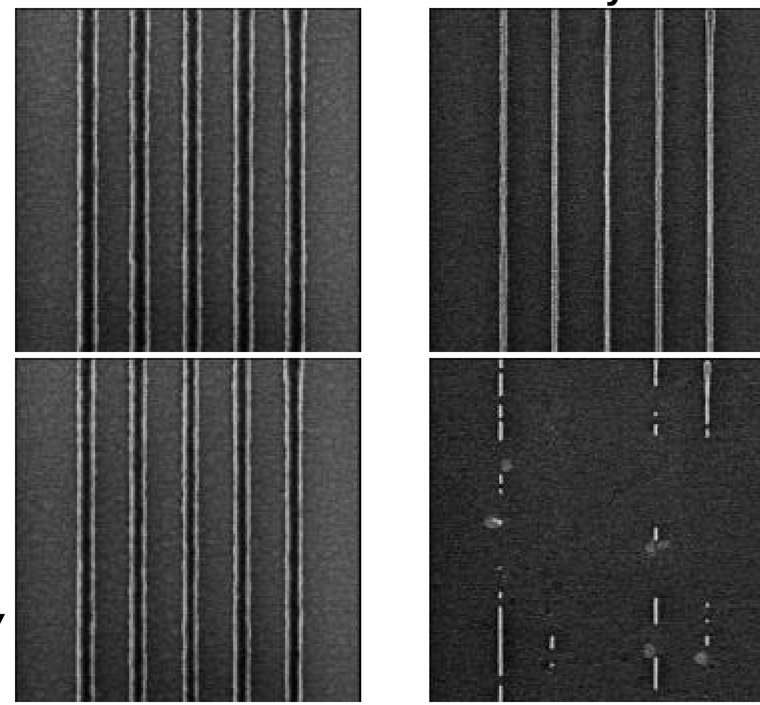
18 mJ/cm2



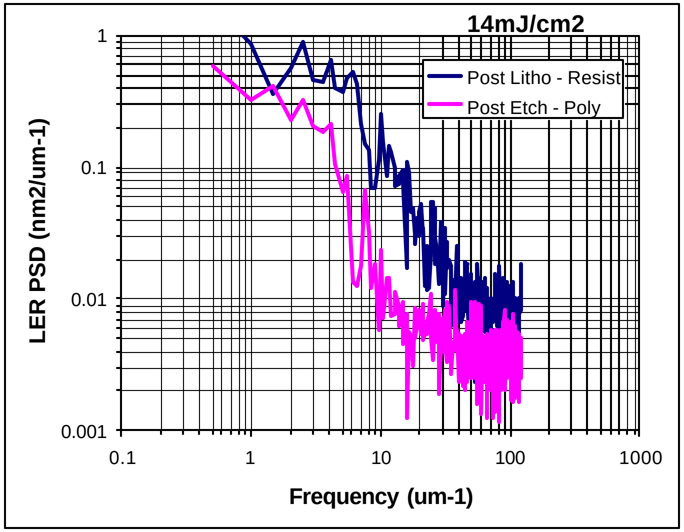
Resist Poly

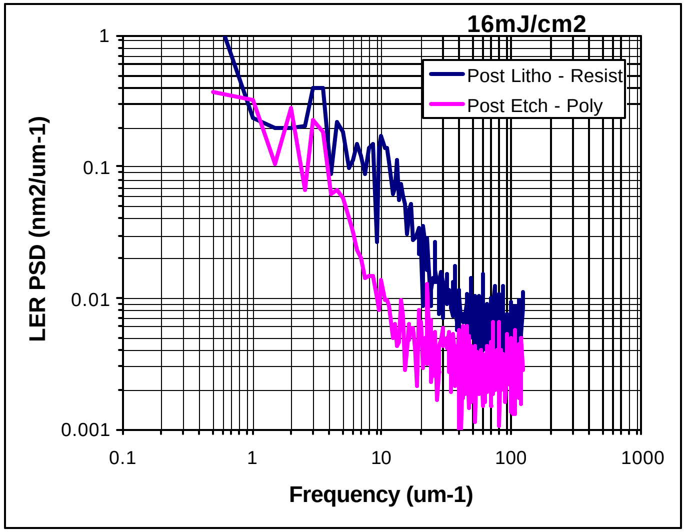
20 mJ/cm2

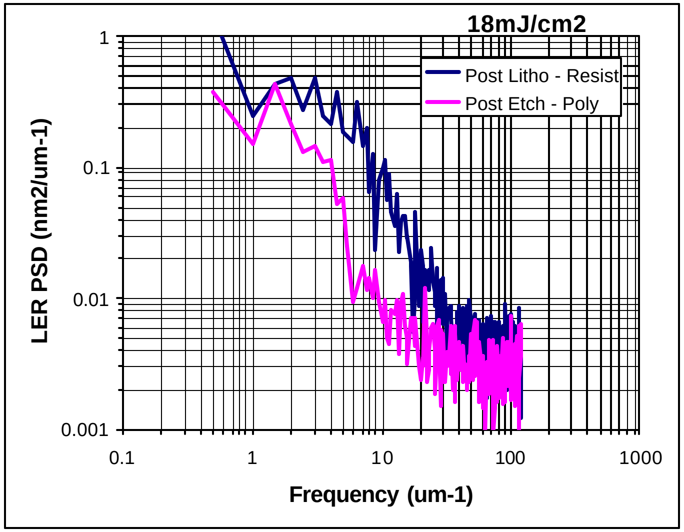
22 mJ/cm2

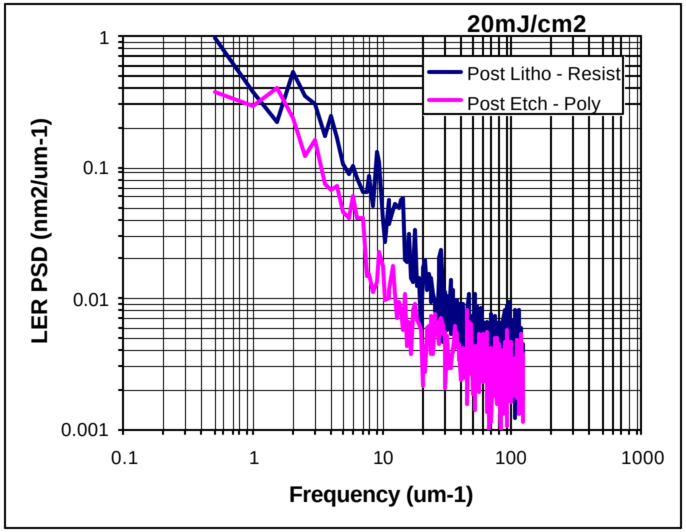


Post-Etch LER









After etch, LER in poly can be reduced from the LER of the resist mask

Smoothing by good etch processes may be able to affect more than just the high frequency components

Acknowledgements

Sincere appreciation is expressed to the following individuals for their assistance in many facets of this work:

- **Karen Turnquest, Uzo Okoroanyanwu, Dave Kyser, Jongwook Kye, Jeff Schefske, Bryan Choo, Cyrus Tabery, Rex Ugalde, Cal Gabriel** (AMD)
- **Prof. Grant Willson, Andrew Jamieson, Tim Michaelson** (Univ. Texas, Austin)
- **Patrick Naulleau** (CXRO, LBNL)
- **Chuck Masud** (ASML)
- **Koji Toyoda** (Canon)
- **Manny Jaramillo, Peng Zhang, Maud Rao, Leslie Barber** (Air Products)

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