Measuring chemical image in photoresist

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Motivation

- Modeling work has suggested resist with photo decomposable base (PDB) results in better LWR at a given dose than resist with conventional quencher
- This improvement comes from increased deprotection slope
- Experimental validation of model claims is paramount

Outline

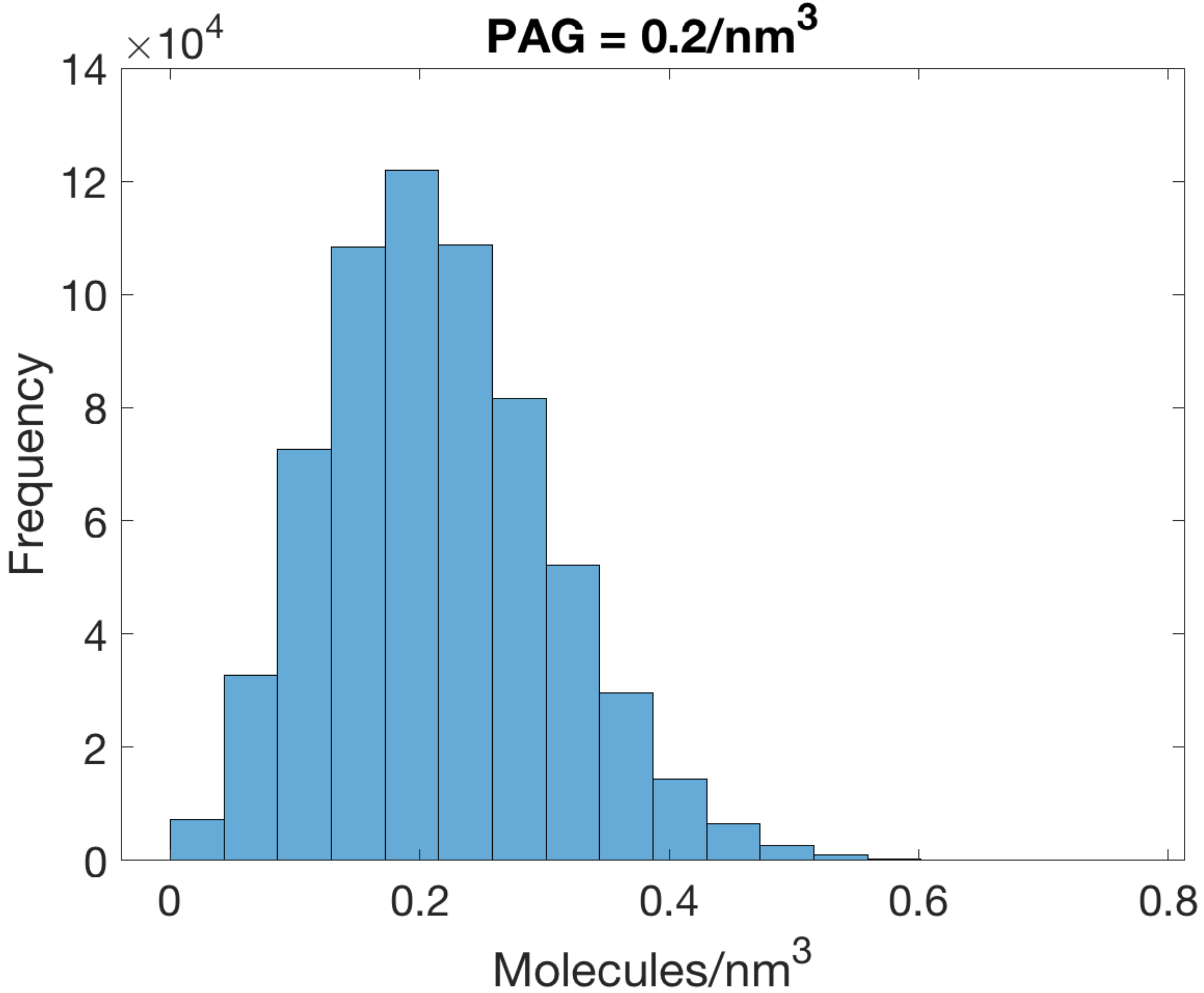
- Introduce the model
- Discuss the results
- Experimental plan

Model

- Model resist using the Multivariate Poisson Propagation Model (MPPM)
- Model cells are populated with photons, PAGs, and Quenchers according to the Poisson distribution
  - Molecules according to mean chemical loading
  - Photons according to aerial image intensity
- Deterministic reaction/ diffusion
- Output of the model is a “deprotection” image

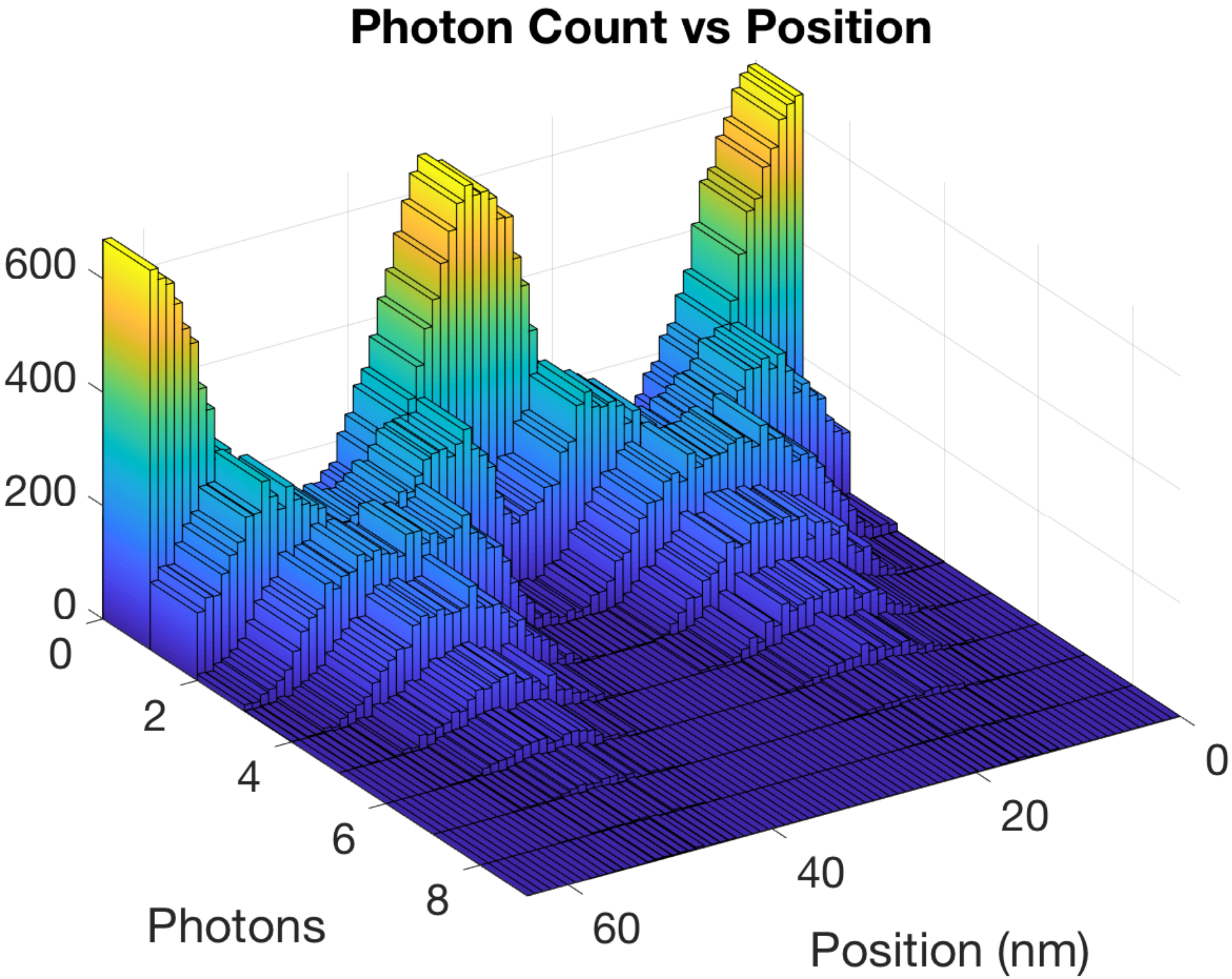
Illustration

- PAG Image: white noise
- Histogram reveals Poisson distribution



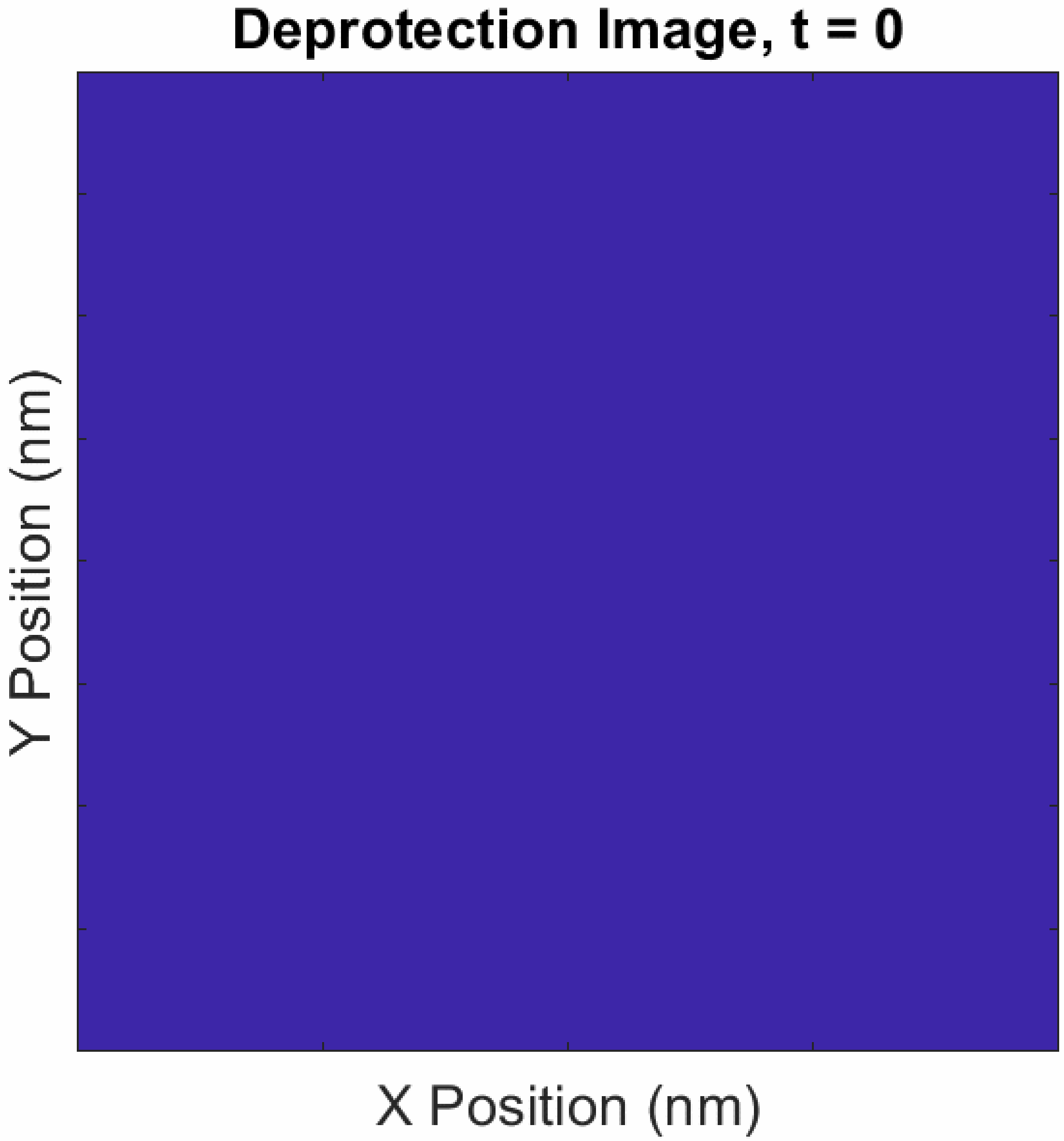
Illustration

- Photon image is similarly populated with white noise, now spatially distributed
- This histogram shows spatial distribution of photon counts



Illustration

- Photon image is then amplified stochastically by a yield term (not shown) A blurred version is then used along with the PAG image to generate an initial acid image
- Acid and base images fed into reaction/ diffusion simulation

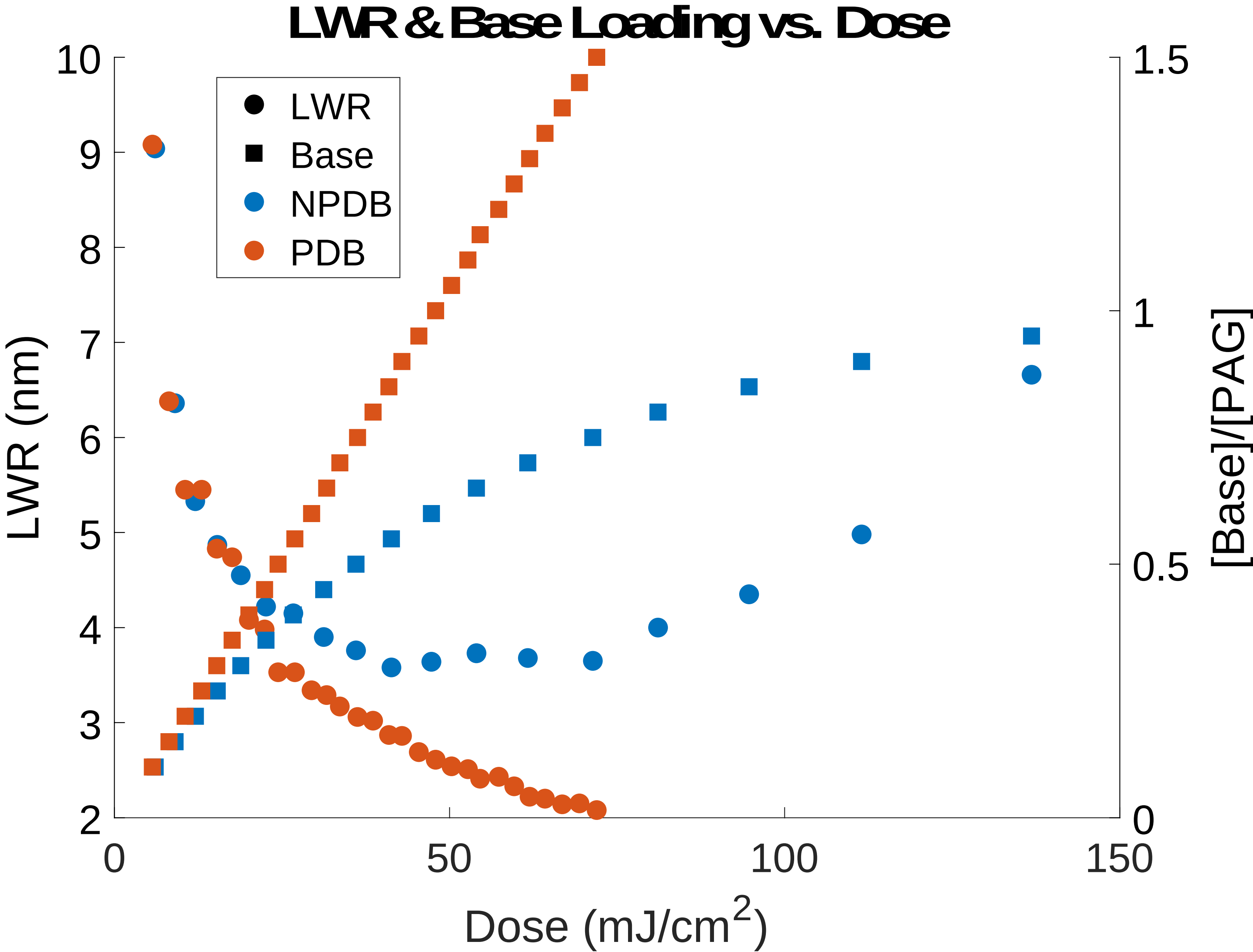


Modeling Approach

- Analyze effect of base loading
  - Photo-decomposable and conventional quencher
  - Keep CD fixed by adjusting dose
- 16 nm 1:1 line/ space pattern
- Analyze the resulting deprotection image using a commercially available lithography analysis software
- $LER = \frac{3*\sigma_D}{Slope}$

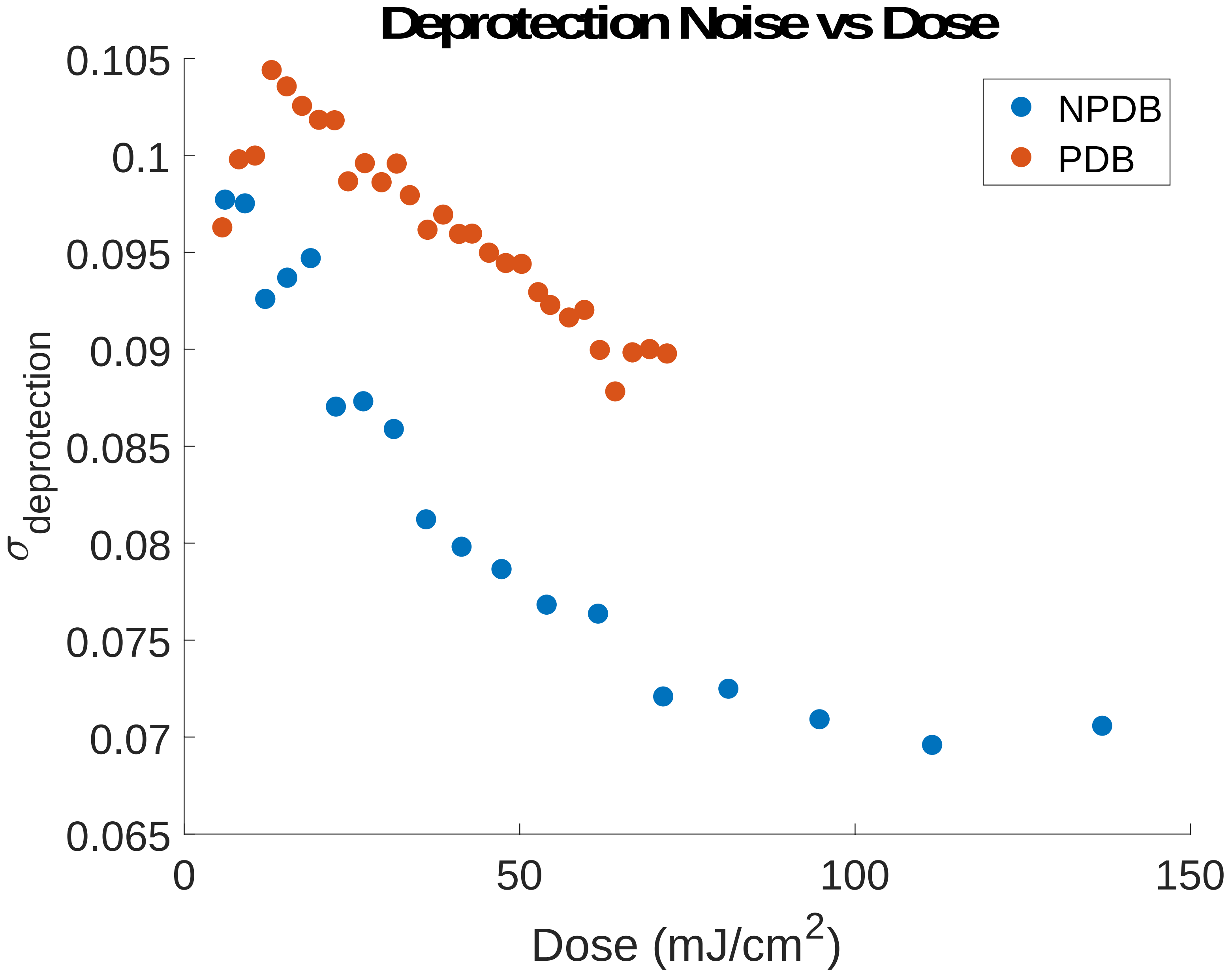
LWR

- At the same dose, PDB can provide lower LWR than NPDB
- PDB allows base loadings that are greater than PAG loading
- Are improvements in noise, slope, or both?



Noise

- PDB noise is greater for the same dose



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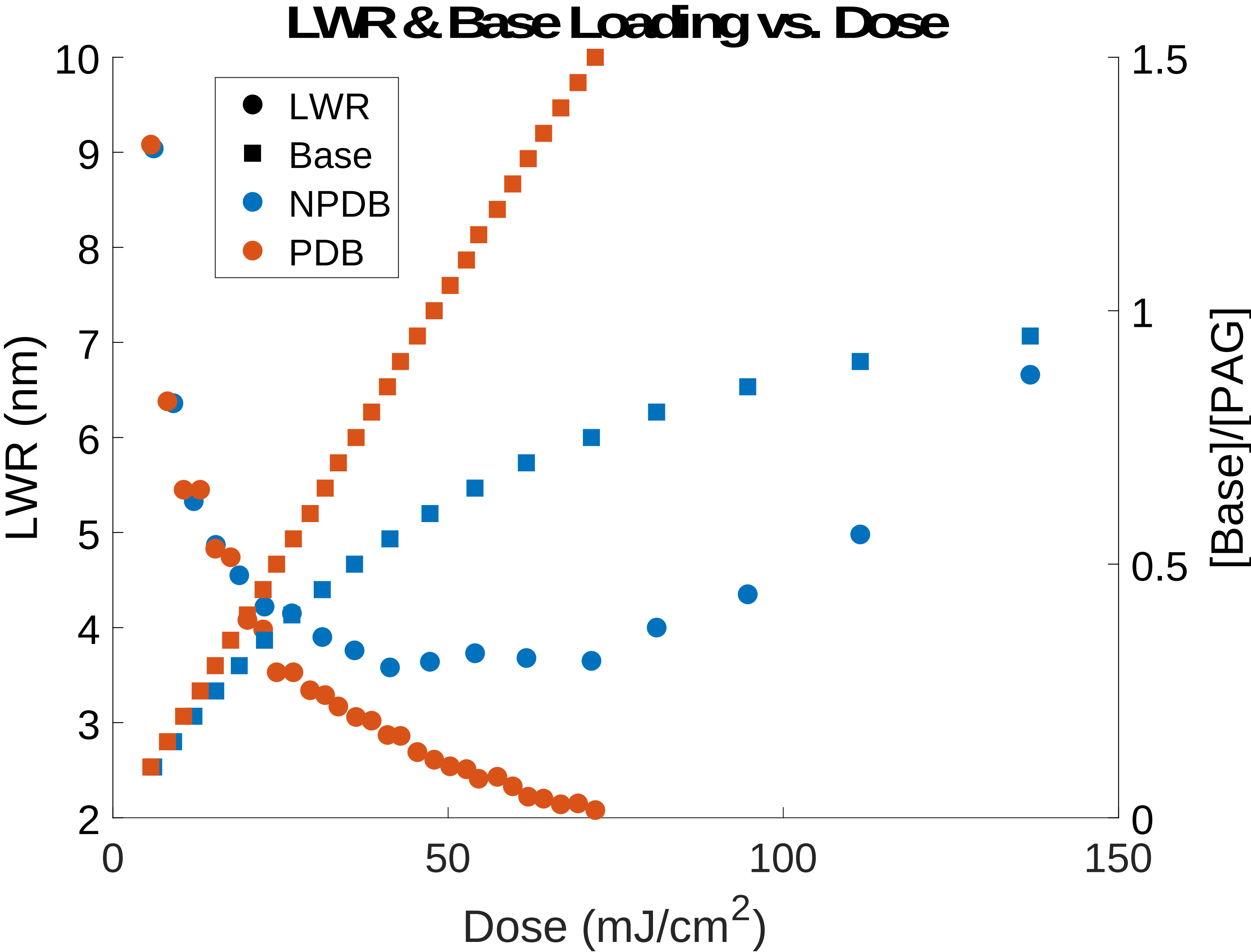
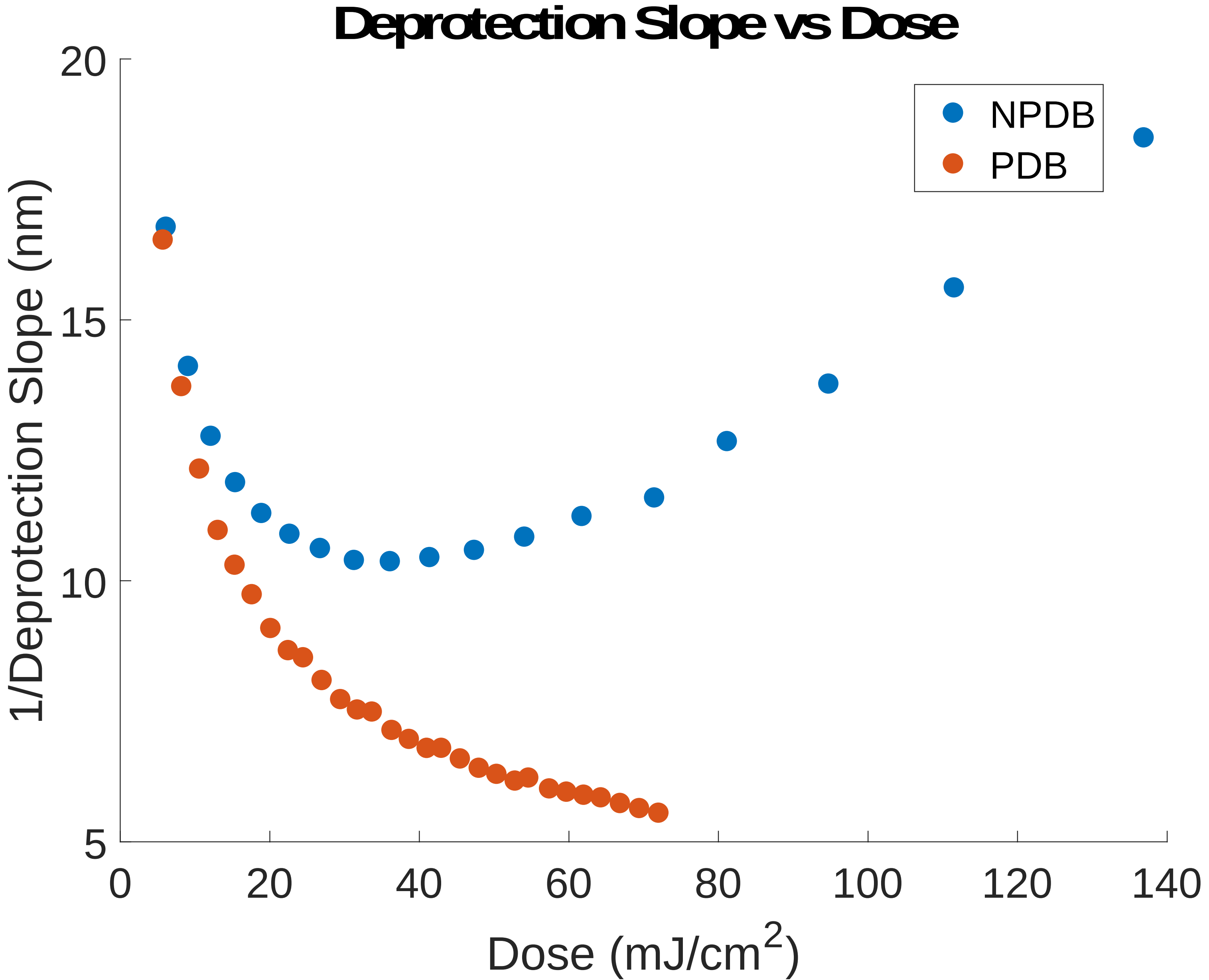


Slope

- Benefit of base loading comes from slope
- No degradation of slope at high base loadings

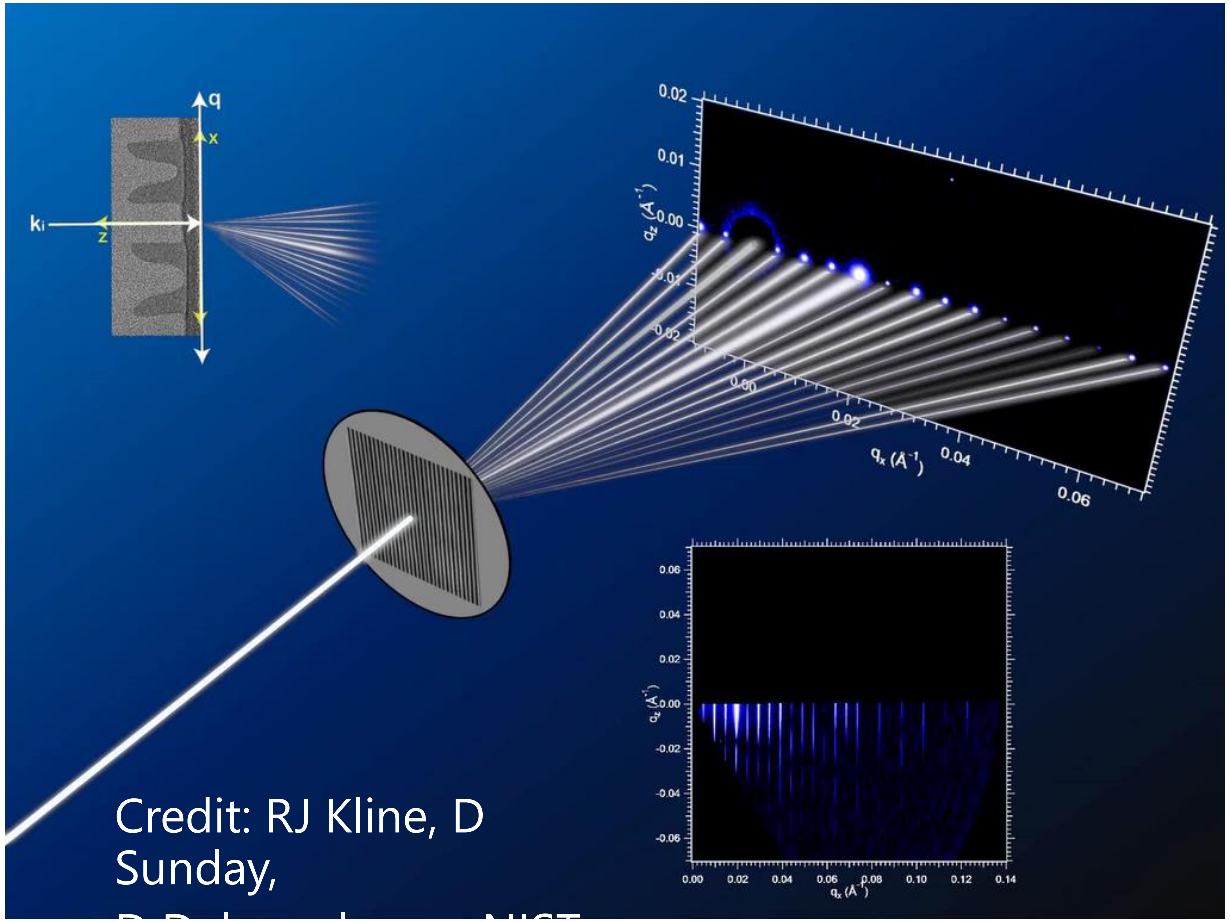


Experimental Plan

- To empirically test the role of PDB, we have partnered with industry to obtain a commercial photoresist with custom quencher loadings
- Expose and develop line/space patterns to test LER vs dose relationship
- Use RSoXS and AFM to probe the latent, chemical image in the resist prior to development

RSoXS: Resonant Soft X-ray Scattering

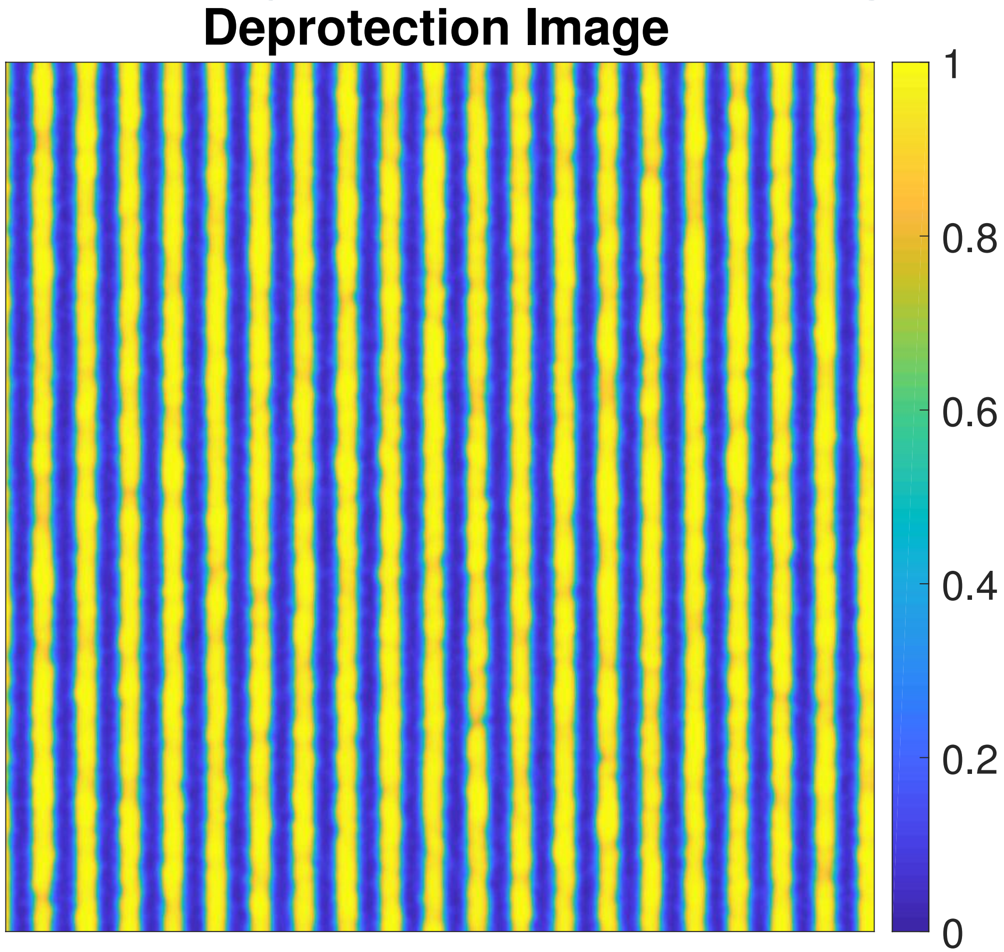
- Experimentally rooted in CD-SAXS



Credit: RJ Kline, D Sunday,
D Delongchamp, NIST

RSoXS: Resonant Soft X-ray Scattering

- Uses soft X-rays: Sensitive to changes in bond density/ structure
- n = 1-β+iδ



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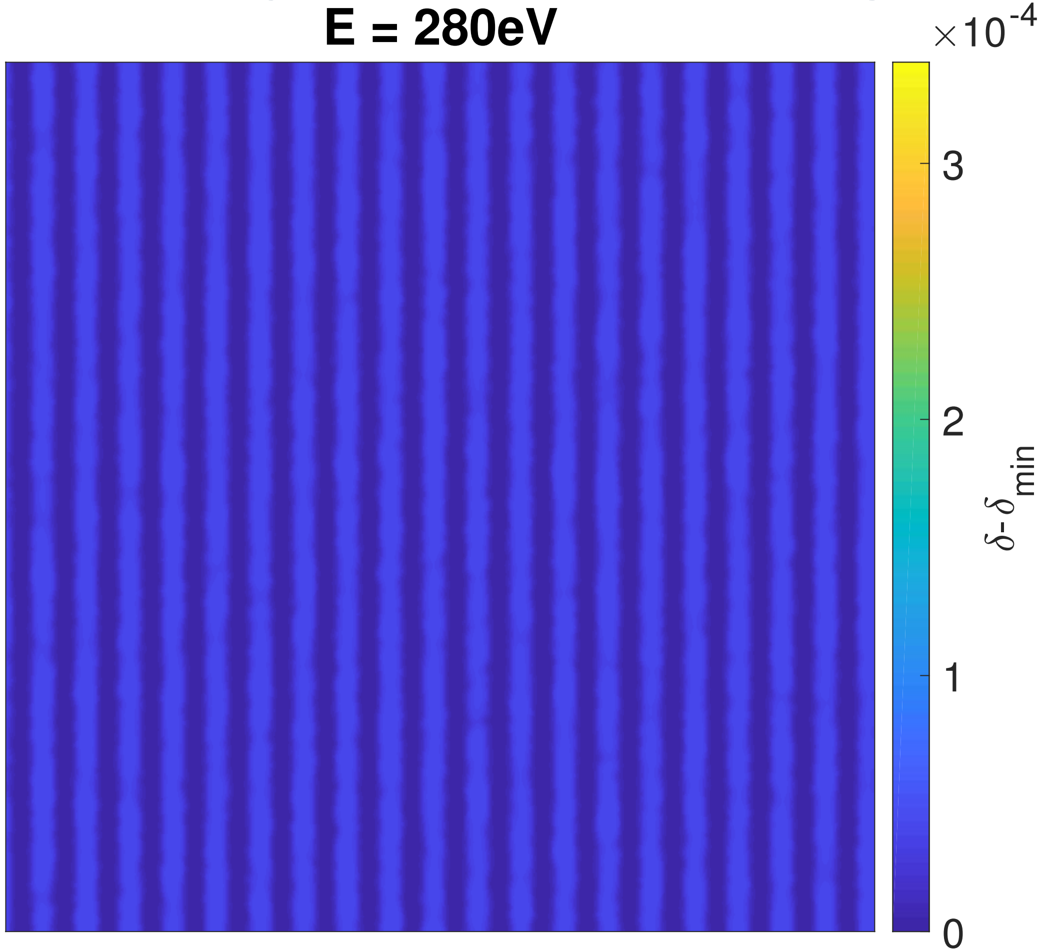

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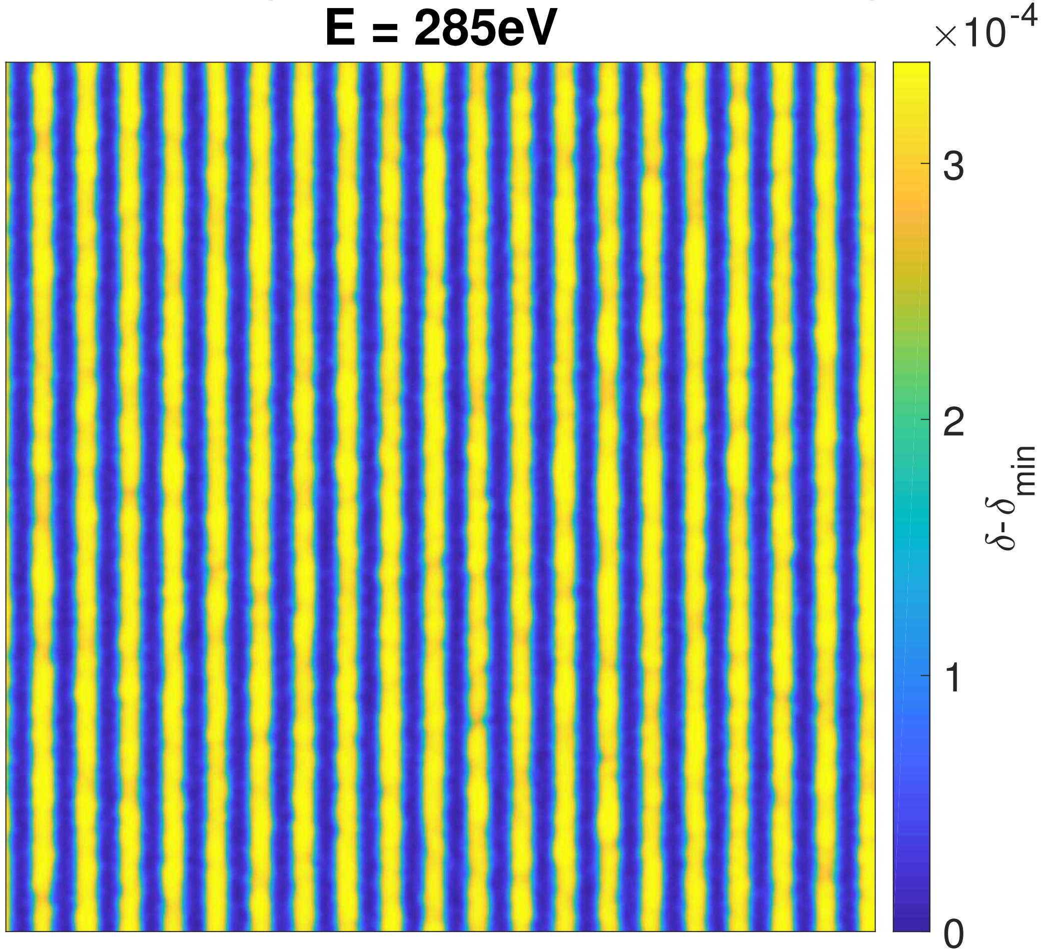
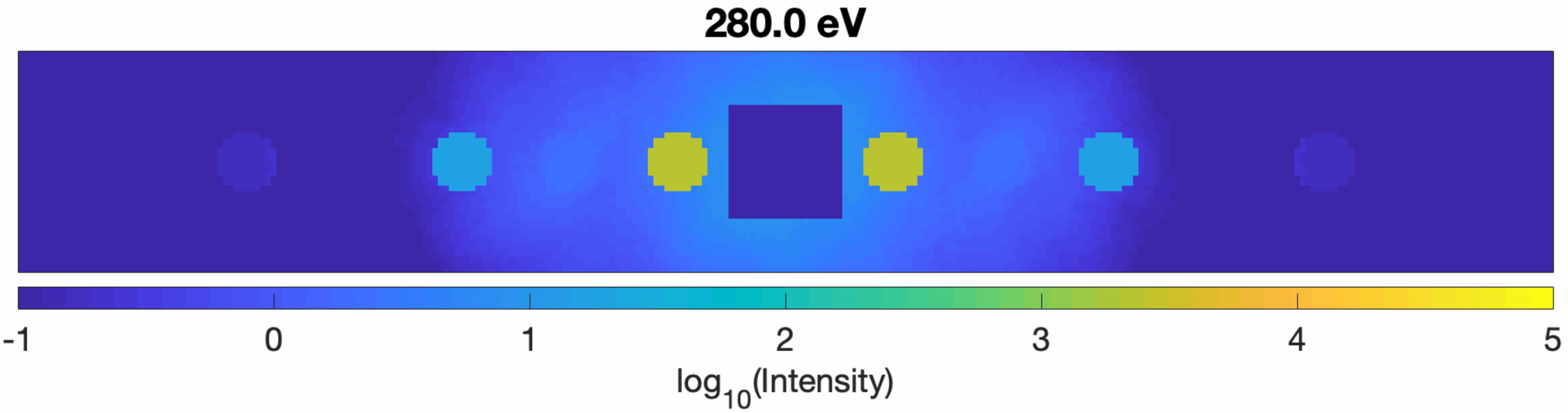
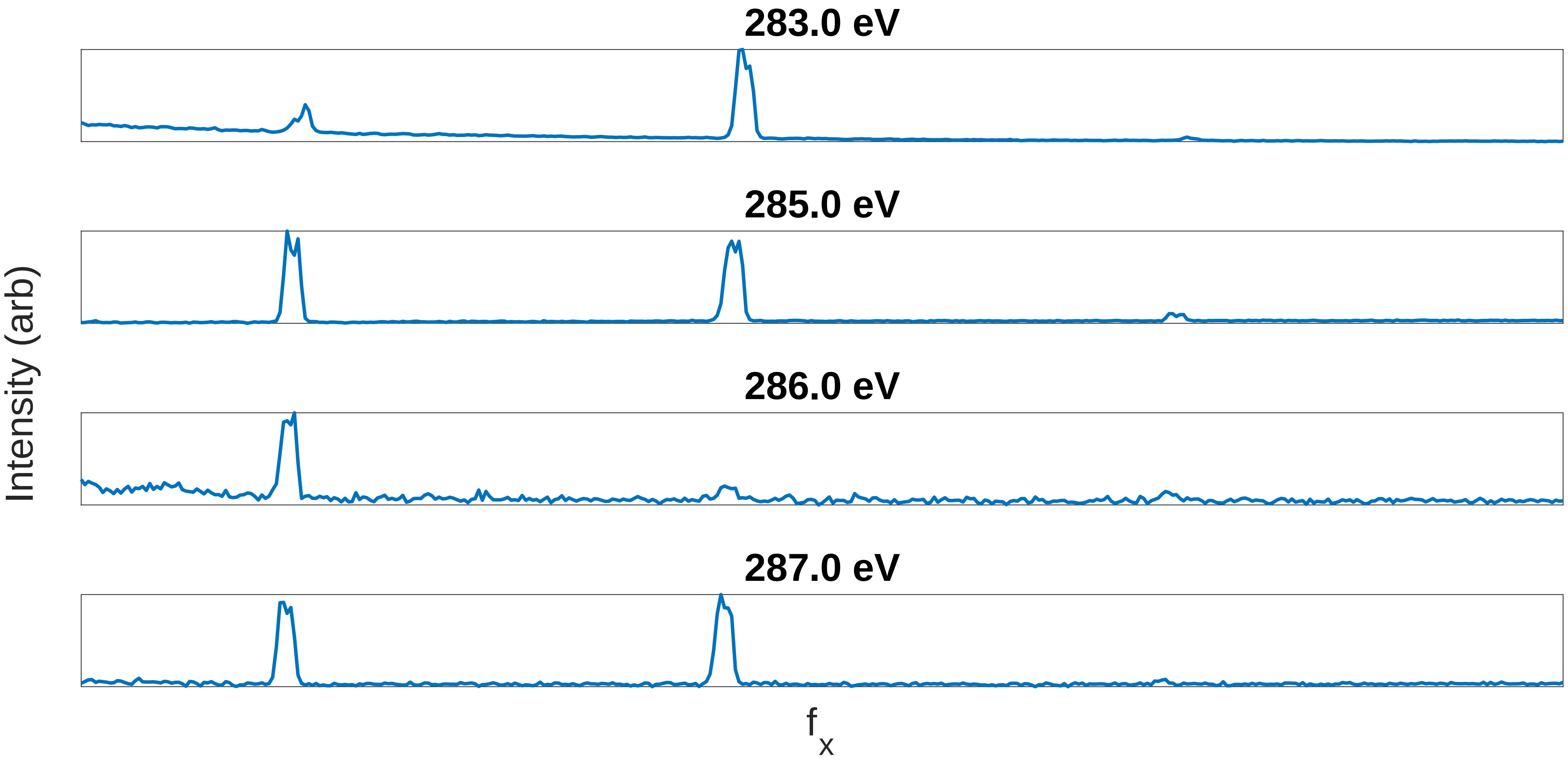


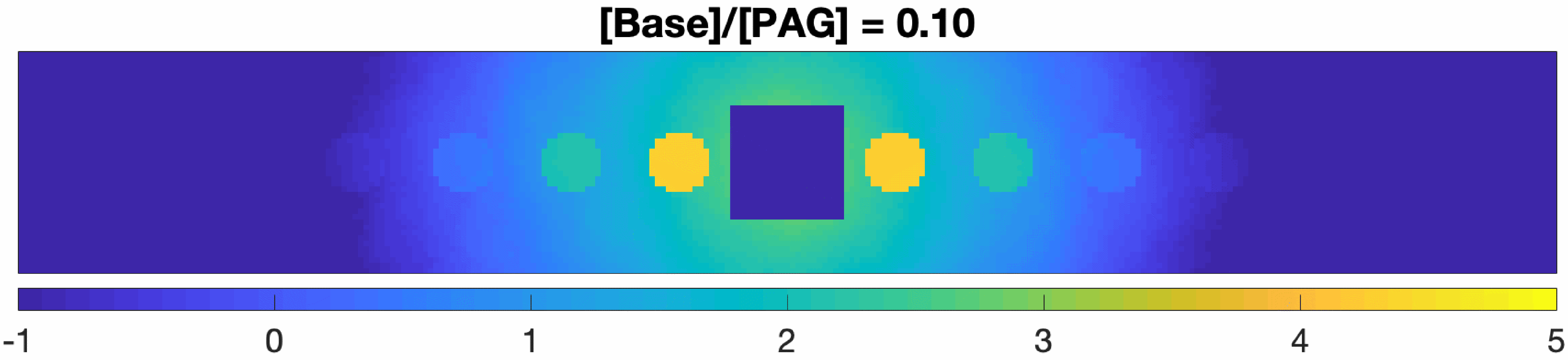
Simulated Scatter: Energy Dependence

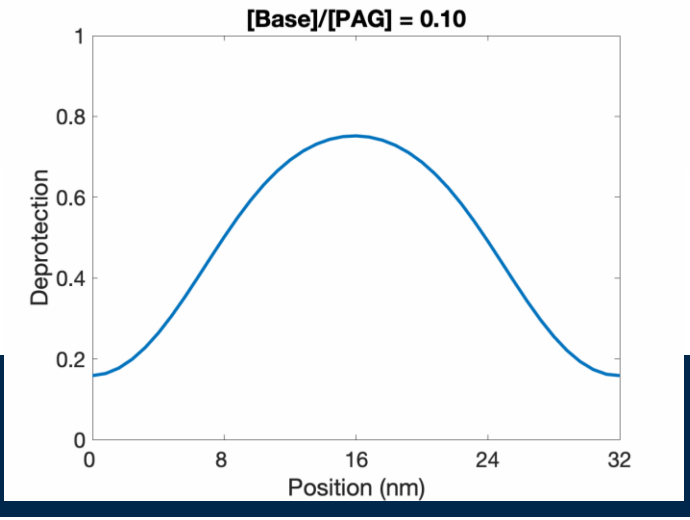


Preliminary Experimental Results



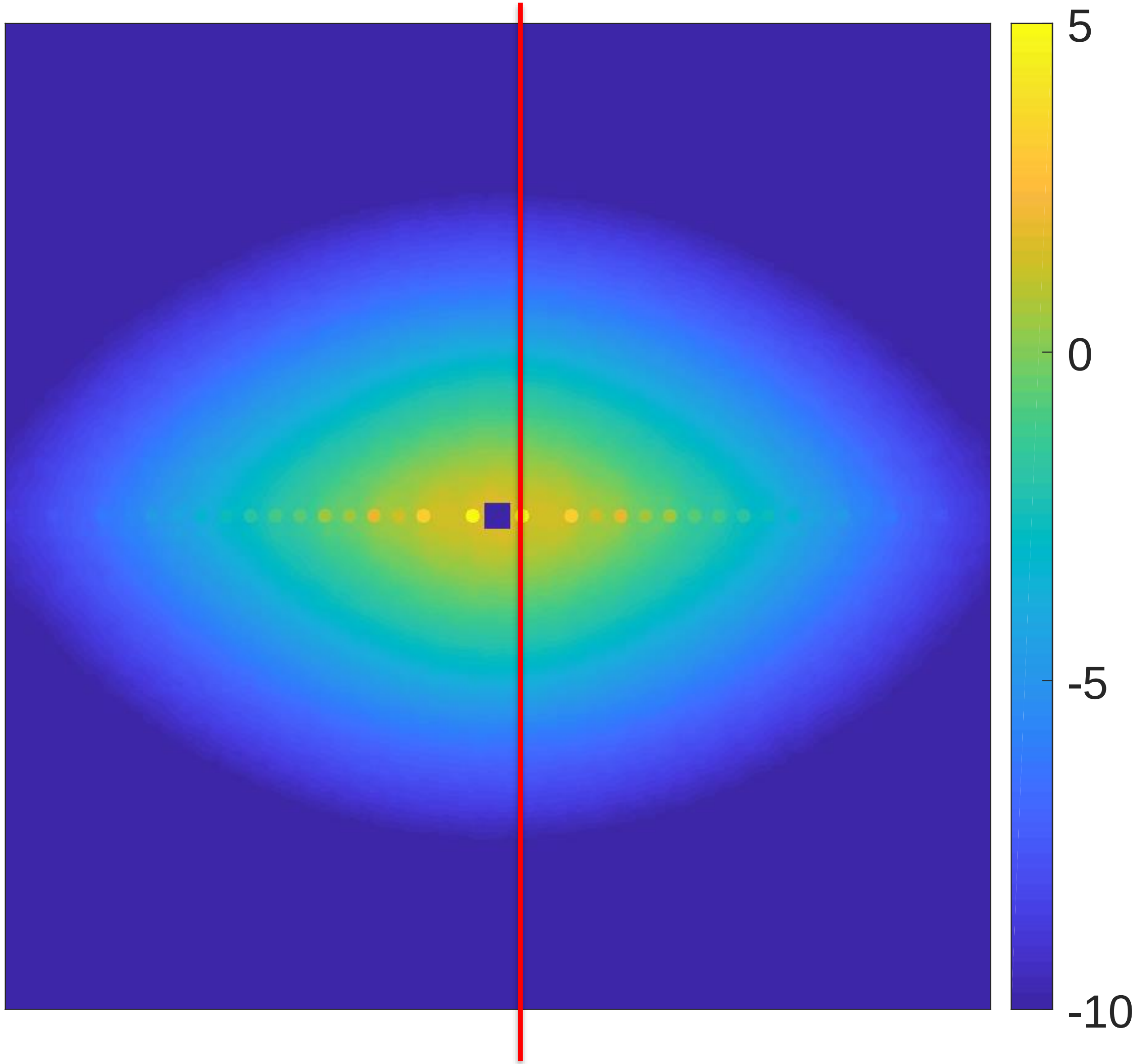
Simulated Scatter: PDB Dependence





Roughness

- CD-SAX technique is capable of extracting roughness information from developed lines
- Can we do the same with RSoXS?



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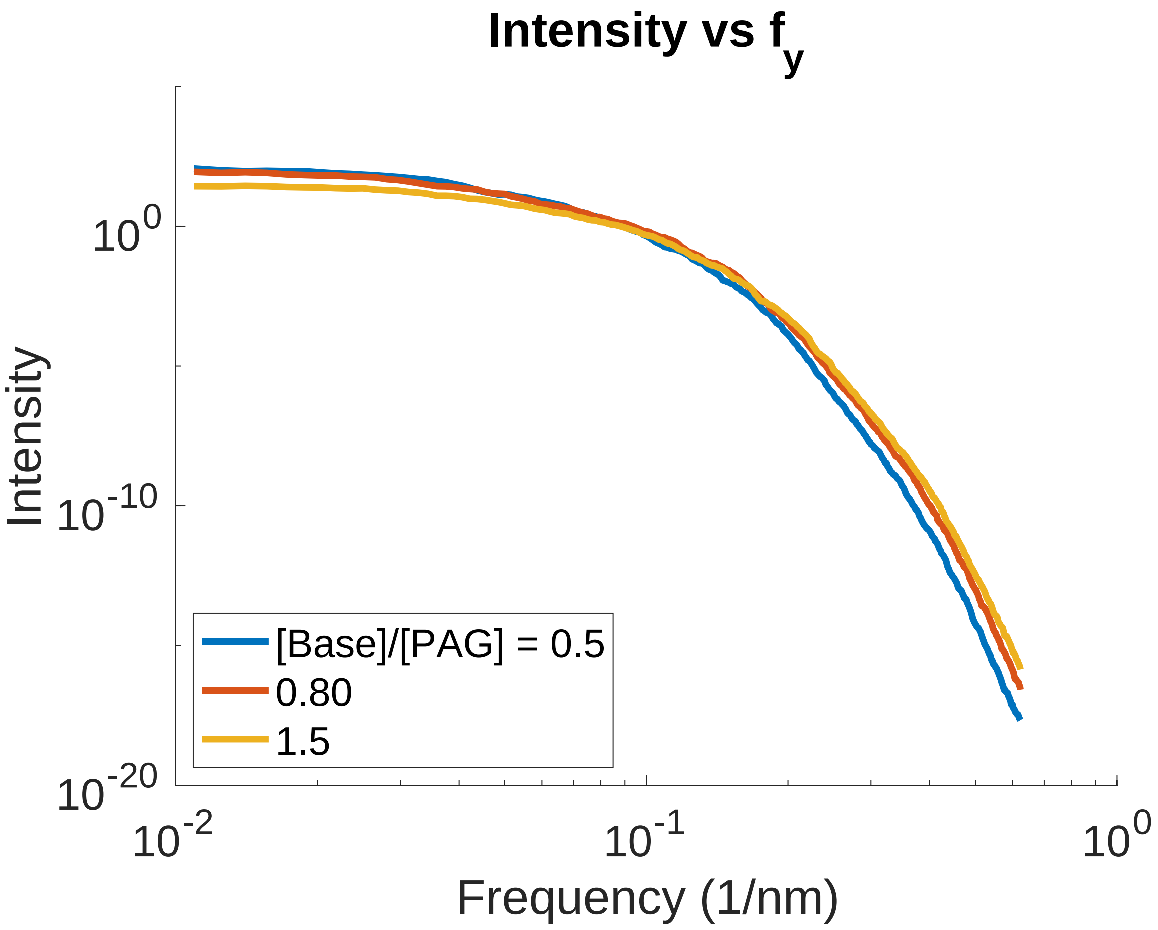
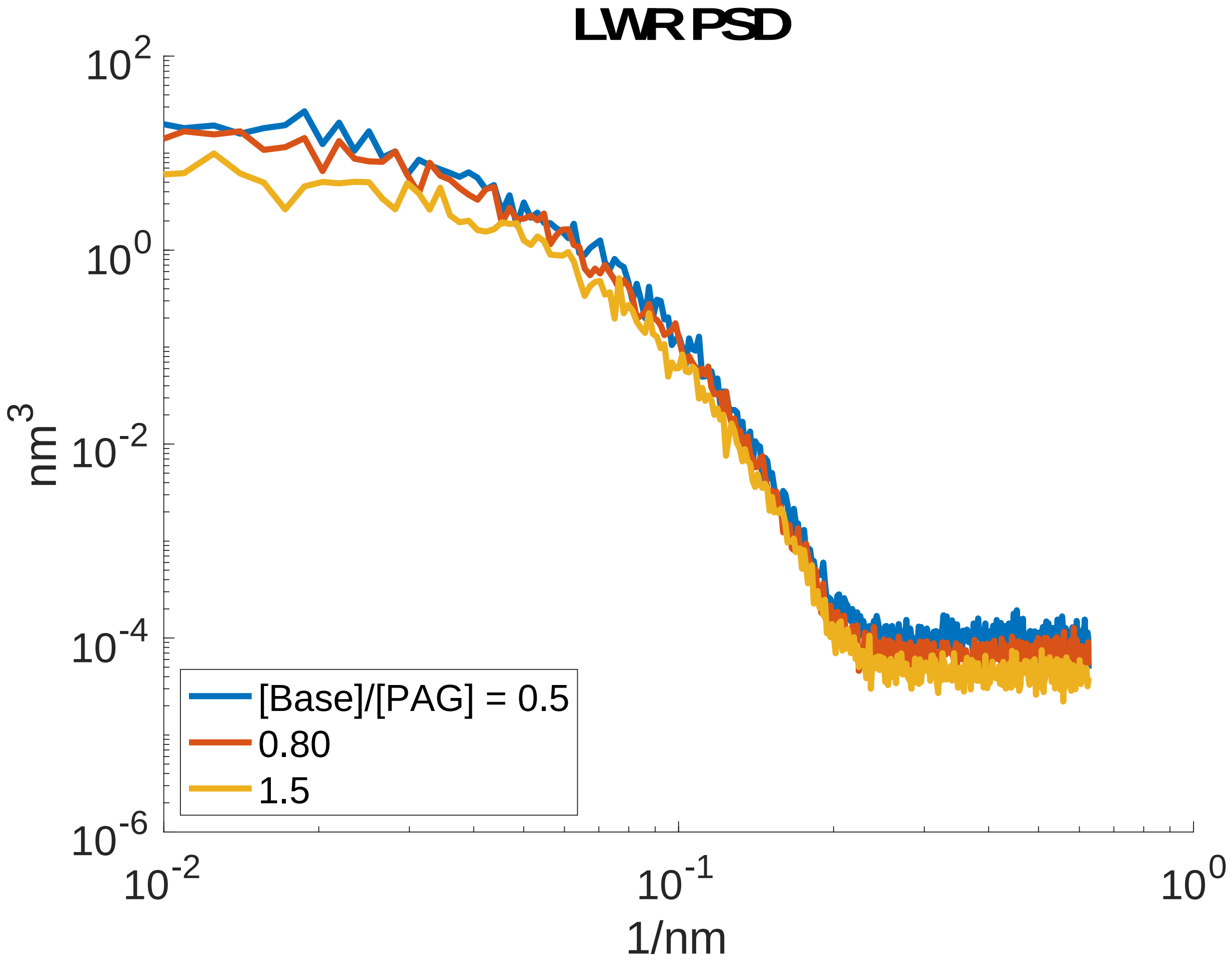
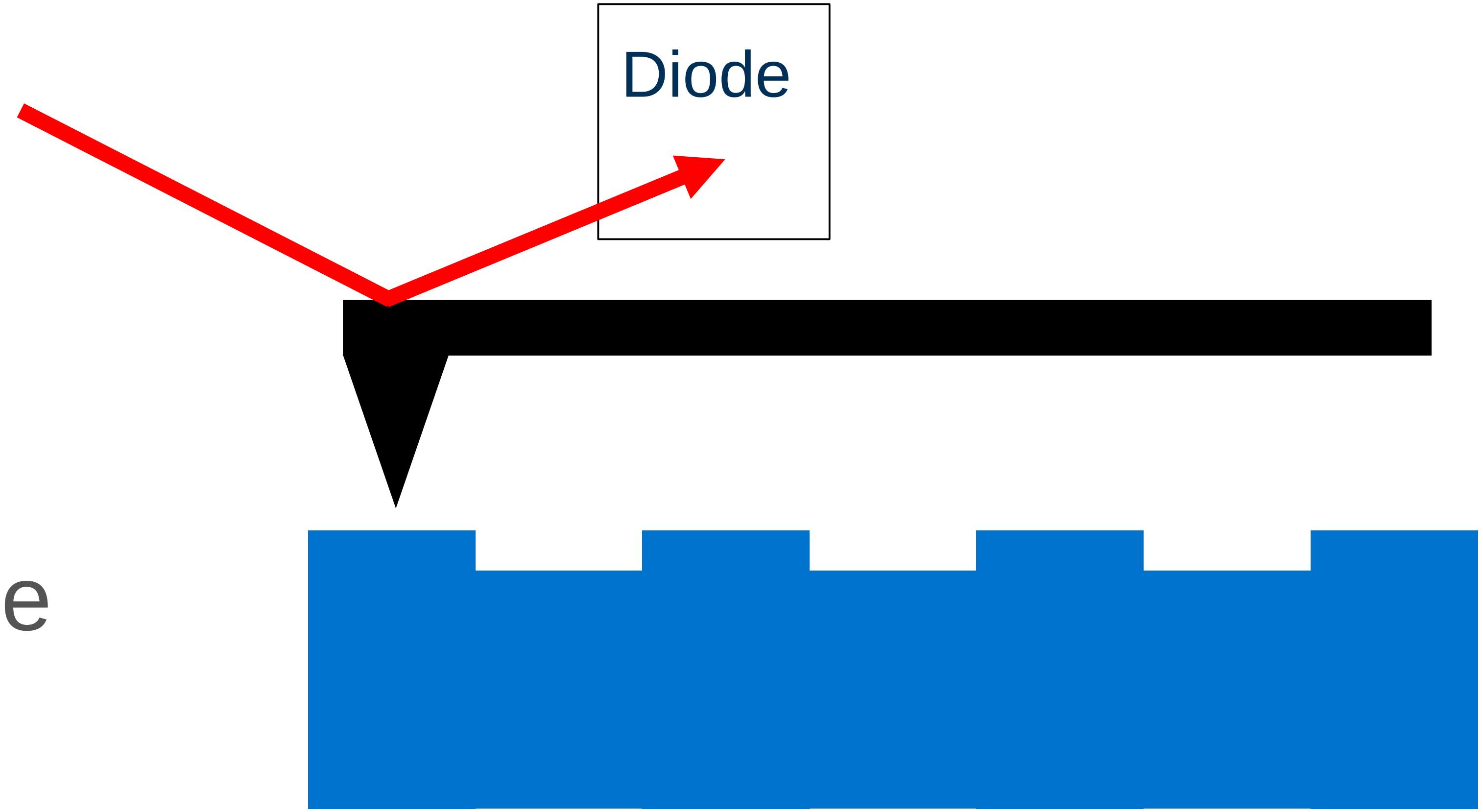
Roughness


Intensity vs f_y
Intensity
10^{0}
10^{-10}
10^{-20}
10^{-2}
10^{-1}
10^{0}
Frequency (1/nm)
[Base]/[PAG] = 0.5
0.80
1.5


LWR PSD
nm^{3}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-2}
10^{-1}
10^{0}
1/nm
[Base]/[PAG] = 0.5
0.80
1.5

AFM

- Can be used to characterize the physical grating produced by exposure
- Provides complementary information to RSoXS



Conclusion

- MPPM model provides insight into the sources of LER and suggests potential mitigation strategies
- Experimental approach to evaluating model’s accuracy:
  - Standard exposure and development at a variety of base loadings
  - RSoXS to measure the latent, chemical image in the resist
  - AFM to measure the thickness change that results from exposure

Acknowledgements

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- Isvar Cordova
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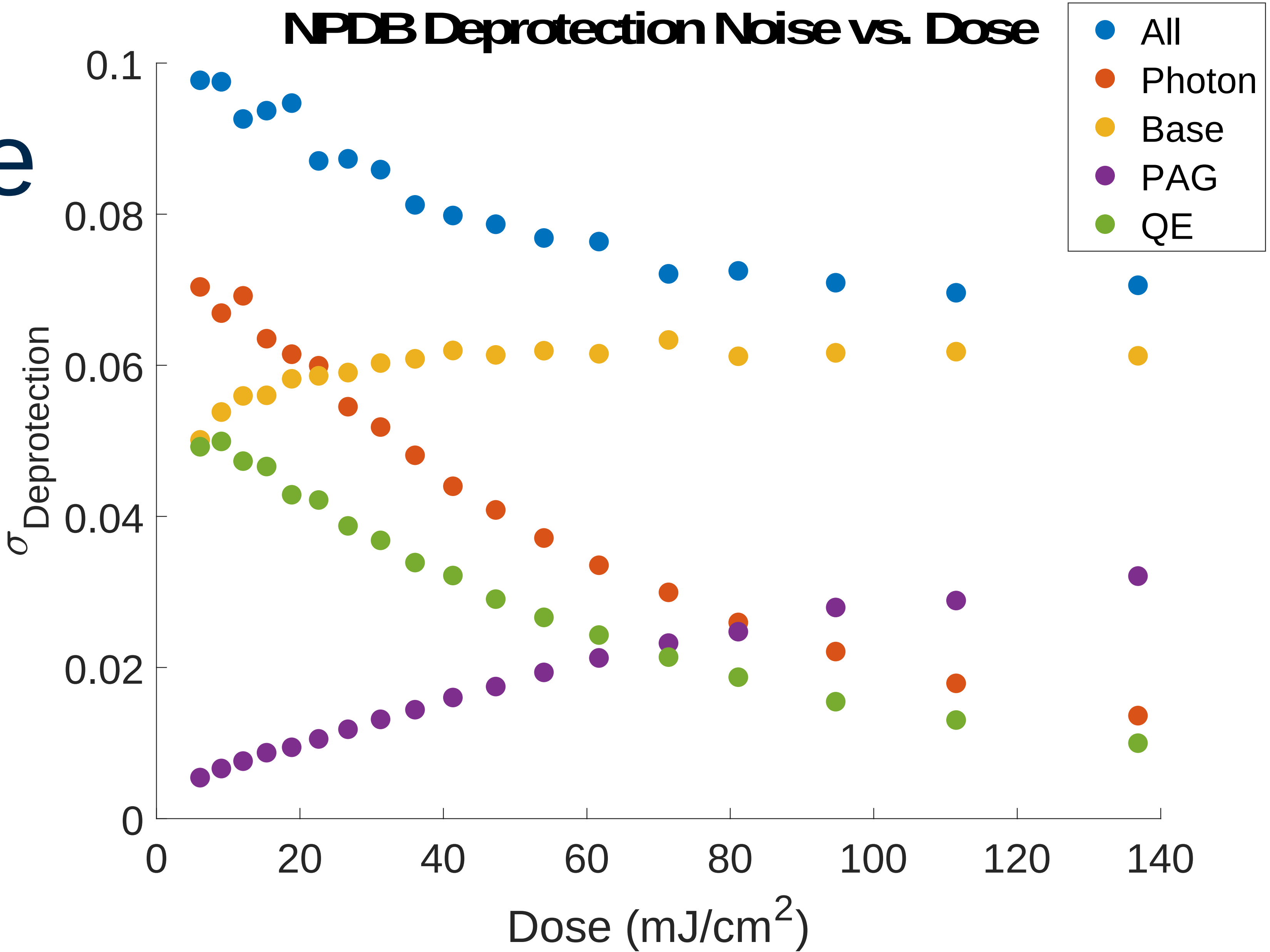
ZEISS
Mentor Graphics
QUALCOMM
ARM
ASML

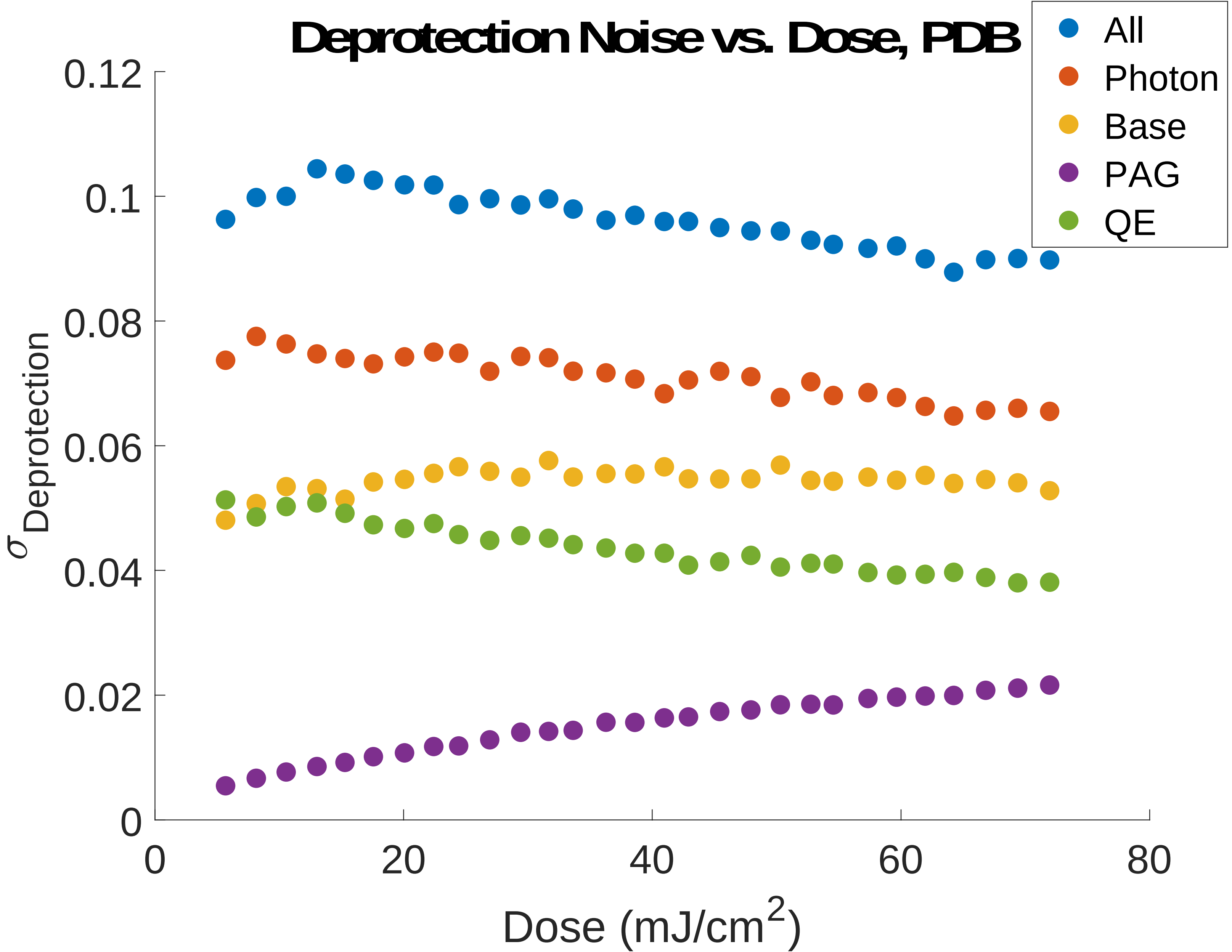
NPDB: Noise

- Benefit of MPPM is that stochastic terms can be toggled on and off
- For the high base loadings (doses), base is the largest contributor to deprotection noise
- Improvement in deprotection noise can only partially explain LWR trends



PDB: Noise

- Photon noise is the dominate contributor to deprotection noise at all base loadings/ doses
- QE is a more consistent contributor
- PAG contributions remain low



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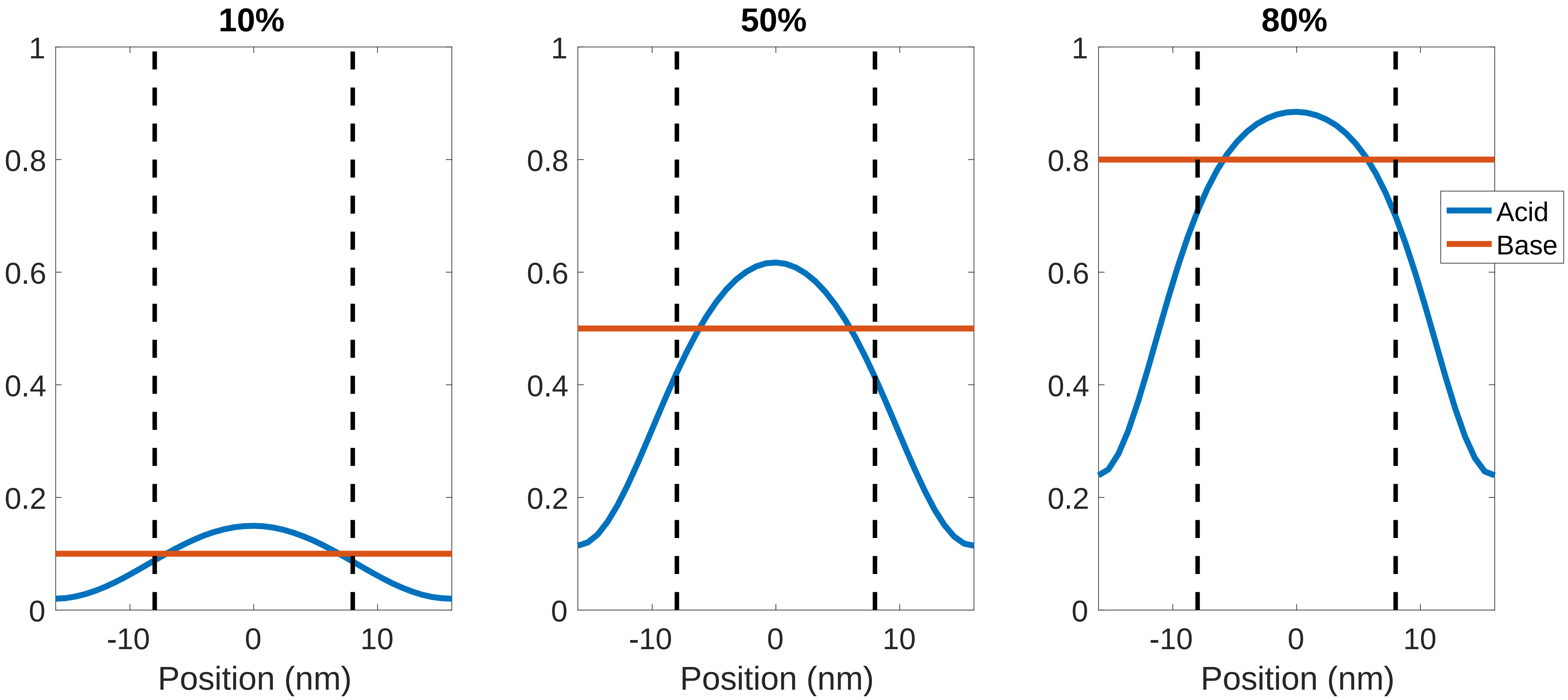
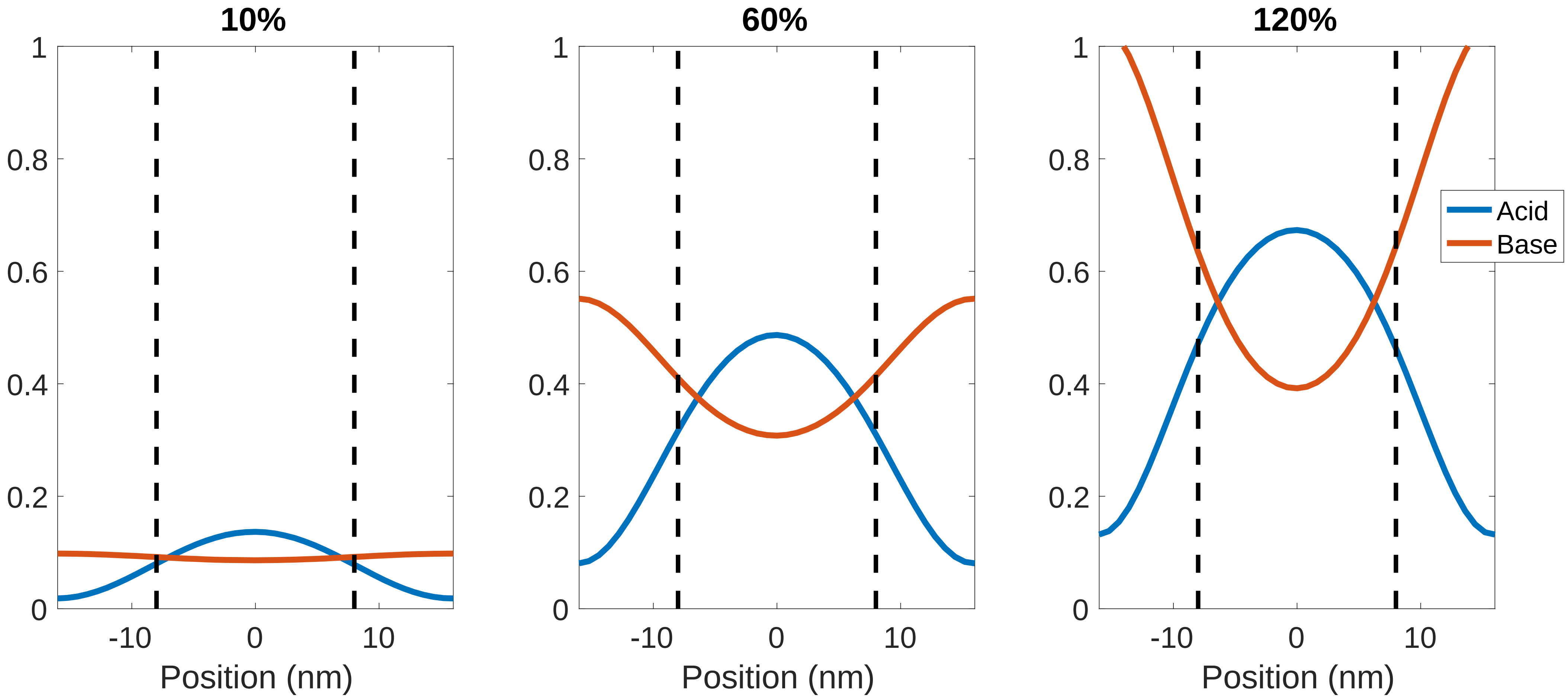
RSoXS: Resonant Soft X-ray Scattering

- Exposure and post-exposure bake process produces a chemical diffraction grating
- Small angle X-ray scattering technique that utilizes **chemical** changes to produce contrast
- X-rays of different energies probe effectively different gratings

Initial Acid Profiles-NPDB

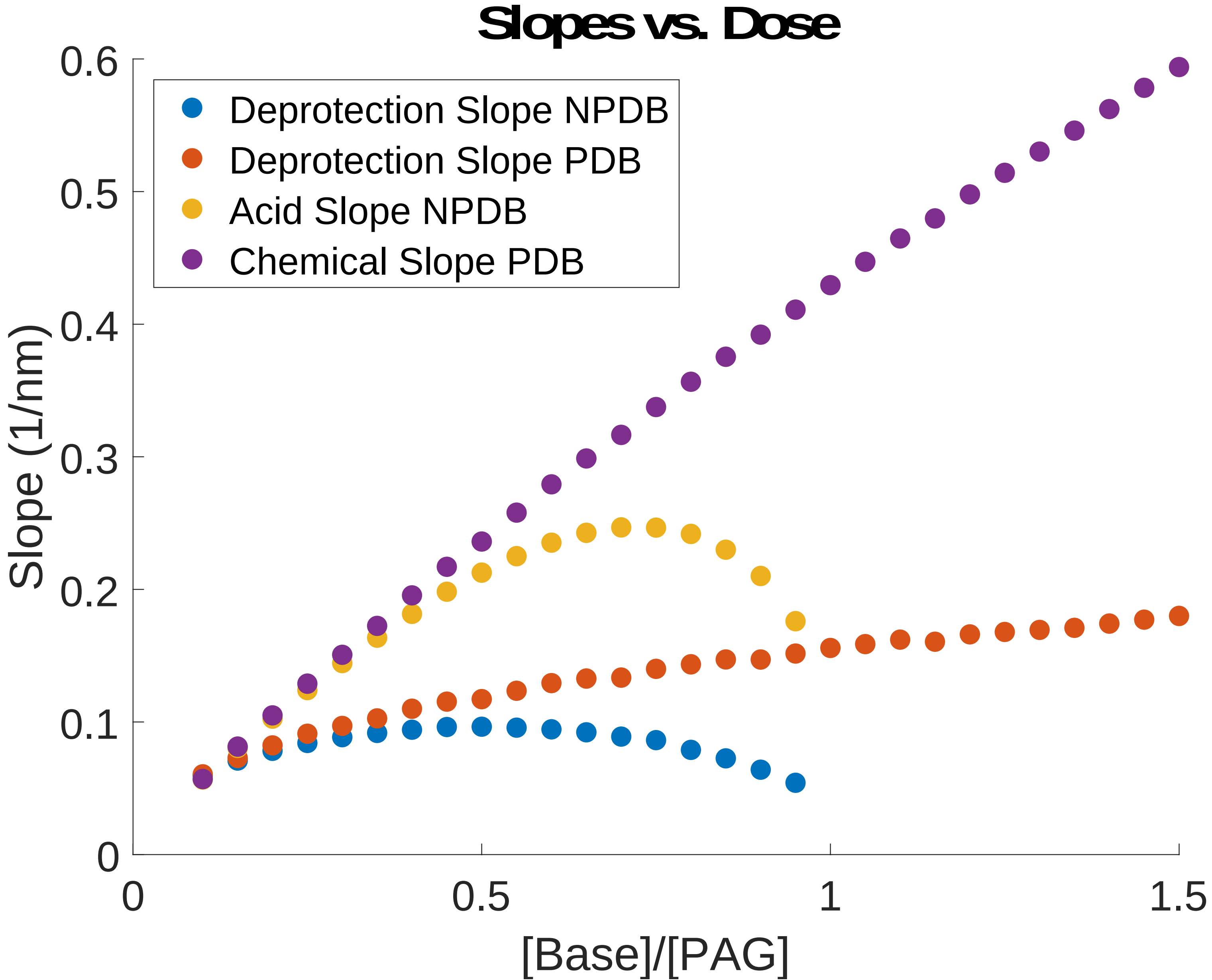


Initial Chemical Profiles- PDB



Chemical Slope

Improved chemical slope leads to improved deprotection slope



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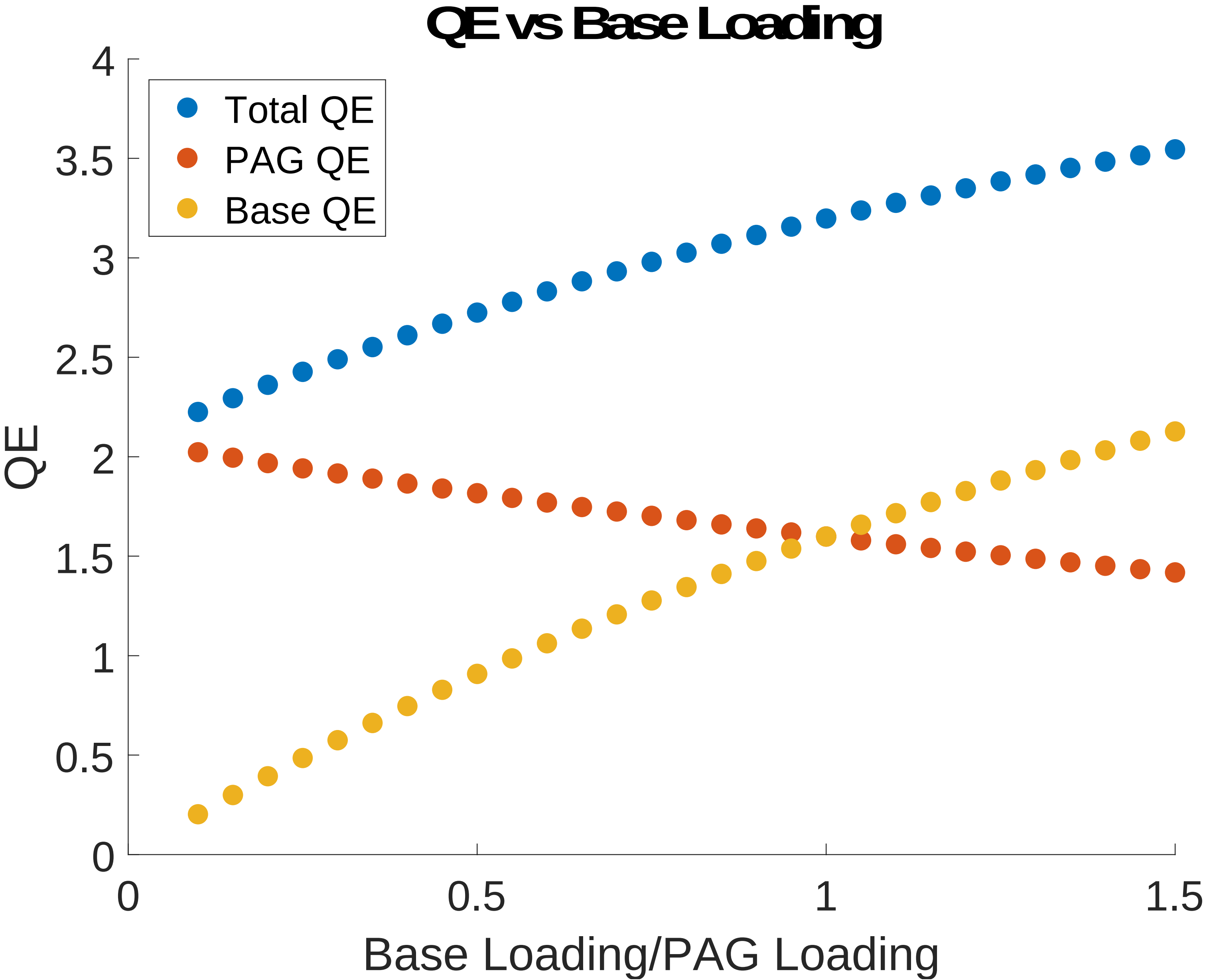
PDB

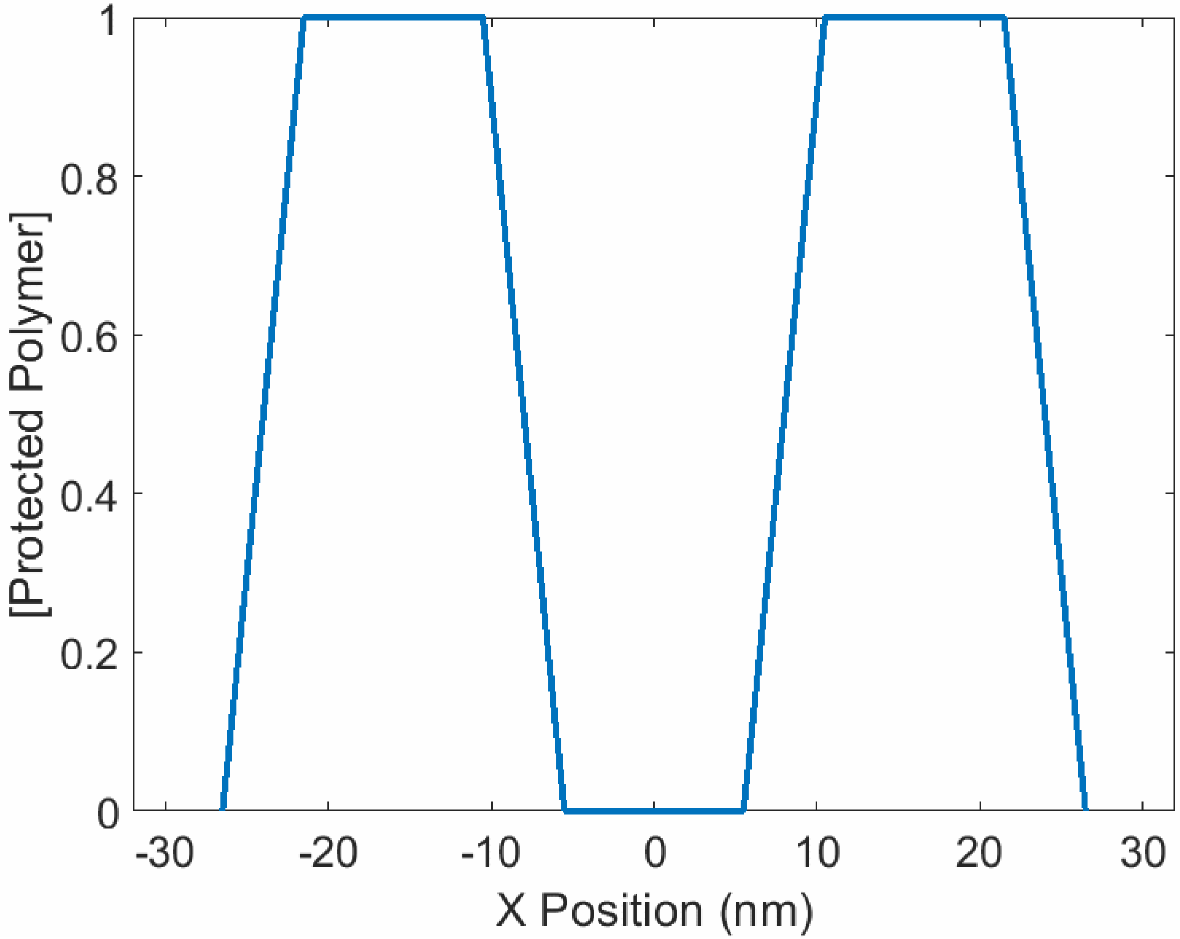
- EUV photons can decompose base like they activate PAG
- Decomposition comes at cost: resist is electron-limited, and PAG and Base are now competing for resources
- Model both PAG and Base as photoactive compounds (PAC) and use PAG saturation data to model this effect



Slope → Resolution

Steeper slope means more features can fit into an area

Right: slope = 0.2 nm^{-1}



Acid Slope

The deprotection reaction provides insight:

$$\frac{\partial \rho_d}{\partial t} = k_d \rho_a (1 - \rho_d)$$

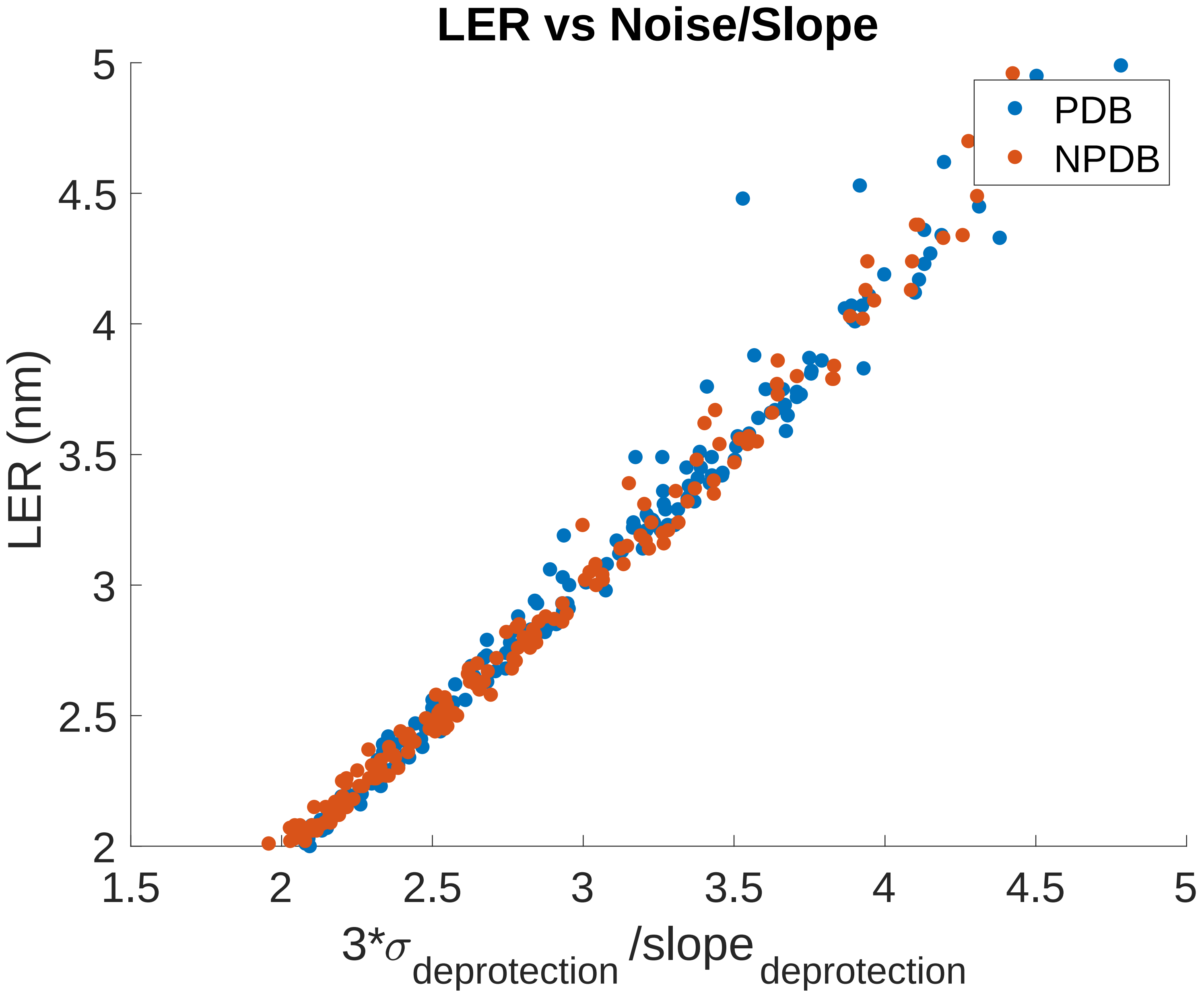
Taking the spatial derivative of the rate equation and swapping the order of differentiation:

$$\frac{\partial}{\partial t}\left(\frac{\partial \rho_d}{\partial x}\right) = k_d (\frac{\partial \rho_a}{\partial x}(1 - \rho_d) - \rho_a \frac{\partial \rho_d}{\partial x})$$

- Additional acid initially helps, but as time progresses, reaction slows in deprotected region, and slope degrades. This degradation is worse if the acid concentration is higher

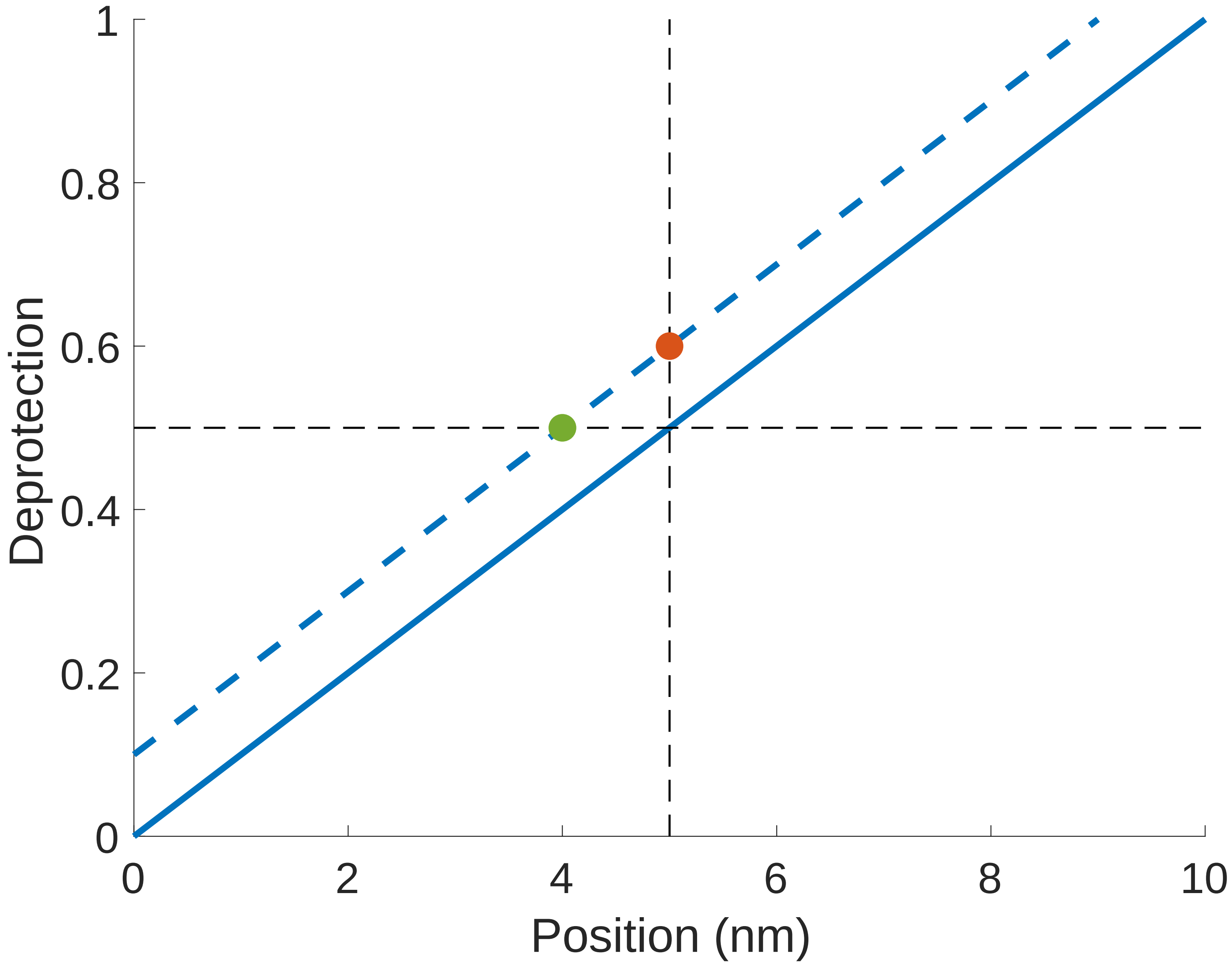
Noise/Slope

- $LER = \frac{3 * \sigma_D}{Slope}$
- Provides two metrics by which LER can be analyzed



Noise/Slope

$$LER = \frac{3\,\sigma_D}{\partial D / \partial x}$$



Simple Noise Model

- Due to Gallatin and Naulleau, JM3, 2018
- $A = \sum_{i=1}^{P} Y_i - B$, P, Y and B are all Poisson random variables
- $E[A] = E[P] * E[Y] - E[B]$
- $SD[A] = sqrt(E[P] * Var[Y] + Var[P] * E[Y]^2 + Var[B])$
- Noise/Signal goes to infinity as B->E[P]E[Y]
- Benefit of base is slowing of resist, allowing P to increase at same CD

Simple Noise Model, PDB

- Additional term for base decomposed. Acts like added acid
- A: acid, Q: quencher, Ya: acid yield, Yb: base yield, P: photon
- $A = \sum_{i=1}^{P} Ya_i - B + \sum_{i=1}^{P} Yb_i$ (extra additive term from decomposing base)
- $E[A] = E[P] * (E[Ya] + E[Yb]) - E[B]$
- $SD[A] = sqrt(E[P] * (Var[Ya] + Var[Yb]) + Var[P] * (E[Ya] + E[Yb])^2 + Var[B])$

Reaction/ Diffusion

- The reaction diffusion process serves to filter the input chemical and photon shot noise while producing the deprotection image
- This filtering process is key to smoothing out the resulting lithographic patterns

Diffuse React

- $\frac{\partial \rho_{Acid}}{\partial t} = D\Delta\rho_{Acid} - k_{A,B}\,\rho_{Acid}\,\rho_{Base}$
- $\frac{\partial \rho_{Base}}{\partial t} = D\Delta\rho_{Base} - k_{A,B}\,\rho_{Acid}\,\rho_{Base}$
- $\frac{\partial \rho_{Deprotection}}{\partial t} = k_{A,D}\,\rho_{Acid}(1 - \rho_{Deprotection})$