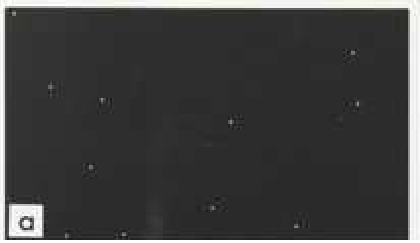
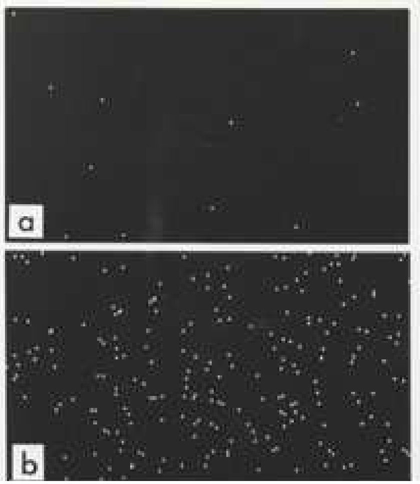
“Shot Noise”

G. Gallatin


a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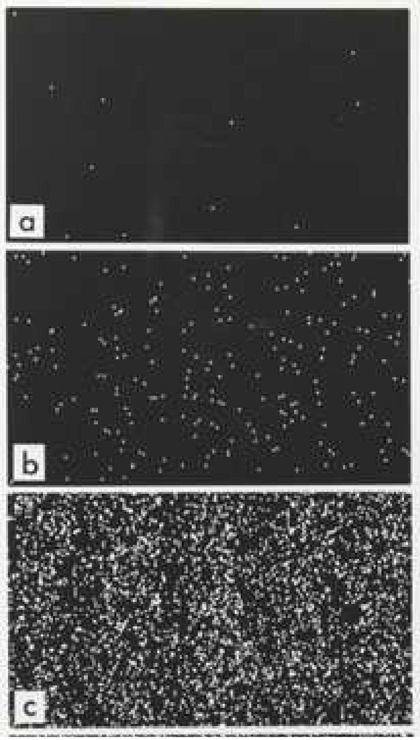
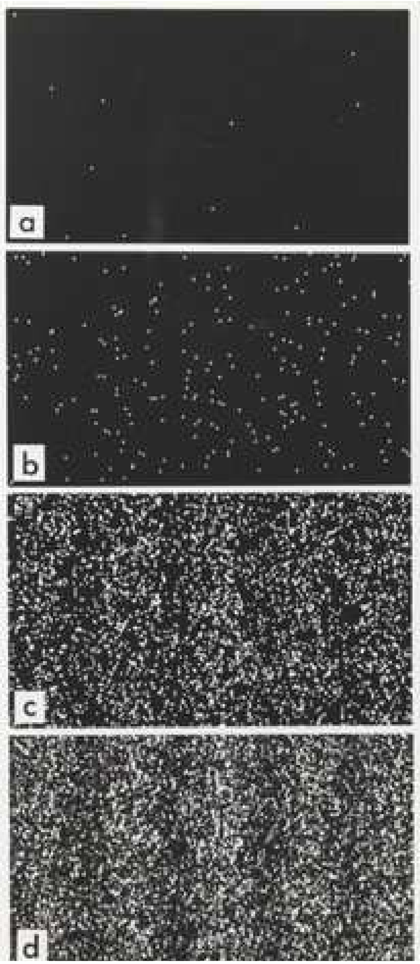
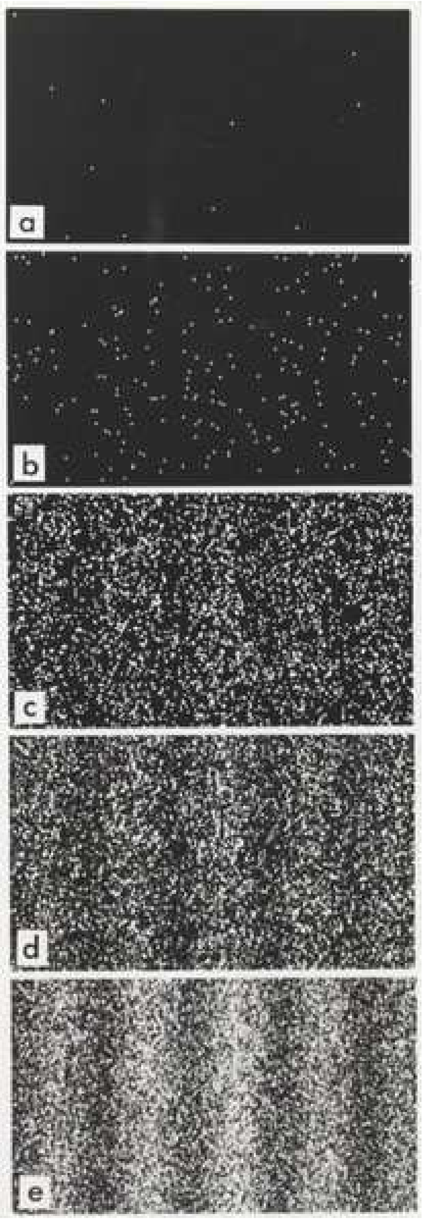

a
b
c


a
b
c
d

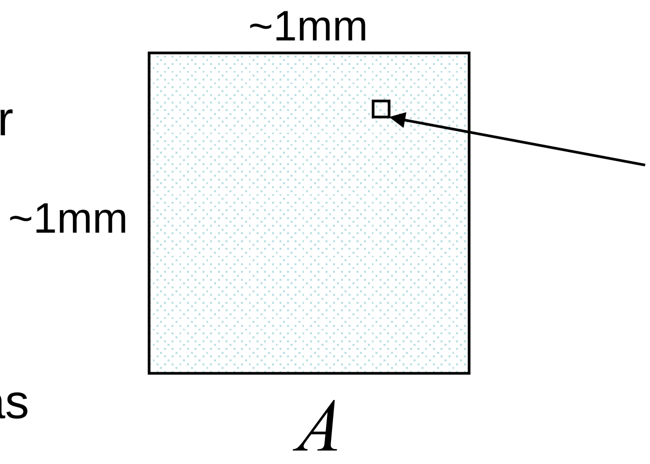

a
b
c
d
e

Probability distribution for absorbing a photon and releasing an acid ~ Image intensity

Exposure tool fixes exposure dose over mm^2 areas

⇩

N is fixed in mm^2 areas



Any single feature lives in an area a ~ micron^2

➔ $a << A$

Probability for releasing a fixed number of acids $P(\vec{r}_1,\vec{r}_2,\cdots,\vec{r}_N)=P(\vec{r}_1)P(\vec{r}_2)\cdots P(\vec{r}_N)$

Probability of getting n acids in area $a << A$ $P_n(a << A)=Poisson$

"Shot noise for free"

Consistent with quantum mechanics

➔ Interference patterns build up one absorption at a time

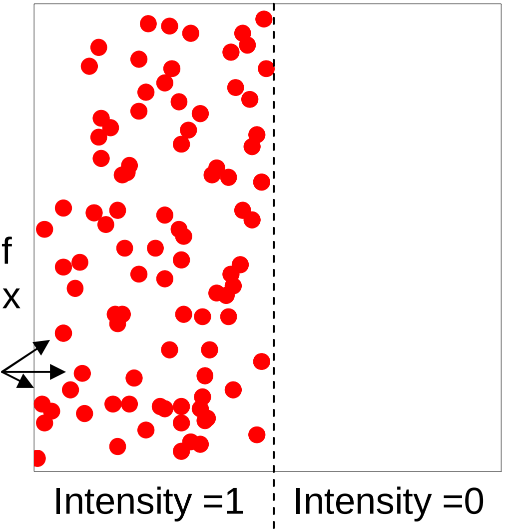
Even with the net number of acids fixed on the macroscale get "shot noise" on the microscale.

LER Model → RLS Model

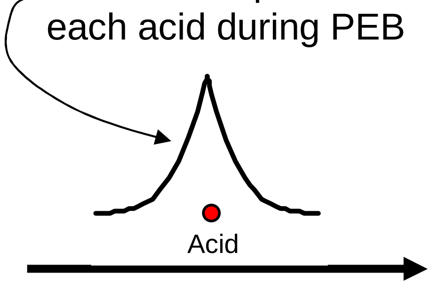
Gallatin SPIE 2005

2D Illustration

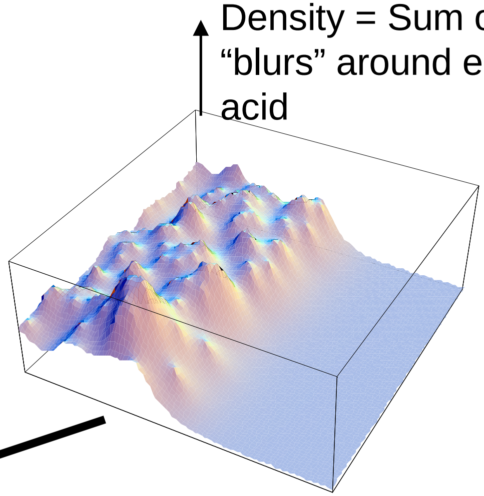
Sensitivity
Exposure dose releases acids. Image intensity at position x
→ Probability of acid release at x



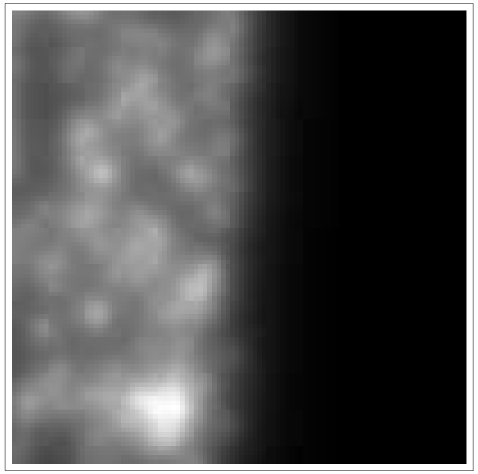
Resolution
Diffusion/deprotection "blur" develops around each acid during PEB



Net Deprotection Density = Sum of "blurs" around each acid



Grayscale plot net deprotection density



Resist edge position occurs at a fixed value of deprotection
~Critical Ionization Model

Development

Burns,et.al., JVST B 2002

Resist edge with low spatial frequency content

= **LER**

Exposure

$\rho_{PAG}(\vec{r},t) = \text{PAG density at position } \vec{r} \text{ at time } t$

$$\rho_{PAG}(\vec{r},t) = \rho_{PAG}(\vec{r},0) - \rho_{Acid}(\vec{r},t)$$

$$\frac{\partial \rho_{Acid}(\vec{r},t)}{\partial t} = \alpha Q v I(\vec{r})\rho_{PAG}(\vec{r},t) = \alpha Q v I(\vec{r})(\rho_{PAG}(\vec{r},0) - \rho_{Acid}(\vec{r},t))$$

$\alpha = \text{resist absorptivity (} \exp[-\alpha T] = \text{transmitted intensity}, T = \text{resist thickness)}$

$Q = \text{"Quantum Efficiency"} = \#\text{ acids generated/absorbed photon.}$

$v = \text{photon - PAG interaction volume}$(Only PAGs within volume v surrounding the position of absorption can be affected)

$I(\vec{r},t) = \text{Image intensity (\# photons/(area} \times \text{time))}$

$$\text{Solution}: \rho_{Acid}(\vec{r},t) = \rho_{PAG}(\vec{r},0)(1 - \exp[-\alpha Q v I(\vec{r})t]) = \rho_{PAG}(\vec{r},0)(1 - \exp[-\alpha Q v E(\vec{r})])$$

$E(\vec{r}) = I(\vec{r})t = \text{Dose (\#photons/area)}$

$\alpha Q v = \text{Dill C (area/\#photons)} \quad \Rightarrow \quad 1/\text{C} = \text{Saturation Dose} = E_{sat}(\#\text{photons/area})$

Exposure Statistics

Previous slide ➔ Exposure is deterministic. **IT IS NOT**

Quantum Mechanics ➔ Probability of photon absorption ~ Image Intensity

$\rho_{Acid}(\vec{r},t)$ should be interpreted as a probability

Probability of a PAG to release an acid at position $\vec{r} = \left(1-e^{-CE(\vec{r})}\right)$

Probability of a PAG not to release an acid at position $\vec{r} = e^{-CE(\vec{r})}$

Let $a=1 \Leftrightarrow$ acid released

$a=0 \Leftrightarrow$ acid NOT released

Probabitity distribution for an acid to be generated at $\vec{r}$

$$P_{acid}(\vec{r},a) = \delta_{a,1}\left(1-e^{-CE(\vec{r})}\right) + \delta_{a,0}e^{-CE(\vec{r})}$$

Net probability distribution

$$P_{acid}^{net}(\vec{r}_1,a_1,\vec{r}_2,a_2,\cdots,\vec{r}_N,a_N) = P_{acid}(\vec{r}_1,a_1)P_{acid}(\vec{r}_2,a_2)\cdots P_{acid}(\vec{r}_N,a_N)$$

Need to combine the acid release distribution with the PAG location probability distribution

Consider N PAG molecules uniformly distributed throughout the resist volume

Each PAG can be anywhere with volume V

$$\Rightarrow \text{Probability distribution for one PAG} = \frac{1}{V}$$

$$\Rightarrow \quad \text{Joint probability distribution for all } N \text{ PAG's} = P_{PAG} = V^{-N} = \left(AT\right)^{-N}$$

$N =$ the total number of PAG molecules loaded into the resist volum $V = AT$

$$\Rightarrow \quad \rho_{PAG}\left(\vec{r},0\right) = \frac{N}{V} = \frac{N}{AT}$$

LER Model

Result: $\sigma_{LER} = \sqrt{\left(\frac{1}{\rho_{PAG}}\right)\left(\frac{1}{\alpha Q v}\right)^2 \frac{\int_V d^3r'\rho_D\left(\vec{r}_s - \vec{r}'\right)^2\left(1-\exp[-\alpha Q v E(\vec{r}')] - \frac{\rho_{Base}}{\rho_{PAG}}\right)}{\left(\int_V d^3r'\rho_D\left(\vec{r}_s - \vec{r}'\right)\partial'_{\perp}E(\vec{r}')\exp[-\alpha Q v E(\vec{r}')]\right)^2}}$

Put all the pieces together….do the math to get ***approximate*** scaling law……

$$\underbrace{\underset{\substack{\uparrow\\\text{LER}}}{\sigma_{LER}} \approx \underset{\substack{\uparrow\\\text{Constant}}}{c}\left(\frac{I}{\partial I}\right)_{edge}\sqrt{\frac{1}{\rho_{PAG}\alpha Q v \underset{\substack{\uparrow\\\text{Dose}}}{E_{size}} \underset{\substack{\uparrow\\\text{“Blur “}}}{R^3}}}}_{\text{RLS Tradeoff}}$$

$I =$ Image Intensity

$E = I \times t_{\text{exposure}} =$ Dose

$\alpha =$ Absorptivity

$Q =$ Quantum Efficiency

$R = \sqrt{Dt} =$ PEB Diffusion Range

↖Intrinsic Resist “Blur”

$v =$ Photon - Acid interaction volume

$\rho_{PAG} =$ #PAGs/volume

Also get…

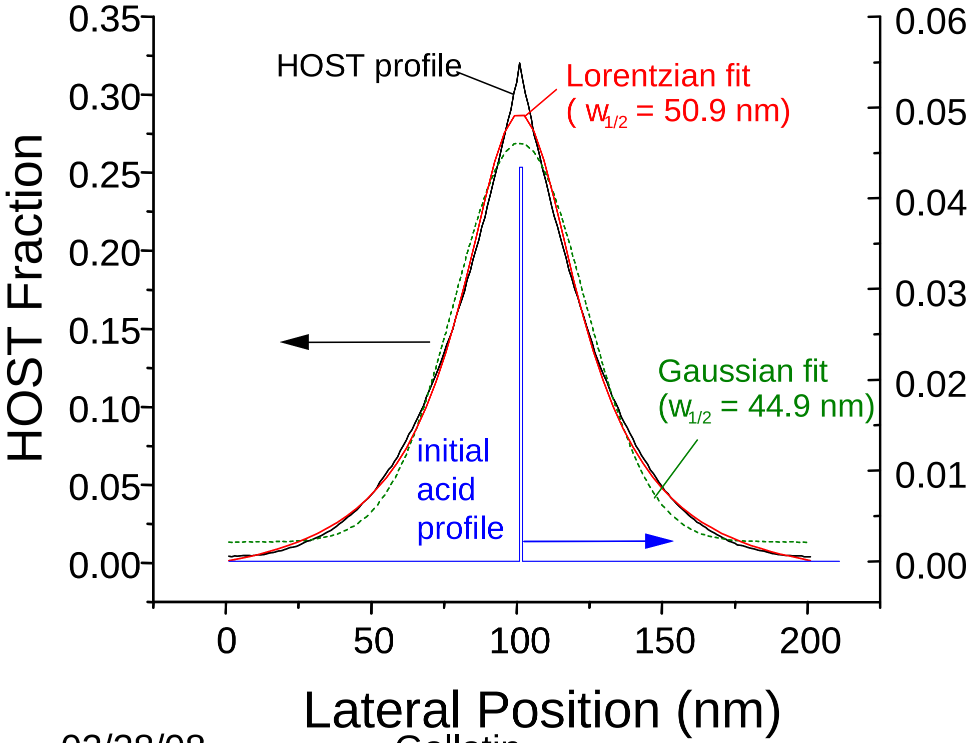
- The explicit analytic form for the deprotection distribution around a released acid.
- The spatial frequency content (on average) of the roughness.

Evaluate 1D result

- Matches full numerical simulation Hinsberg, et. al, SPIE 03
- And experimental shape Hoffnagle, Opt. Letts. 02

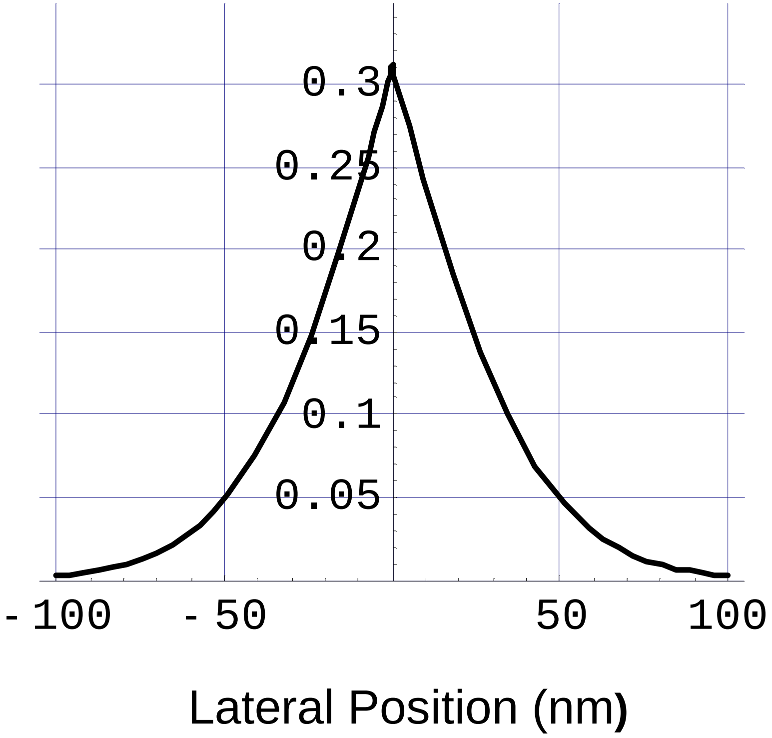
Numerical Chemical Kinetics Result

1D Simulation



1D Analytic Form

~ Area integral of full 3D form



LER Model → Analytical form of the PSD

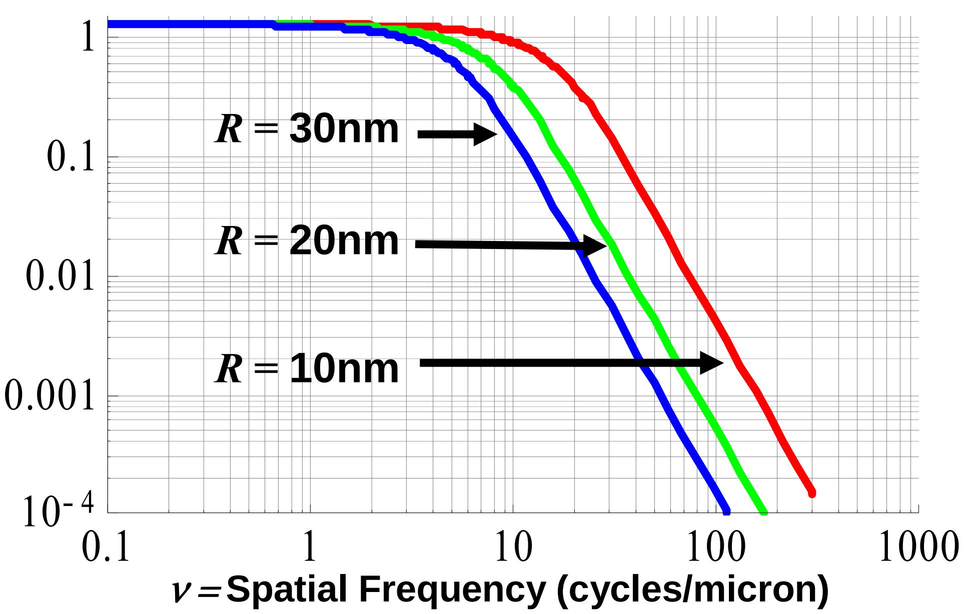
Formula below is valid for small *k*. For large *k*, compute PSD perturbatively for an analytic solution or do the integral numerically.

$$PSD(\beta) = norm \times \underbrace{\frac{1}{(R\beta)^3}\left[\begin{array}{l} 2(R\beta)e^{-2(R\beta)^2}\left(\sqrt{2\pi} - 2\sqrt{\pi}e^{(R\beta)^2}\right) \\ + 2\pi\left(1 - 2(R\beta)^2\right)erf(R\beta) \\ + \pi\left(4(R\beta)^2 - 1\right)erf\left(\sqrt{2}R\beta\right) \end{array}\right]}_{\text{PSD “shape”: Depends only on } R\beta = R2\pi\nu}$$

Normalization factor ~ $\sigma_{LER}{}^2$

Can determine resist parameters from roughness data

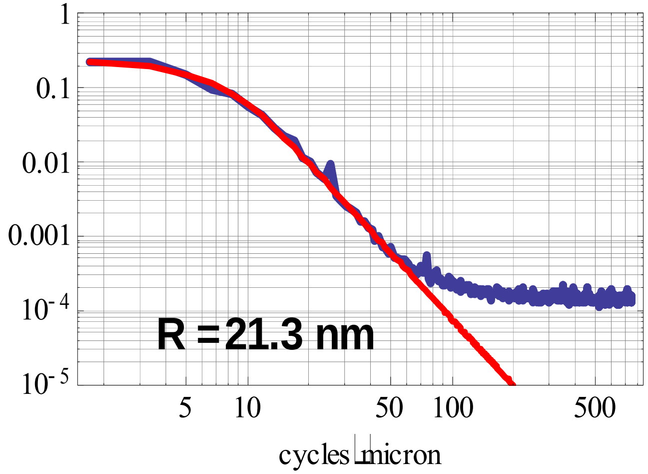
- rms roughness → σ_{LER} → *norm*
- Intrinsic resist “blur” *R* is determined by fitting the analytic PSD “shape” to |FFT(data)|^2 / *norm*



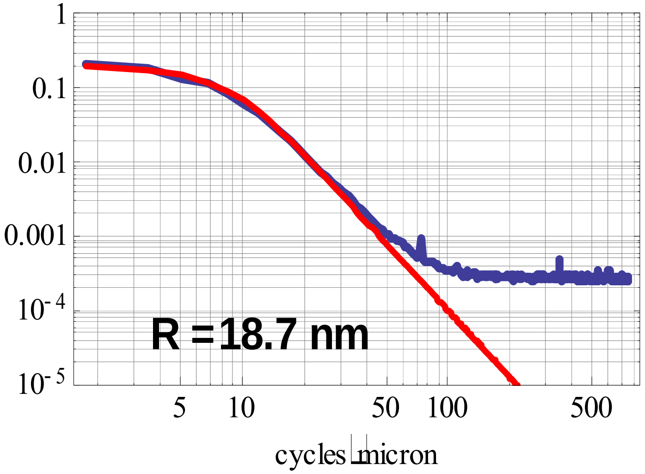
Lowest Dose

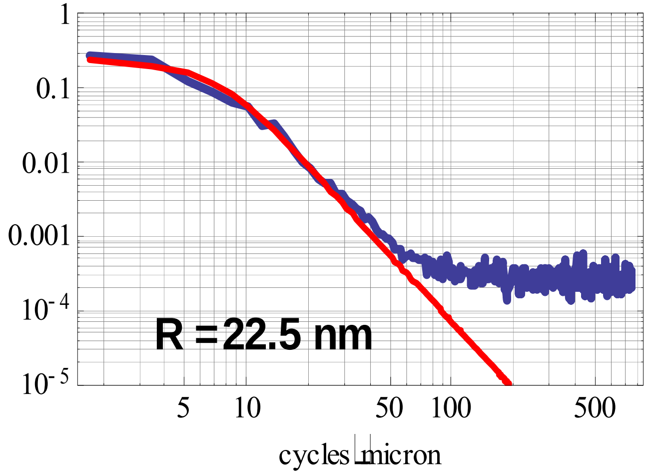
5435
EUV2D

Highest Dose

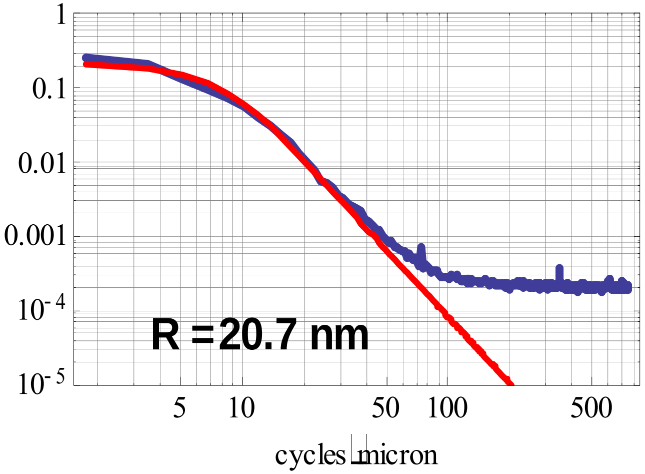


60 nm





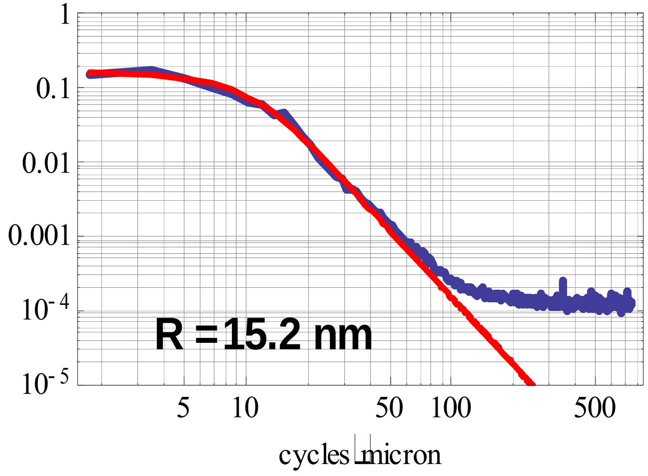
50 nm



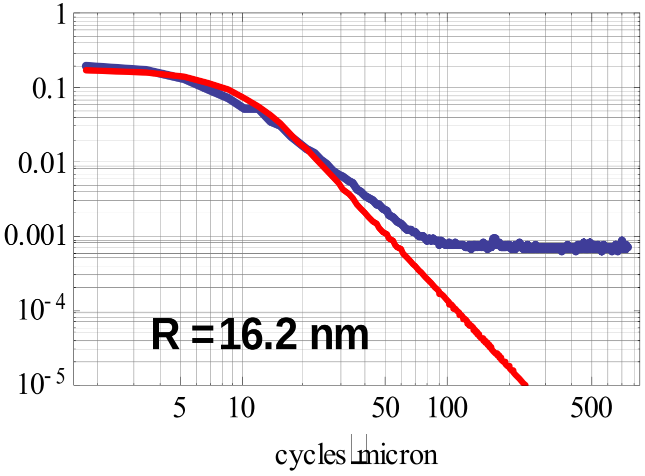
5271 MET2D

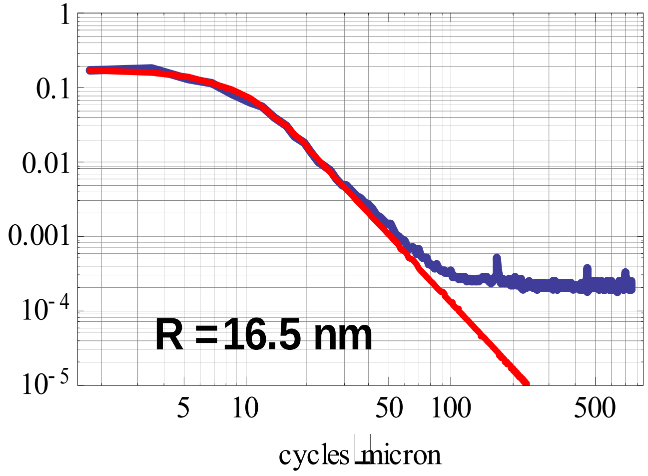
Lowest Dose

Highest Dose

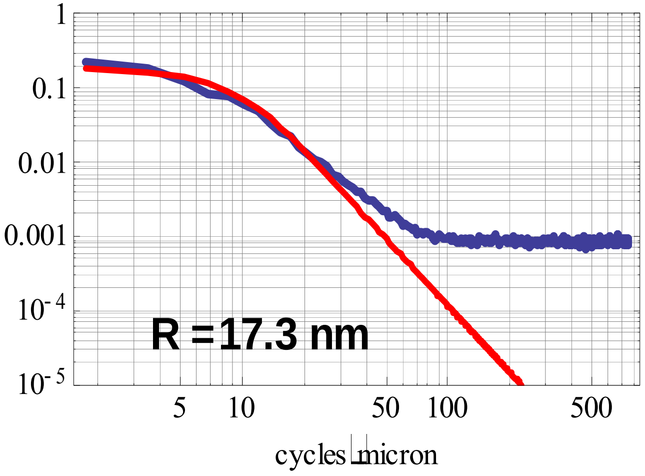


60 nm





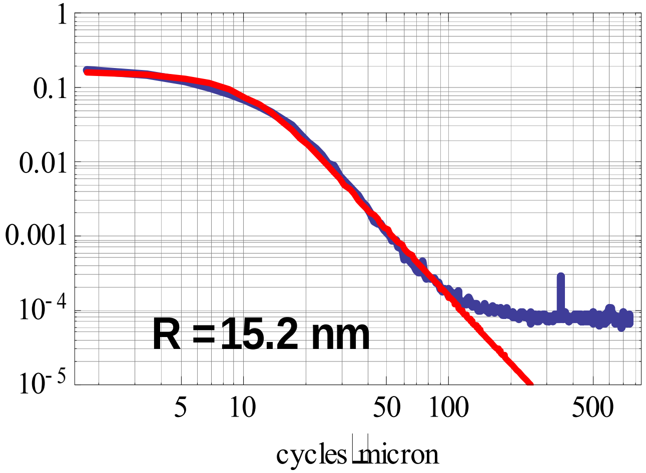
50 nm



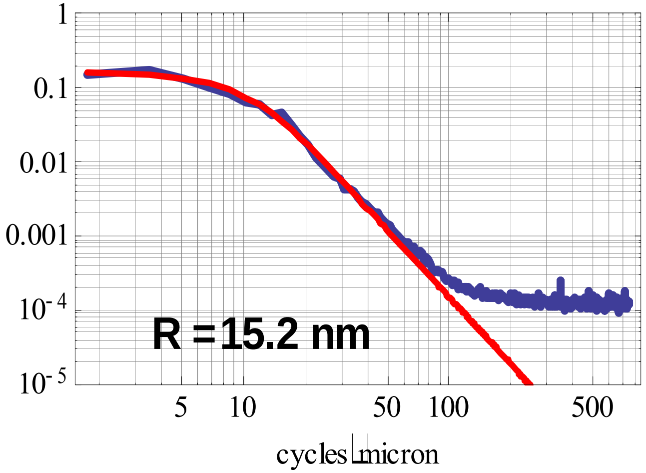
Lowest Dose

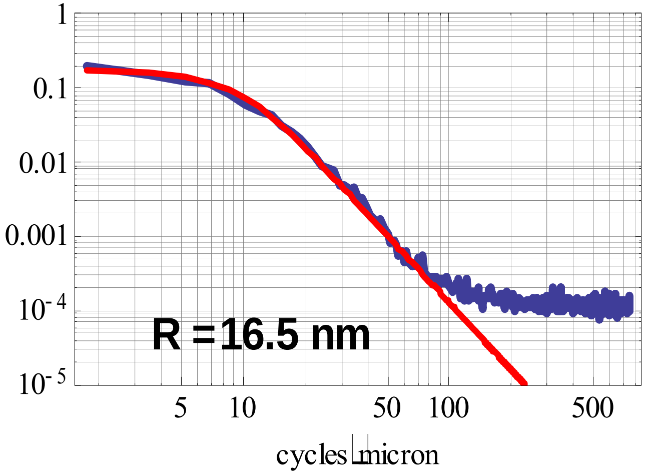
5496

Highest Dose

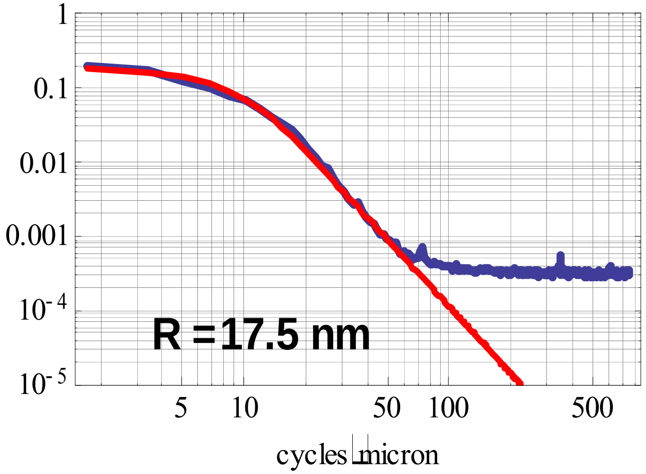


60 nm





50 nm

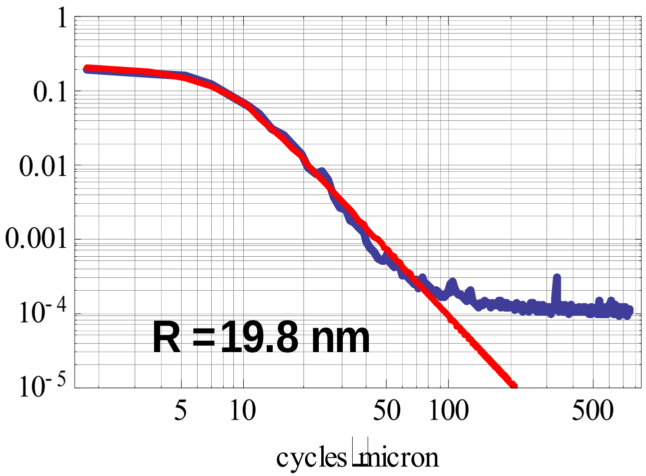


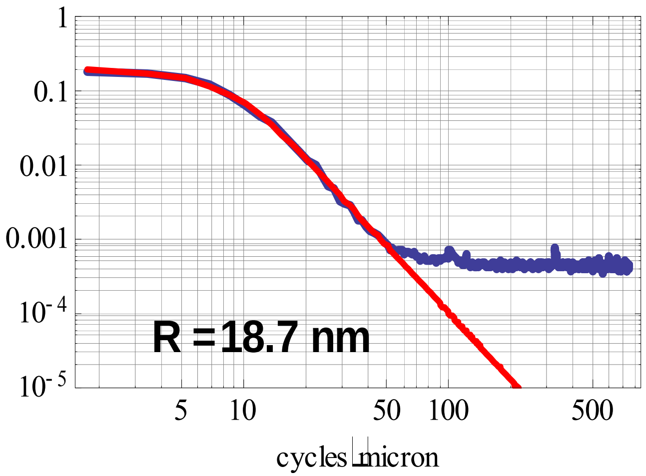
EH

Lowest Dose

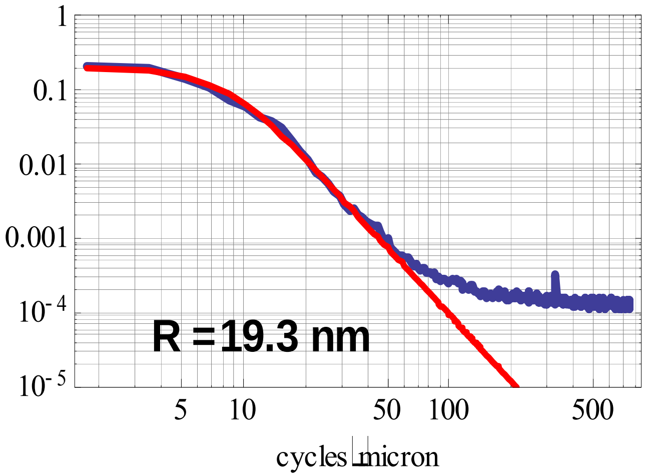
Highest Dose

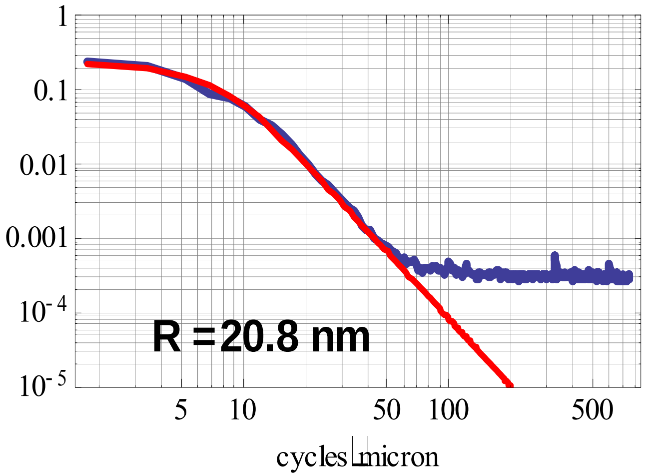
60 nm





50 nm



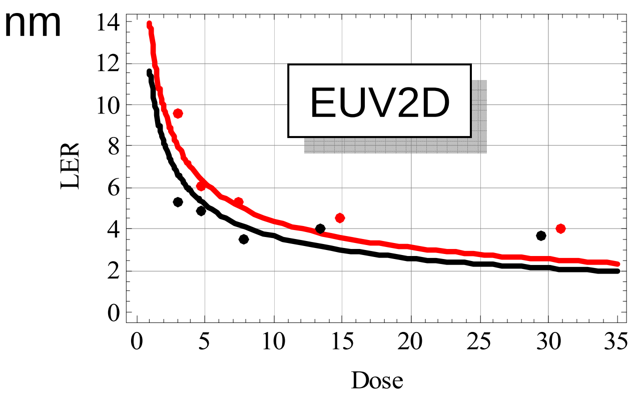


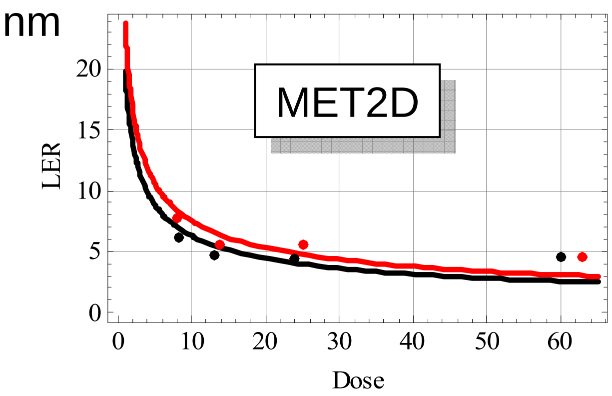
LER Data Compared to the Scaling Law

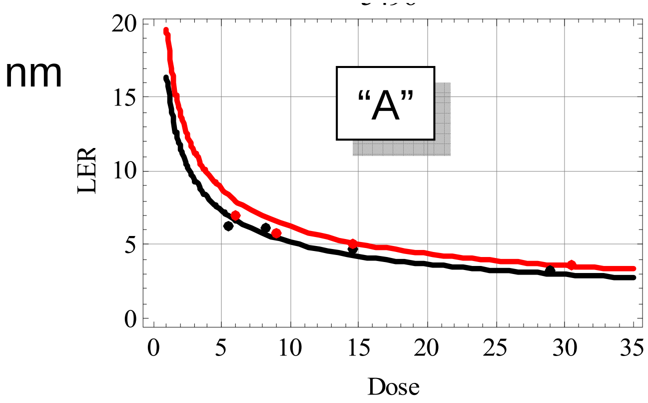
$$\sigma_{LER} \approx c \frac{1}{ILS}\sqrt{\frac{1}{\rho_{PAG}\,\alpha\, Q\, v\, E_{size} R^3}}$$

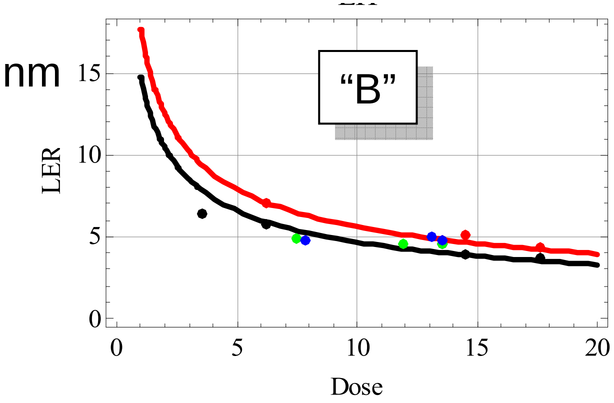
$$c \approx 2$$

Red = 50 nm dense L/S
Black = 60 nm dense L/S
Dots = data, Curve = model using measured values of ILS, PAG density, Dill-C, Dose, Blur,….





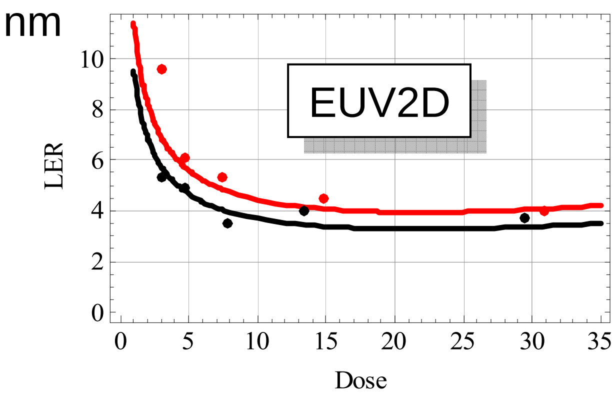


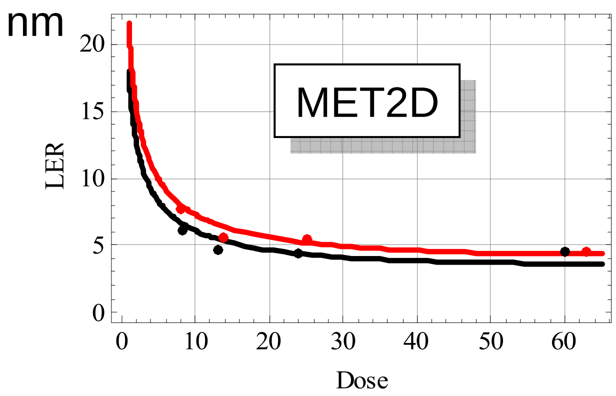


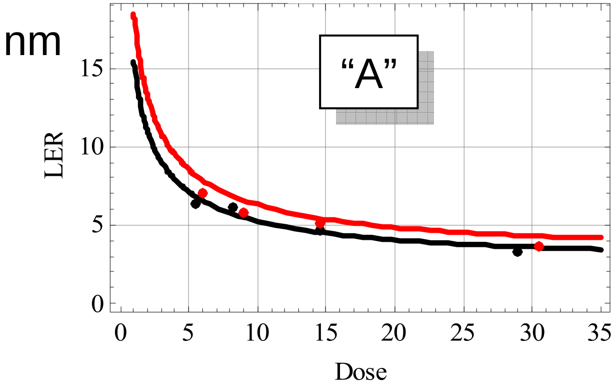
LER Data Compared to the Scaling Law with Saturation Effects Included

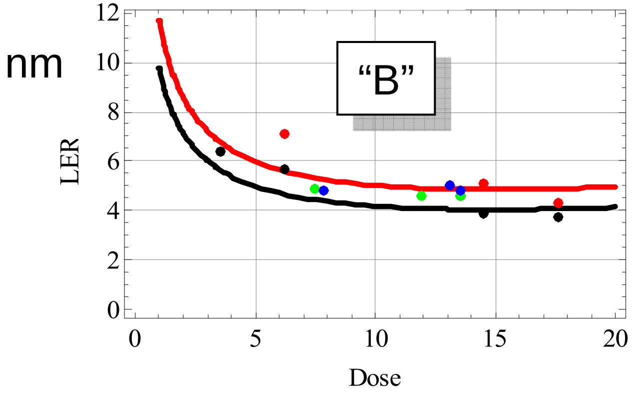
$$\sigma_{LER} \approx c \left(\frac{I}{\partial I}\right)_{edge} \sqrt{\frac{1}{\rho_{PAG}\alpha Q v E_{size} R^3 e^{-\alpha Q v E_{size}}}}$$

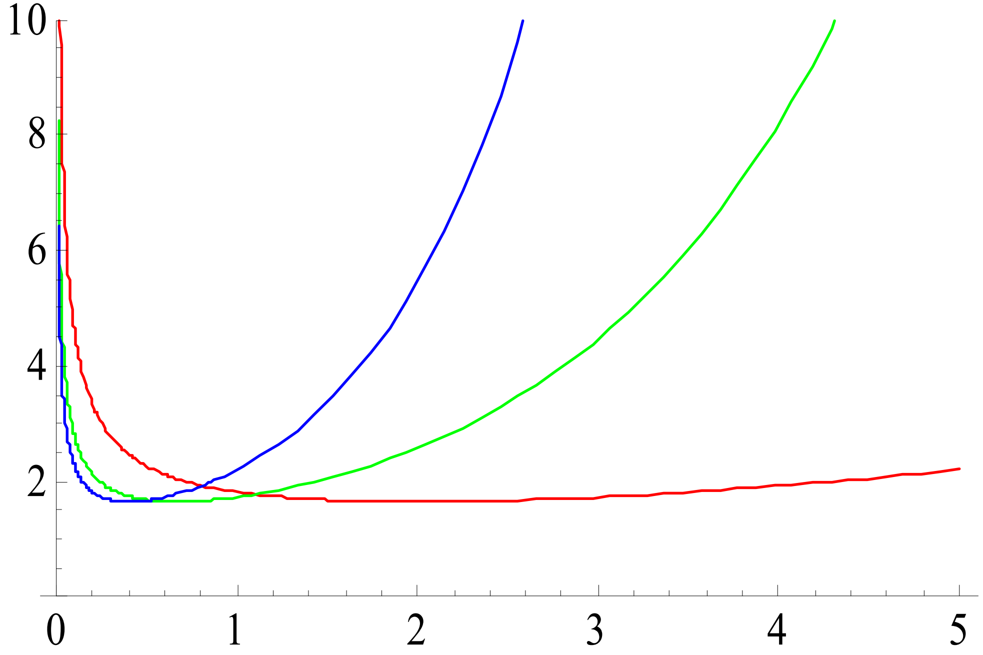
$$c \approx 1.5$$










10
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