“Shot Noise”

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

Exposure tool fixes exposure dose over mm² areas

\( N \) is fixed in mm² areas

Any single feature lives in an area \( a \sim \text{micron}^2 \)

\( \Rightarrow a \ll A \)

Probability for releasing a fixed number of acids

\[
P(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_N) = P(\vec{r}_1)P(\vec{r}_2)\cdots P(\vec{r}_N)
\]

Probability of getting \( n \) acids in area \( a \ll A \)

\[
P_n(a \ll A) = \text{Poisson}
\]

"Shot noise for free"

Consistent with quantum mechanics

\( \Rightarrow \) 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

**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

**Grayscale plot net deprotection density**

Net Deprotection Density = Sum of “blurs” around each acid

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

Development

Resist edge with low spatial frequency content = LER

Burns, et al., JVST B 2002
**Exposure**

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

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

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

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

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

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

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

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

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

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

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

Quantum Mechanics ➔ **Probability** of photon absorption ~ Image Intensity

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

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

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

Let \( a = 1 \iff \text{acid released} \)

\( a = 0 \iff \text{acid NOT released} \)

Probability 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

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

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

\[ \Rightarrow \text{Joint probability distribution for all } N \text{ PAG's} = P_{PAG} = V^{-N} = (AT)^{-N} \]

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

\[ \Rightarrow \rho_{PAG}(\hat{r},0) = \frac{N}{V} = \frac{N}{AT} \]
LER Model

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

Put all the pieces together….do the math to get \textit{approximate} scaling law……

\[ \sigma_{LER} \approx c \left( \frac{I}{\partial I} \right)_{edge} \sqrt{\frac{1}{\rho_{PAG} \alpha Qv E_{size} R^3}} \]

- \( I = \text{Image Intensity} \)
- \( E = I \times t_{\text{exposure}} = \text{Dose} \)
- \( \alpha = \text{Absorptivity} \)
- \( Q = \text{Quantum Efficiency} \)
- \( R = \sqrt{Di} = \text{PEB Diffusion Range} \)
- \( \rho_{PAG} = \#\text{PAGs/volume} \)
- \( \rho_{Base} = \text{Intrinsic Resist “Blur”} \)
- \( v = \text{Photon - Acid interaction volume} \)

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

HOST Fraction

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<th>0.05</th>
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<th>0.20</th>
<th>0.25</th>
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**1D Analytic Form**

~ Area integral of full 3D form

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<th>50</th>
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<tbody>
<tr>
<td>HOST Fraction</td>
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**LER Model** → **Analytical form**

of the PSD

\[
PSD(\beta) = \text{norm} \times \frac{1}{(R\beta)^3} \left[ 2(R\beta)e^{-2(R\beta)^2} \left( \sqrt{2\pi} - 2\sqrt{\pi}e^{(R\beta)^2} \right) \\
+ 2\pi(1-(2R\beta)^2)\text{erf}(R\beta) \\
+ \pi(4(R\beta)^2-1)\text{erf}(\sqrt{2R\beta}) \right]
\]

Normalization factor \( \sim \sigma_{LER}^2 \)

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

**PSD “shape”:** Depends only on \( R\beta = R2\pi\nu \)

Can determine resist parameters from roughness data

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

\( 02/28/08 \) 

Gallatin
The diagrams illustrate the impact of different doses on the surface roughness (R) of EUV2D structures. The graphs show the relationship between cycles per micron and the roughness value, with logarithmic scales for both axes.

**Lowest Dose**
- **60 nm**: Roughness R = 21.3 nm
- **50 nm**: Roughness R = 22.5 nm

**Highest Dose**
- **60 nm**: Roughness R = 18.7 nm
- **50 nm**: Roughness R = 20.7 nm

In these plots, the red line represents the calculated roughness value, while the blue line indicates the measured roughness. The graphs demonstrate how increasing the dose affects the surface roughness at different scales.
Lowest Dose

5271 MET2D

Highest Dose

R = 15.2 nm

R = 16.2 nm

R = 16.5 nm

R = 17.3 nm

60 nm

50 nm
LER Data Compared to the Scaling Law

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

\[ c \approx 2 \]

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,....

nm

nm

nm

nm

EUV2D

MET2D

"A"

"B"
LER Data Compared to the Scaling Law with Saturation Effects Included

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

\[ c \approx 1.5 \]