More on Stochastics and the Phenomenon of Line-Edge Roughness

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34th International Photopolymer Science and Technology Conference
Chiba, Japan, June 28, 2017
Conclusions

• We need more than just $3\sigma$ to understand roughness
  – We need the power spectral density (PSD) to understand the relationship between LWR and LCDU

• Using biased roughness can be very misleading
  – We need to measure the unbiased roughness

• After litho, resist blur = correlation length

• There is an optimum resist blur for stochastics

• New simple model predicts the optimum resist blur and the scaling of minimum LER
Randomness in Lithography

- Photon count
- PAG positions
- Absorption/acid generation
- Polymer chain length
- Blocking position
- Reaction-diffusion
- Dissolution
The Importance of Correlations

• **White noise**: uncorrelated, each random event is independent
  – Photon shot noise, absorption, chemical concentration, acid generation
  – Produces a flat power spectral density (PSD)

• **Correlating mechanisms**: random events that are not independent
  – Secondary electron generation, acid generation, reaction-diffusion, development front propagation
  – Lowers (smooths) the PSD on length scales below the correlation length (i.e., high frequency roughness)
Are these edges different?
All have the same $3\sigma$ roughness!

Knowing the roughness standard deviation is **not good enough**

$L = 512 \Delta x, \sigma = \text{fixed}$
The Power Spectral Density

PSD = variance per increment of frequency

1/f
What Gives the PSD its Shape?

Uncorrelated white noise

Acid diffusion

Correlation Length

PSD (nm$^3$) vs. Frequency (1/nm)
The Power Spectral Density

\[ \text{Variance} = \text{area under the curve} \]

\( (\text{Derived from other three parameters}) \)

Correlation Length \( \xi \)

\[ \frac{1}{2\pi \xi} \]

Slope \( \propto \) roughness exponent \( H \)

PSD(0)
The Same $3\sigma$, but Different PSDs

$\xi = 10 \Delta x$
$H = 0.5$

These PSDs will have different device feature impact

$\xi = 100 \Delta x$
$H = 0.5$
Example 1: Does etch reduce roughness?

• Experiment: Measure roughness before and after etch
  – 3s roughness (for long lines) goes down
  – What happens to device features?

• We need to look at unbiased PSDs to understand the impact of etch on roughness
  – Does PSD(0) change?
  – How much does etch increase correlation length?
Before and After Etch: a biased view

Biased LWR Before Etch: 4.9 nm
Biased LWR After Etch: 3.6 nm

27% reduction

Biased PSD(0) is 12% lower
Before and After Etch: an unbiased view

Unbiased LWR Before Etch: 3.5 nm
Unbiased LWR After Etch: 2.6 nm

26% reduction

Etch increases the correlation length (7nm → 13nm)

Unbiased PSD(0) is unchanged

With Noise Subtraction

PSD (nm$^3$)

Frequency (1/nm)
Does Etch Reduce Roughness?

• Biased measurement, without noise subtraction, gives a false picture since after etch SEM images generally have lower noise

• Only unbiased PSD measurement (after noise subtraction) gives you the right picture
  – In this example, etch increased the correlation length, but did not lower PSD(0)
  – Within-feature roughness will decrease due to etch, but LCDU will remain the same
Finite-Length Features

\[ \sigma_{LWR}(L) \quad \text{Within-feature roughness} \]

LCDU: Feature-to-feature variation of mean CD
(local CDU)

\[ \sigma_{CDU}(L) \]
Conservation of Roughness

• For all features of the same CD and pitch, for any length $L$,

$$\sigma^2_{CDU}(L) + \sigma^2_{LWR}(L) = \sigma^2_{LWR}(\infty)$$

• Different line lengths partition the total roughness into within-feature and feature-to-feature variation

$$\sigma^2_{CDU}(L) \approx \frac{PSD(0)}{L} \left[1 - \frac{\xi}{L}\right] \quad \sigma^2_{LWR}(\infty) \approx PSD(0) / [(2H + 1)\xi]$$
Conservation of Roughness

We need to measure $\sigma(\infty)$, PSD(0), and $\xi$ to understand roughness for device features.
Measuring Roughness is Hard

• We need to measure the PSD parameters to understand how roughness impacts device features (LWR and LCDU)

• SEM images contain both random and systematic errors that bias our results
  – Random noise in the image produces white noise
  – Systematic field variations (intensity, distortion) increase the apparent low-frequency roughness

• Conclusions based on biased roughness measurements are often wrong
What is the EUV Image?

Here is a typical aerial image from an EUV scanner … or is it?

18nm HP
What is the EUV Image?

EUV image, average over 1nm X 1nm
Dose = 20 mJ/cm²
Line-Edge Roughness (Simple Model)

• Consider a small deviation in resist development rate ($\Delta R$). The resulting change in resist edge position ($x$) will be approximately

$$\Delta x = \frac{dx}{dR} \Delta R$$

• For some random variation in development rate $\sigma_R$, the resulting LER is

$$\sigma_{LER} = \frac{\sigma_R}{dR/dx}$$
Lithography Information Transfer

- Lithography can be thought of as a sequential transfer of information.

Diagram:

1. Design
2. Mask
3. Aerial Image
4. Latent Image
5. Developed Resist Image
6. Etched Image

Steps:
- Mask Fabrication
- Image Formation
- Exposure and PEB
- Development
- Etch
Consider Exposure through Development

• The only source of information is the aerial image
  – Subsequent process steps do not add information
  – It is possible to add noise (increase $\sigma$) and lose information (decrease gradient), but the signal to noise can never improve

$$\sigma_{LER} = \frac{\sigma_R}{dR/dx} \geq \frac{\sigma_m}{dm/dx} \geq \frac{\sigma_h}{dh/dx} \geq \frac{\sigma_{I_{abs}}}{dI_{abs}/dx}$$

• A fundamental limit of LER is the last term in this sequence (you can’t do any better than the information in the image)
What is the LER limit?

• The distribution of the number of absorbed photons ($N_{abs}$) is Poisson

$$\sigma_{N_{abs}} = \sqrt{N_{abs}}$$

• The gradient of absorbed photons is determined by the image log-slope

$$ILS = \frac{d \ln I}{dx} = \frac{1}{N_{abs}} \frac{dN_{abs}}{dx}$$
What is the LER limit?

• The best possible LER is then

$$Best\ Case\ \sigma_{LER} = \frac{\sigma_{I_{abs}}}{dI_{abs}/dx} = \frac{1}{ILS \sqrt{N_{abs}}}$$

• How many photons are absorbed? It depends on the volume $V$ you are looking at:

At the feature edge: $N_{abs} = \alpha VE$

$\alpha = $ resist absorption coefficient
$E = $ dose (#photons/area) incident on the volume
What is the Correct Volume to Average Over?

• Two suppositions about the ambit volume $V$:
• First,

\[ V = \xi^3 \quad \text{where } \xi = \max(\text{polymer size, resist blur}) \]

• Second, after litho: resist blur = correlation length
  – Correlation length comes from measurement of the roughness power spectral density (PSD)
Complication: Blur lowers ILS

• Effective ILS is a function of resist blur

Diffusion: \[ \frac{\partial \ln I_{\text{eff}}}{\partial x} \approx \frac{\partial \ln I}{\partial x} \left( e^{-2(\pi \xi / CD)^2} \right) \]

Reaction-Diffusion: \[ \frac{\partial \ln I_{\text{eff}}}{\partial x} \approx \frac{\partial \ln I}{\partial x} \left( \frac{1 - e^{-2(\pi \xi / CD)^2}}{2(\pi \xi / CD)^2} \right) \]

where \( \xi = \) diffusion length and \( CD = \) half-pitch

Impact of Blur on ILS and LER

$$\text{Best Case } \sigma_{\text{LER}} = \frac{1}{\text{ILS}_{\text{eff}} \sqrt{\alpha E \xi^3}}$$

**Optimum Blur:**

- **Diffusion:** $\xi_{\text{opt}} \approx \frac{\text{CD}}{5}$
- **Reaction-Diffusion:** $\xi_{\text{opt}} \approx \frac{\text{CD}}{3}$

**CD = 15 nm**

![Graph](image-url)
Simple Model: Scaling Relationship

• Using the optimum resist blur,

$$\text{min } \sigma_{LER} \propto \frac{1}{\text{NILS} \sqrt{\alpha ECD}}$$

• This is a mathematical version of the RLS trade-off

• We can always make it worse!
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Thank You

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