Randomness in Lithography

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

Impact of Gradient on LER

\[ \sigma_{LER} = \frac{33}{dm/dx} + 5 \]

\[ \text{LER, nm} \]

Protected Polymer Gradient (dm/dx), 1µm

Line-Edge Roughness (Simple Model)

- Consider a small deviation in resist development rate. The resulting change in resist edge position will be approximately

\[ \Delta x = \frac{dx}{dR} \Delta R \]

- For some variation in development rate \( \sigma_R \),

\[ \sigma_{LER} = \frac{\sigma_R}{dR/dx} = \frac{\sigma_R}{dm/dx} \]

Stochastic View of Exposure + Reaction-Diffusion

- Uncertainty in deblocked polymer concentration:

\[ \left( \frac{\sigma_R}{\sigma_{	ext{DEV}}(\text{DEV})} \right)^2 = \frac{1}{\sigma_{R,\text{blocked}}^2} \left( \frac{\sigma_{R,\text{DEB}}}{\sigma_{R,\text{DEV}}} \right)^2 \left( \frac{2 \sigma_{R}}{\sigma_{R,\text{DEV}}} \right)^2 \left( \frac{\sigma_{R,\text{DEB}}}{\sigma_{R,\text{DEV}}} \right)^2 + \left[ \frac{2 \sigma_{R}}{\sigma_{R,\text{DEV}}} \right]^2 \left( \frac{\sigma_{R,\text{DEB}}}{\sigma_{R,\text{DEV}}} \right)^2 \]

- Deblocking reaction
- Reaction-diffusion
- PAG concentration, exposure
- Photon shot noise

Line-Edge Roughness (A Simple Model)

- Add the finite size of a resist molecule, \( \sigma_0 \)

\[ \sigma_{LER} = \frac{\sigma_0}{dm/dx} + \sigma_0 \]

- What affects the three terms of this model?
  - Molecular size
  - Acid diffusion length
  - Dose
  - Image NILS
  - Others…
Effect of Polymer Size

- As polymer size increases (\(1\)):
  \[
  \sigma_{LER} = \frac{\sigma_m}{dm/dx} + \sigma_0
  \]
  - Solubility of the polymer is a function of the total number of deprotection events associated with that polymer
  - These events are averaged over the volume of one polymer
  - There is an optimum polymer size

Effect of Diffusion

- As diffusion length increases (\(1\)):
  \[
  \sigma_{LER} = \frac{\sigma_m}{dm/dx} + \sigma_0
  \]
  - Smoothing is caused by the diffusion of a catalyst
  - This catalyst diffusion leads to correlation
  - Diffusion also smears away the image

Effect of Dose

- As dose increases (\(1\)):
  \[
  \sigma_{LER} = \frac{\sigma_m}{dm/dx} + \sigma_0
  \]
  - Increasing dose improves the chemical gradient (to a point)
  - Increasing dose reduces uncertainty (to a point)
  - Diminishing returns for higher dose (in fact, there is an optimum), but we are a long ways away from that for EUV

Optimizing LER

- There is an optimum polymer size
  - Current materials are probably close to optimum
- There is an optimum diffusion length
  - Current materials probably diffuse too much
  - Optimum diffusion length scales with feature size
  - There is a dose penalty for lower diffusivity
- There is an optimum dose
  - The best dose is higher than what we now use (definitely true for EUV)

Conclusions

- LER is the ultimate limiter to resolution in optical lithography (for both EUV and 193i)
  - Current best LER results for EUV is not good enough
- A good LER model is needed to optimize resist process and material properties and to find the minimum possible LER
  - Progress is being made, but a predictive LER model does not yet exist
  - How low can LER go? What is the ultimate resolution limit? Will we understand LER before it is too late?

Lecture 67: What have we Learned?

- What are the three terms of our basic LER model?
- How does polymer size affect those three terms?
- How does diffusion length affect those three terms?
- How does dose affect those three terms?