Advanced Issues and Technology (AIT) Modules

Purpose: Explain the top advanced issues and concepts in optical projection printing and electron-beam lithography.

* **AIT-1: LER and CAR**
  AIT-2: Resolution Enhancement and PSM
  AIT-3: Small Features and Defects
  AIT-4: Aberrations
  AIT-5: Maskless, High-NA, Immersion, EUV, Imprint

Each module is a 20-25 min presentation of about a dozen slides.

Suggested reading:
  - Griffin: Plummer, Deal and Chapter 5
  - Wong: 31-45, 55-58, 71-90, Fig 4.1, Fig. 4.10

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What is Line Edge Roughness (LER)?

- Undesirable variations in pattern shape attributed to assignable causes in the lithographic process
  - these variations transfer to the underlying layer
  - They are due to many factors

Williamson, EIPBN 04
III.A. EUV Resolution
MET at ALS

- Results demonstrate that we are currently resist limited, not optic limited

Brainard: VNL
Resist Profile

150 nm scale

Divots and bumps

Gradual linewidth change

By Williamson and used in Yuan SPIE 04
Resist Similar to Mechanical Fracture of Silicon

Cut-Set silicon surface 10 nm rms

After hydrogen anneal 0.1 nm rms
UV210 AFM Top Surface Data

Whole Image
Area Ra: 0.5346 nm
Area RMS: 0.6697 nm
Avg. Height: 2.7095 nm
Max. Range: 5.7202 nm

Partial Image
Area Ra:
Area RMS:
Avg. Height:
Height. Max

Williamson, EIPBN 04

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AFM—Understanding Shape

- AFM data allows a glimpse of roughness 2-D shape.
- Roughness peak:peak spacing is 50 nm while height is 2 nm.
  - Roughness is like “low, rolling hills” with x-y scale much larger than z scale.

Williamson, EIPBN 04
Results– Roughness Collection & Measurement

- LER is measured as variation from a perfectly straight line.
- As aerial image profile degrades, line edge roughness gets larger—worse.

Both are top-down images of developed UVII-HS resist. Top image received best aerial image, bottom image received poorest.

Williamson, EIPBN 04
Results– Image Contrast Correlates with Line Edge Roughness

- For all three resists, correlation was strongest between LER and \( \frac{\text{max-min}}{\text{max+min}} \) contrast
  - LER proportional to \( \text{contrast}^{-0.9} \) in UVII-HS and SEPR-463.
  - Possibly background flare or similar contrast degrading phenomena most responsible for image-induced LER.
  - Data fit standard contrast best, but still significant noise in data

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Williamson, EIPBN 04
Physical Interpretation of 3-Step Process and potential for an acid bottleneck

Electrons $\lambda_1$ => Acid $\lambda_1 \lambda_2$ => Deprotection $\lambda_1 \lambda_2 \lambda_3$

Acid Bottleneck when $\lambda_2 < 1$

$$\frac{\sqrt{VAR}}{AVE} = \frac{\sqrt{1 + \lambda_3 + \lambda_2 \lambda_3}}{\sqrt{\lambda_1 \lambda_2 \lambda_3}} = \sqrt{\frac{1}{\lambda} + \frac{1}{\lambda_1 \lambda_2} + \frac{1}{\lambda_1 \lambda_2 \lambda_3}} = \sqrt{\frac{1}{N_1} + \frac{1}{N_2} + \frac{1}{N_3}}$$

- Noise power contribution from the total number of each species is additive inversely to number of events!
- For 400 electrons, 40 acid and 5,000 deprotections the acid contribution clearly dominates!
- The discrete number of electrons and deprotections do contribute and make the relative variance (0.1664) slightly larger than that from the acid alone (0.158).
- The result agrees with the amplifier noise and gain model described in the text by Oliver Wells

Neureuther, Pease et al., EIPBN 05

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Electrons per Contact Printed

Contacts Cleared

Low slope =>
StDev/AVE = 0.11-.22 => N = 20-80

Requires about 4500 regardless of size! But \( N_{\text{EFFECTIVE}} \) is under 100!

Neureuther, Pease et al., EiPBN 05

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Motivation from Initial Results

- Modeling of sequential processes showed that there is an acid bottleneck for electron beam exposure of chemically amplified resists

\[
Combined = \frac{\sqrt{VAR}}{AVE} = \sqrt{\frac{1}{N_1} + \frac{1}{N_2} + \frac{1}{N_3}} = \sqrt{\frac{1}{400} + \frac{1}{40} + \frac{1}{500}} = 0.172
\]

- Experiments showed that the noise in printing contact holes in IBM-KRS resist was far greater than that of electron arrival. (Top Crust?)
Chemically Amplified Resist (CAR) Profiles

• SEM from Zuniga for 60 sec and 120 sec bake: all exposed areas continue to get wider.
CAR Linewidth vs. Bake Time

Modeling Deep UV Resists: Experimental Evidence of Type II Diffusion

Linewidth (um): Microstepper 248nm NA=0.6 Sigma=0.5 x 10^-3

- Apex-E
- Apex-M
- SNR-248

Type II Diffusion in t-BOC Resists?

Bake Time in Seconds

Marco Zuniga SPIE

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Chemically Amplified Resist Mechanisms

- Photoproduced acid locally deprotects t-BOC that is characterized by a reaction equation.
- In the catalytic process the photoproduced acid moves to new t-BOC sites and its motion is characterized by a diffusion equation.
- The dissociation of the t-BOC material also temporarily increases the free volume locally increasing the diffusivity exponentially.
- Then the dissociated material slowly relaxes and densifies thereby reducing the diffusivity.
- Base quenchers can consume unwanted photoproduced acid in regions lightly exposed by flare.
CAR Resist with Base

\[ \frac{\partial A}{\partial t} = k_r (P_0 - A)H \]  
Deprotection Rate

\[ \frac{\partial H}{\partial t} = -k_l HQ + \nabla(D \nabla H) \]  
Acid loss and acid diffusion rate

\[ \frac{\partial Q}{\partial t} = -k_l HQ \]  
Quencher loss rate

\[ \frac{\partial F}{\partial t} = k_r (P_0 - A)H - k_l F \]  
Free volume generation and elimination rate

\[ D = D_0 \exp\left(\frac{\alpha F}{1 + \nu F}\right) \]  
Diffusivity model

Croffie, SPIE 3999-16

Acid supply may be buffered by Resist Matrix, Seiji Nagahara, SPIE 05

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Simulation Extraction of Resist Parameters in 2D

Sequentially double exposed cross 2D

The sequentially double exposed corner shape determines the type of acid diffusion and enables 2D pattern prediction.

STORM sim. and exp., Lei Yuan
Modeling Chemically-Amplified Resist Systems

- Double Expose Sharp Tip (DEST) resist testing
- NF-Diffusion, quencher and buffered acid models in Storm (Nagahara, NEC)
- Continuous LER Simulation with STORM
- Accurate resist edge location prediction from 2D image

Statistical effects in exposure and deprotection with their impact on lateral dissolution

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Diffusion Calibration via DEST: IBM APEX-E

Yuan, SPIE 2005
Top Surface Effects via DEST: Shipley UV210

UV210 DEST printed on bare silicon (a) SEM (b) STORM-3D simulation

Yuan, SPIE 2005
Stending-Wave Reduction with Reduced non-Fickean Diffusion

(a) (b)

STORM-3D simulation of standing wave effect on DEST assuming (a) Fickian diffusion (b) Reduced non-Fickian diffusion (for same diffusion length).
Substrate Effects via DEST: IBM APEX-E

APEX-E DEST on (a) bare silicon (b) 80A silicon nitride (c) 900A silicon nitride (d) AR3-600 coating with RTC top coating

Yuan, SPIE 2005
Top Surface and Substrate Effects via DEST: Shipley UV210

UV210 DEST (a) on bare silicon (b) on 80A silicon nitride (c) on AR3-600 coating

Yuan, SPIE 2005

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Elimination of Resist Poisoning by Quencher Addition in low-k Processes

• Via-First Dual Damascene Process

Acid Equilibrium Quencher (AEQ) Model

\[ \text{HA} \leftrightarrow \text{H}^+ + \text{A}^- \]

\[ [\text{H}^+] = K_a \frac{[\text{HA}]_{\text{generated}} - [\text{Q}]}{[\text{Q}]} \]

\( K_a \): acid dissociation constant

\( [\text{Q}] \): quencher concentration

Acid Buffering with Quencher Addition

(1) **Salt** (made by neutralization of quencher and photoacid)

\[ R_3N + HA \rightarrow R_3NH^+ + A^- \]

(2) **Photoacid** (works as a weak acid in organic matrices)

\[ HA \rightleftharpoons H^+ + A^- \]

**Acid Equilibrium Quencher (AEQ) Model**

\[ [H^+] = K_a \frac{[HA]_{generated}}{[Q]} - [Q] \]

STORM Modeling by Acid Equilibrium Quencher (AEQ) Model

\[
\frac{d[HA]}{dt} = -K_d [HA] + K_c [H][A] - K_n Q[HA]
\]

\[
\frac{d[H^+]}{dt} = \nabla(D_H \nabla[H^+]) + K_d [HA] - K_c [H][A] - K_l [H^+]
\]

\[
\frac{dQ}{dt} = D_Q \nabla^2 Q - K_n Q[HA]
\]

\[
\frac{dP}{dt} = K_r (1 - P)[H^+]
\]

\[ [A] = [HA]_0 - [HA] \]

- [HA]: inactive photoacid
- [H^+]: free active acid
- [A]: conjugate base
- Q: quencher concentration
- P: deprotected concentration

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