Line edge roughness during plasma etching
LER/CER history

• Line (and contact) edge roughness (LER/CER) became a major IC industry concern with the use of 193 nm (ArF) resists
• Degrades device performance, leakage, yield and reliability
• Countermeasures
  – Litho/etch process optimization
  – Add pattern transfer layer

As dimensions continue to shrink, even this is not adequate

Etched with 248 nm resist
LER = 7.7 nm

Etched with 193 nm resist
LER = 17.1 nm

Etched with 193 nm resist and a:C
LER = 7.8 nm
Overview of mechanisms

• Litho
  – Nonhomogeneous resist film—“soft” and “hard” patches
  – Dimensions (resist thickness and CD) are close to the size of polymer aggregates

• Etch
  – Factors: Ion bombardment, radicals, heat, polymer deposition, but also linewidth and spacewidth seem to matter
  – Ions and radicals attack soft areas in resist mask, creating rough surface and edges that transfer down into underlying films
    – Worse when etching thick films with strong bonds, like SiO2
  – Film stress, adhesion, and stress relief may also play a role
    – Volume expansion from ion implantation into mask
    – Wafer heating and cooling in plasma
    – Polymers deposited on mask and feature sidewalls
LER and “wiggling”

• Line edges may be rough, or lines may wiggle or wander—are these caused by different mechanisms?
  – LER mainly from ions interacting with polymer aggregates?
  – Wiggling mainly from stress relief?

Etched dielectrics:

LER without wiggling

Wiggling without LER
Role of photoresist

- Both 248 nm and 193 nm resists use chemical amplification to make up for the relatively low intensity of DUV light produced by the KrF and ArF lasers.
- Chemically amplified resists form “spongy” walls—photoacid diffusion and catalytic reaction form coiled polymer chains or polymer aggregates, leading to a roughened sidewall when developed.
- The developed resist is nonhomogeneous and likely to be further roughened by the physical and chemical action of plasma etching.

LER evolution:
Single-damascene trench etching

- Resist is heavily distorted by plasma etching
CER evolution:
Dual-damascene via etching

- Resist is heavily distorted by plasma etching
- Dense vias (i.e. overlapping exposure areas) are worse

<table>
<thead>
<tr>
<th>DARC etch</th>
<th>Oxide etch</th>
<th>MSL etch</th>
<th>Oxide etch</th>
<th>Ash</th>
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<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
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Dense via

Iso via
Role of mask dimensions

- LER gets much worse as resist thickness and CD decrease
- Maximum LER spec is expressed as % of drawn CD
- Growing disconnect between requirement and reality
Effect of chiller temperature (MERIE etcher)

- LER degrades at high and low temperatures (minimized at 15-20°C)—evidence of competing mechanisms
  - Resist roughening is reduced as temperature is lowered
  - More attack of cap and barrier films at low temperature

Lateral etching of barrier can occur on a cold wafer
Effect of RF power (MERIE etcher)

- LER degrades at high power (especially when combined with high temperature) and appears to be minimized near 800 W
- Increase in LER at very low power may be caused by overetching from missed endpoint (slow etch rate, weak signal)
Summary

• Line edge roughness is a common and potentially serious problem when patterning 193 nm photoresist

• Both lithography and plasma etching play a role in LER
  – Polymer aggregates in the resist cause it to be susceptible to roughening during both developing and etching
  – Worse as resist is thinner and narrower, or when features are closer together
  – Etching distorts roughness further—ion bombardment, radicals, heat, polymer deposition
  – LER vs. wiggling, and the role of stress

• Modeling of LER/CER will need to account for all of this…
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Goals of IMPACT’s Plasma Team

- Couple models at various scales to understand plasma-surface interaction and predict profile evolution
- Build even stronger interactions between PIs and sponsors
- Key Projects
  - Develop fast algorithms to determine energy and angular distributions of all plasma species
  - Develop fundamental models for plasma-surface interactions
  - Develop predictable profile simulator for etch and deposition processes
Plasma, Surface, and Feature Scale Models

**Particle-in-cell, Monte Carlo collision (PIC-MCC)**
- Energy and angle of all species

**Molecular dynamics (MD) simulations and beam experiments**
- Fundamental surface reactions

**Monte Carlo feature scale model coupling with reactor model**
- Origin of surface evolution

- Couple models at various scales to understand plasma-surface interaction and predict profile evolution

![Image of plasma and feature scale models](image)

**Neutral energy distributions**

**Ion and hot electron density**

2 nm hole in Si etched with 200 eV CF$_2^+$

Resist etched by 150 eV Ar$^+$; VUV; at 100°C

<table>
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<tr>
<th>Energy (eV)</th>
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<td>10 mTorr</td>
<td>500 mTorr</td>
<td>80 mTorr</td>
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</table>

**Low DC**
- Low $W_b$

**High DC**
- Low $W_b$
- High $W_b$
Faculty Presentation: Plasma
Michael A. Lieberman
Emi Kawamura and Ying Wang
Electrical Engineering, UC Berkeley
Electromagnetic Effects

- Electromagnetic effects in capacitive discharges (joint with D. Graves)
Future Milestones

- Develop fast algorithms to determine the energy and angular distributions of energetic ions, fast neutrals, secondary electrons, and photons on the wafer surface.
- Validate with particle-in-cell simulations and/or experiments.
- Provide energy and angular distributions as input to the feature profile simulator.
Faculty Presentation: Plasma
David B. Graves
Joseph Vegh
Chemical Engineering, UC Berkeley
MD Simulated Hole Etched via CF$_3^+$ in Si

- After ~8400 CF$_3^+$ impacts (~2.7x10$^{17}$ cm$^{-2}$)
- C – Red
  F – Green
  Si – White
- Hole contour shown in blue
- Nominal hole depth ~8.4 nm
- Nominal hole width ~2.2-3.2 nm
- Note ‘halo’ of damage around hole ~1 nm thick
Beam Studies of PR Roughness

- Expose sample to controlled fluxes of ions, radicals, photons: beam-exposed samples follow roughness observed in plasmas

Ar$^+$ & VUV Beam

100°C

200 nm
Future Milestones

- Plasma-surface interactions in **nanoscale feature shape evolution**

- Expose low-k dielectrics and photoresist with beams of ions, radicals and photons under vacuum conditions; measure **etch/roughening rates**

- Use **molecular dynamics** simulations to develop insights into how features etch in the presence of depositing and etching precursors
Faculty Presentation: Plasma

Jane P. Chang
John Hoang

Chemical and Biomolecular Eng., UCLA
Results from a Hybrid Model

Reactor Model Plasma Conditions

DOE shows general decrease in etch depth from center to edge

DOE shows general increase in SWA from center to edge

• Calibrated hybrid model explains general trends in SWA and etch depth

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Extension of Feature Scale Model into 3D

- 3-D feature scale modeling finds application in predicting LER
- Estimate 3D surface normal for neutrals and using 2D projections of interface cells in x-y plane and x-z plane
Future Milestones

- Use experimental beam systems to measure the pertinent kinetics parameters, such as sticking and recombination coefficients, etch yields, angular etch dependencies to quantify the etching of SiO$_x$Cl$_y$ films

- Formulate reaction mechanisms to be incorporated in a Monte Carlo simulator to account for surface evolution, especially with competing etching/deposition processes

- Extend the model into 3-D and convert the code to run in parallel using MPI

- Integrate inputs from plasma models, reactor models, and MD simulations to further improve the predictive capability of the profile simulator.