“An Industrial Example of Oxide Etch Process Control and Optimization”

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Jing Yao
Kai Meng
Yi Qian
Agenda

• Plasma Etch Process physics
• Industrial Practices
  – SPC Practice
  – A Process Improvement Experiment
• Proposed DOE and RSM methods
• Process control improvements and recommendations
Layered Wafer Manufacturing Process

• 3 basic operations:
  – Film Deposition
  – Photolithography
  – Etch

• This cycle is repeated to build up various layers in the devices.
Types of Etching

• Etch techniques
  – Wet etch (Isotropic)
  – Dry etch / Plasma etch (Anisotropic)

Anisotropy is critical in submicron feature fabrication!
Plasma Etching Steps

- Plasma etching uses RF power to drive material removal by chemical reaction

- Steps:
  - Formation of active gas species, e.g. \( \text{CF}_4 + e^- \rightarrow \text{CF}_3^+ + \text{F} + 2e^- \)
  - Transport of the active species to the wafer surface
  - Reaction at the surface
    \( \text{SiO}_2 + 4\text{F} \rightarrow \text{SiF}_4 + \text{O}_2 \)
  - Pump away volatile products
Physical vs Chemical Etching

<table>
<thead>
<tr>
<th></th>
<th>Physical Method</th>
<th>Chemical Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanism</td>
<td>Ion Bombardment</td>
<td>Chemical Reaction</td>
</tr>
<tr>
<td>Etch Rate</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Selectivity</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Bombardment-induced damage</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Anisotropy</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

- Industry often uses hybrid technique: physical method to enhance chemical etching
- This gives anisotropic etch profile, reasonably good selectivity, and moderate bombardment-induced damage.
Plasma Etch Parameters

• Gas chemistry
  – Fluorocarbon gases (C$_4$F$_6$, CF$_4$, C$_4$F$_8$, etc)
    Atomic F is active etchant for SiO$_2$
    SiO$_2$ + 4F $\rightarrow$ SiF$_4$ + O$_2$
    Carbon reacts with oxygen to form passivation layer on Si $\rightarrow$ provides selectivity
  – O$_2$: Under certain level, O$_2$ scavenge C in Fluorocarbon, results in higher F concentration $\rightarrow$ Higher etch rate
  – Ar: Ar$^+$ ion beam enhances chemical reaction
Plasma Etch Parameters

- **Pressure**
  - Low pressure reduces ion-neutral collision on sidewalls (lateral etch), enhances anisotropic etching

- **Bias Power**
  - Increase bias power enhances physical bombardment of ions

- **Etch Time**

- **Temperature**
Critical Issues

- Anisotropy
- Selectivity
- Microscopic Uniformity
- Etch Depth
- Critical Dimension (CD)

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Background

• Industry Practices in a DRAM wafer fabrication plant in Singapore

• Current Technology:
  – 95nm 1GB DRAM on 200mm wafers
  – 78nm 1GB DRAM on 300mm wafers

• Information source
  – Interview with process engineer
  – Scaled data based on experiments data
    (actual data unknown)
Focused Output

• Etch Depth
  – Measuring Method
    • Test wafer ONLY!
      – Over-etch on test wafer
      – Cost
    • 5 sites measurement
  – Percentage over-etch on test wafer
    • 20%-60% over-etch on test wafer
    • Selectivity

• Critical Dimension
  – Measuring Method
    • Test or production wafer
    • 5 sites measurement
SPC Practice

- SPC analysis tools are installed in all production machines
  - X-bar chart and R chart

- Different test methods for different outputs
  - Etch Depth
    - Insert test wafer into production lots
    - Infrequent: ~200 hours
    - Increase frequency when special attention needed
  - Critical Dimension
    - Test 1 wafer per lot (25 wafers)
    - 5 sites average
SPC Practice

- Rules: similar to Western Electrical Handbook rules
- UCL/LCL are set by process engineer
  - Based on USL/LSL
  - UCL/LCL are little bit tighter than USL/LSL
  - Tighten UCL/LCL based on experience
  - UCL/LCL are not based on standard deviation!
- Process pass SPC most of the time
- Stop a machine when a measurement is outside UCL/LCL, other rules mostly ignored
- Slow response
SPC Improvement

- Set UCL/LCL based on sample standard deviation
- Use more effective control chart, like CUSUM or EWMA chart, to improve response time
- Use multivariate process control
A Process Improvement Experiment

• Problem
  – Under-etch
  – Discovered by quality assurance from finished products
  – Process improvement is necessary because no issues found on the machine

• Approach
  1. Focus on two inputs ($C_4F_6$ Flow Rate, Bias Power)
  2. Vary inputs one step away from current value
  3. Test with all inputs combinations
  4. Change third input (Time)
  5. Repeat 1 to 3
  6. Find the best result
A Process Improvement Experiment

- 1 wafer, no replicates
- 5 sites average

Goal:
- CD: 100 ± 5 nm
- Etch Depth: 1.4 um with 60%~70% over etch on test wafer [2.25um, 2.4 um]

<table>
<thead>
<tr>
<th>Etch Depth (um)</th>
<th>C4F6 (sccm)</th>
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<tbody>
<tr>
<td>14.5</td>
<td>15</td>
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<tr>
<td>1300</td>
<td>1.72</td>
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<td>1500</td>
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200 sec

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<tr>
<th>CD (nm)</th>
<th>C4F6 (sccm)</th>
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<tr>
<td>14.5</td>
<td>15</td>
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<tr>
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<td>100</td>
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<tr>
<td>1400</td>
<td>110</td>
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<tr>
<td>1500</td>
<td>118</td>
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190 sec

<table>
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<tr>
<th>C4F6 (sccm)</th>
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<tr>
<td>14.5</td>
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<td>15</td>
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<td>1300</td>
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<tr>
<td>1400</td>
</tr>
<tr>
<td>1500</td>
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</table>

sccm : Standard Cubic Centimeters per Minute
A Process Improvement Experiment

- A combination of DOE and OFAT
  - Rely on theoretical study and experience
- Find an optimal based on tested input combinations
- No Response Surface analysis
- No replicates or center points
  - Hard to prove model accuracy
- No variance study
- Confidence Level unknown!
Experimental Design

- **Bias Power and C\textsubscript{4}F\textsubscript{6}**
  - Central composite design
  - 3 levels
- **Etching Time**
  - 2 levels

<table>
<thead>
<tr>
<th>Factor</th>
<th>Actual test levels (coded test level)</th>
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<tr>
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<tr>
<td>X1-Bias Power</td>
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<tr>
<td>X2-C4F6</td>
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<tr>
<td>X3-Etching Time</td>
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</table>
## Run Data

<table>
<thead>
<tr>
<th>Trial</th>
<th>Bias Power</th>
<th>C4F6</th>
<th>Time</th>
<th>Etch Depth (um)</th>
<th>Critical Dimension (nm)</th>
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<tr>
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<td>-1</td>
<td>2.28</td>
<td>100</td>
</tr>
</tbody>
</table>

Note: each run data is the mean of 5 sites average on 1 wafer.
Response Models

• Second order polynomial models
  – models built using coded variables
  – no transformations of output variables attempted

\[ Y = b_0 + \sum_{i=1}^{3} b_i X_i + \sum_{j=i+1}^{3} \sum_{i=1}^{3} b_{ij} X_i X_j + \sum_{i=1}^{3} b_{ii} X_i^2 \]
Model Evaluation

- RSM fitting
  - ANOVA performed
  - Each output model claimed significant at >99.8% confidence level or higher

- Regression coefficients shown for significant terms
Etch Depth

- Response Surface model
  \[ ED = 1.970 + 0.407x_1 - 0.080x_2 + 0.038x_3 + 0.052x_1^2 \]
- Residual

![Residual Plots for Etch Depth](image)

- Normal Probability Plot of the Residuals
- Residuals Versus the Fitted Values
- Histogram of the Residuals
- Residuals Versus the Order of the Data
Etch Depth – Contour Plot

- Etch Depth most sensitive to Bias Power
- Bias Power ↑, or Time ↑, or \( C_4F_6 \) ↓ → Etch Depth ↑
Critical Dimension

- **Response Surface model**
  \[ CD = 101.111 + 7.750x_1 - 6.583x_2 + 1.556x_3 \]

- **Residual**
**Critical Dimension – Contour Plot**

- **CD most sensitive to Bias Power & C₄F₆**
- **Bias Power↑, or Time↑, or C₄F₆↓ → CD↑**
Process Optimization

- Optimization criteria for Oxide etch and the best values attainable within the resulting optimized factor space

<table>
<thead>
<tr>
<th>Factor</th>
<th>Optimization Criteria</th>
<th>Best Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Etch Depth</td>
<td>$2.25 \mu m \leq CD \leq 2.40 \mu m$</td>
<td>$2.25 \mu m$</td>
</tr>
<tr>
<td>Critical Dimension</td>
<td>$100 \pm 5nm$</td>
<td>$100nm$</td>
</tr>
</tbody>
</table>

- Optimal Input

<table>
<thead>
<tr>
<th></th>
<th>X1-Bias Power</th>
<th>X2-C4F6</th>
<th>X3-Etching Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>1487 W</td>
<td>15.48 sccm</td>
<td>190 sec</td>
</tr>
<tr>
<td>Actual</td>
<td>1500 W</td>
<td>15.5 sccm</td>
<td>190 sec</td>
</tr>
</tbody>
</table>
**2³ Full Factorial Design**

- Only consider linear relationships
- Drop other 10 test points (possible test points for lack-of-fit)

<table>
<thead>
<tr>
<th>Trial</th>
<th>Bias Power</th>
<th>C4F6</th>
<th>Time</th>
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</table>
Etch Depth

- Predicted Value \((p<0.01)\)
  \[
  ED = 2.020 + 0.418x_1 - 0.083x_2 + 0.043x_3
  \]
- Residual

![Residual Plots for Etch Depth]

- Normal Probability Plot of the Residuals
- Residuals Versus the Fitted Values
- Histogram of the Residuals
- Residuals Versus the Order of the Data
Critical Dimension

- Predicted Value (p<0.01)
  \[ CD = 100.875 + 8.125x_1 - 6.625x_2 + 1.625x_3 \]

- Residual
DOE Improvement

• Adding replicates at center points
  – Use to assess pure error (‘noise’) as percentage of the response
  – Assess lack of fit

• Use Factorial Design
  – Current practice 18 trails
  – $2^3$ with 4 center points 12 trails
  – $3^{3-1}_{III}$ with 6 center points 15 trails

• Analyze Variation
  – consider variation at the desired value

• Randomize run order
  – Esp. in replicates to minimize the trend
Process Control Recommendations

- **SPC Analysis**
  - Use more effective control chart, like CUSUM or EWMA chart
  - Use multivariate process control

- **DOE and RSM optimization**
  - Adding replicates at center points
  - Use Factorial Design
  - Analyze Variation
  - Randomize run order
Thank You!