Enhanced Chamber Management and Fault Detection in Plasma Etch Processes via SEERS (Self Excited Electron Resonance Spectroscopy)

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Outline

- Background
- SEERS (Self Excited Electron Resonance Spectroscopy)?
- Chamber and Process Monitoring through SEERS
- Minimization of Chamber Wall Condition Dependence
- Summary
Background

- Why real-time process monitoring is necessary?

- Wafer size increase (200mm → 300mm)
- Nanometer-scale Device Era
- Novel Process Scheme

- Uniformity Issues
- Smaller Process Window
- Complicated Device Integration
- High Polymeric Gas Adoption
- Various Process Mix

Demand for process stability is significantly increased!!

Real-time Process Monitoring / Fault Detection

Plasma Monitoring + Tool Parameter Monitoring

Why plasma monitoring is more effective than tool parameter monitoring?
### Some Plasma Monitoring Tools

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Main application</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OES</strong> Optical Emission Spectroscopy</td>
<td>Relative emission intensities of excited species</td>
<td>Endpoint detection</td>
<td>Easy access via sight window</td>
<td>Interpretation needs high level of knowledge</td>
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<td></td>
<td></td>
<td></td>
<td>Different species can be identified.</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Supports process development and analysis</td>
<td></td>
</tr>
<tr>
<td><strong>SEERS</strong> Self Excited Electron Resonance Spectroscopy</td>
<td>RF current at chamber wall</td>
<td>Process monitoring</td>
<td>Provides real plasma parameters (electron density, collision rate...)</td>
<td>Needs access to chamber via passive sensor on ground potential</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Easy handling for process monitoring</td>
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<td></td>
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<td>Supports process and chamber development</td>
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<tr>
<td><strong>Impedance Monitor</strong></td>
<td>RF voltage and current at matchbox</td>
<td>RF maintenance</td>
<td>Easy to understand</td>
<td>Provides only fundamental or some harmonics</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>Monitor truly transferred power to plasma</td>
<td></td>
</tr>
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<td></td>
<td></td>
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<td>Supports chamber development and analysis</td>
<td>Less relation to plasma</td>
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</table>

Impact of chamber wall polymer

No impact of chamber wall polymer

Model based calculation

Less relation to plasma
SEERS (Self Excited Electron Resonance Spectroscopy)

- SEERS (Self Excited Electron Resonance Spectroscopy)?

Equivalent Electric Circuit of Plasma Reactor

- stray capacitance

Matchbox

RF generator

Nonlinearity of Sheath Properties

Harmonics in RF Current

Geometric Resonance

Damping Characteristics

Model-Based Estimation

- Electron Plasma Frequency
- Electron Density

✓ Electron Collision Rate
✓ Power Absorption

International SEMATECH AEC/APC XVI Symposium

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SEERS (Self Excited Electron Resonance Spectroscopy)

- Basic Set-up for SEERS

Coaxial sensor and cable

plasma

rf current

1GHz, 2GS/s
50Ohms input

SEERS algorithm
Parameters
$(n_e, \nu, ...)$

RF Power

peak/dc bias voltage

RF Sensor Probe

OES Port

Viewport modified for SEERS

Measured RF Current

Viewport modified for SEERS

FFT

Fundamental Frequency

Harmonics of Fundamental Frequency

Resonance
Electron Collision Rate vs. Electron Density: Effects of Chamber Idle Time

Electron collision rate is a more sensitive indicator for process drift!!
**Physical Backgrounds to Electron Collision Rate**

**Electron Collision Rate**

- **Depends on the neutral’s density.**
- **Depends on power and gas mixture.**
- **Impact of electrons on chemistry via heating.**
- **Feedback from chemistry via cross sections and relative concentration of species.**

\[
\nu_{\text{eff}} \approx \frac{1.6}{l} \sqrt{\frac{U_{\text{bias}}}{2 \pi m_e}} \left( \frac{8kT_e}{\pi m_e} \right) p \frac{p_k}{p} \sum_k \frac{\sigma_k v_{\text{electron}}}{kT_N}
\]

- **Pressure/Gas Temperature**
- **Stochastic heating**
- **Ohmic heating**

**Electron collision rate can be an universal index of plasma process !!**
Chamber and Process Monitoring through SEERS

- Detection of Extremely Small Changes in Chamber

**Lot A**

![Flickering graph]

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<tr>
<th>Time [s]</th>
<th>1</th>
<th>14</th>
<th>27</th>
<th>40</th>
<th>53</th>
<th>66</th>
<th>79</th>
<th>92</th>
<th>105</th>
<th>118</th>
<th>134</th>
<th>144</th>
<th>157</th>
<th>170</th>
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<tr>
<td>Collision Rate [1/s]</td>
<td>0.00E+00</td>
<td>1.00E+09</td>
<td>2.00E+09</td>
<td>3.00E+09</td>
<td>4.00E+09</td>
<td>5.00E+09</td>
<td>6.00E+09</td>
<td>7.00E+09</td>
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**Lot B**

![Flickering graph]

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**Time-resolved collision rate data for different chamber conditions**

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Chamber and Process Monitoring through SEERS

- Some Tool Parameter Data During Main Etch for Lot A and B

Lot A

Lot B

No Particular Event in Tool Parameters Except for Scattered Points!!

* Scattered Points : Data Acquisition Problem.
Electron collision rate explains trends of thickness !!
⇒ Give us Two Benefits ; Thickness Data for All Wafers, Tight Process Control
A correlation between electron collision rate and trench depth is a bit high!!
Minimization of Chamber Wall Condition Dependence

Current Situations of Chamber A

Major Etching Gas Chemistry:

- **HBr/O2/Cl2 Chemistry**:
  - Total Pressure: 50mT
  - \(x\text{HBr}/y\text{Cl2}/z\text{O2}\) Chemistry: Higher HBr Condition
  - \(x``\text{HBr}/y``\text{Cl2}/z``\text{O2}\) Chemistry: Lower HBr Condition

- **HBr/O2 Chemistry**:
  - Total Pressure: 30mT
  - \(a\text{HBr}/b\text{O2}\) Chemistry: Higher HBr Condition
  - \(a``\text{HBr}/b``\text{O2}\) Chemistry: Lower HBr Condition

Chamber Maintenance:

- Manual Dry Cleaning According to RF Time.
- Before starting main lot, dummy wafers for conditioning are employed.
- In case of some devices, manual dry cleaning is also employed.
- Wet Cleaning Cycle: Around 25 Hour of RF Time
- Criteria for Starting Process after Wet Cleaning: Etch Rate, Particle Number After Chamber Conditioning.

* CF6/Ar chemistry for breakthrough step is common!!

Current Issues:

Strong Chamber Wall Condition Dependence, Heavy Polymeric Particle Issues
Minimization of Chamber Wall Condition Dependence

- Monitoring of Device A

- After wet-cleaning, collision rates of the lot are gradually going up. : Light Pink Arrows.
- Right before wet-cleaning, collision rates of the lot are going down. : Light Green Arrows.
Dry cleaning or different chemistries seems to change the chamber wall conditions a lot. So, it takes several wafers to get back to normal conditions.
Minimization of Chamber Wall Condition Dependence

- Monitoring of Device B

- Collision Rate Higher Than 1E9/sec: Unstable Period, Large Fluctuations
- Collision Rate lower than 4E8/sec: Stable Period, Straight Collision Rate Trends.

What happened between these periods? Two Times Wet Cleaning, HBr Gas Change?
Minimization of Chamber Wall Condition Dependence

- Adoption of In-situ Chamber Cleaning

<table>
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<th>Situations in Chamber A</th>
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<tr>
<td><strong>Previous Maintenance</strong></td>
</tr>
<tr>
<td>• Manual Dry Cleaning According to RF Time.</td>
</tr>
<tr>
<td>• Dummy Wafers for conditioning.</td>
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<tr>
<td>• Wet Cleaning Cycle : Around 25 Hour of RF Time</td>
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* Dry Cleaning Condition : HBr+Cl2+O2+SF6 Chemistry, Chamber Conditioning : HBr+Cl2+O2 Chemistry.

* In-situ Chamber Cleaning (ICC) Condition : SF6 Chemistry

In-situ chamber cleaning might give us benefits; Chamber can be kept clean and wafer-to-wafer(also lot-to-lot) variation can be minimized!!
Minimization of Chamber Wall Condition Dependence

- Effects of ICC on Wafer-to-Wafer Variations

- After adoption of ICC, wafer-to-wafer variations decrease dramatically!!
- Conditioning process after wet cleaning seems to be insufficient.
Minimization of Chamber Wall Condition Dependence

Comparison between Etched Depth Variations: Manual Dry Cleaning vs. ICC

- Dry Cleaning: DEPTH AVG: 5373A/RANGE:240A
- ICC: DEPTH AVG: 5111A / RANGE:105A

Adoption of ICC reduces depth variations by nearly 50%!!
Electron collision rate maintains 1E9~2E9 level for RF time 27 hours.

During this period, process variations are quite small irrespective of RF time.

Can electron collision rate of ICC step be a barometer of wet cleaning period?
Potential Problems by Adoption of ICC

- Frequent Use of ICC ⇒ ESC deterioration by direct exposure to the plasma.

ESC deterioration

1. Rough Surface of ESC.
2. Backside He Leak.

There is a significant demand for optimum ICC conditions!!

How to evaluate effectiveness of ICC?

through a conventional method? or through in-situ plasma monitoring?
Summary

- SEERS (Self Excited Electron Resonance Spectroscopy)
  - Effective way to monitor process plasma under industrial environments.
  - Electron collision rate from SEERS (universal index of plasma process).

- Chamber and Process Monitoring through SEERS
  - Identify extremely small changes in chamber conditions.
  - Strong correlation between mean electron collision rate and etched results.
    (Remain oxide thickness in gate etch: $R^2=0.918$, Etched depth in trench etch: $R^2=0.800$)

- Minimization of Chamber Wall Condition Dependence
  - Classify wafer-to-wafer (also lot-to-lot) variations by monitoring electron collision rate.
  - Deploy all devices in several chambers, based on electron collision rate data.
  - Efficiently confirm effects of in-situ chamber cleaning by using SEERS.