REAL-TIME AND WAFER-TO-WAFER CONTROL STRATEGIES TO ADDRESS SEASONING OF PLASMA REACTORS*

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AGENDA

• Seasoning of plasma reactors
• Approach and Methodology
  • Hybrid Plasma Equipment Model
  • Virtual Plasma Equipment Model
• Si etching in Ar/Cl₂
  • Effect of seasoning reactor walls on etch rates
  • Real-time and run-to-run control of etch rates
• Concluding Remarks
SEASONING OF PLASMA REACTORS

- Deposition on reactor walls during a process changes surface reactivity (e.g., seasoning).

- Seasoning changes reactive fluxes to substrate. To control wafer-to-wafer variability:
  - Clean the seasoned chamber following each wafer.
  - Season the chamber prior to process.

- Seasoning of reactor has been computationally investigated:
  - Accounted for variation of IEDs and reactivity on all surfaces
  - Feedback control implemented to mitigate process drifts.

Ref: E.S. Aydil et al., JES 150, G418 (2003)
HYBRID PLASMA EQUIPMENT MODEL (HPEM)

- **Electromagnetics Module**: Antenna generated electric and magnetic fields
- **Electron Energy Transport Module**: Beam and bulk generated sources and transport coefficients.
- **Fluid Kinetics Module**: Electron and Heavy Particle Transport, Poisson’s equation

- **Plasma Chemistry MC Module**: IEADs to surfaces
- **Surface Chemistry Module**: Surface coverage and reactive sticking coefficients.

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VIRTUAL PLASMA EQUIPMENT MODEL (VPEM)

- VPEM—A platform to investigate real-time-control strategies.
  - Sensor Module: Simulated sensors embedded in HPEM
  - Control Module: Implements programmable control scheme
  - Actuator Module: Based on set-point sensor reading, actuator is reset.
Si ETCHING IN Ar/Cl₂: WAFER SURFACE MECHANISM

- Cl adsorbs on forming SiClₓ passivation layer.

\[
\begin{align*}
\text{Cl}(g) + \text{Si}(s) & \rightarrow \text{SiCl}(s), \quad p=0.99 \\
\text{Cl}(g) + \text{SiCl}_n(s) & \rightarrow \text{SiCl}_{n+1}(s) \quad p=0.2
\end{align*}
\]

- Ions etch passivation (for 200 eV).

\[
\begin{align*}
\text{Cl}^+(g) + \text{SiCl}(s) & \rightarrow \text{SiCl}_2(g), \quad p=0.3 \\
\text{Cl}^+(g) + \text{SiCl}_3(s) & \rightarrow \text{SiCl}_4(g), \quad p=0.6 \\
\text{M}^+(g) + \text{SiCl}_x(s) & \rightarrow \text{SiCl}_x(g) \quad p=0.6
\end{align*}
\]

- Etch products further passivates, creating etch blocks.

\[
\begin{align*}
\text{SiCl}_2(g) + \text{Si}(s) & \rightarrow \text{Si}_2\text{Cl}_2(s) \quad p=0.3 \\
\text{SiCl}_2(g) + \text{SiCl}_n(s) & \rightarrow \text{Si}_2\text{Cl}_{n+2} \quad p=0.1-0.2
\end{align*}
\]

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Si ETCHING IN Ar/Cl\textsubscript{2}: WALL SURFACE MECHANISM

- On chamber walls

\[
\text{SiCl}_2(g) + W(s) \rightarrow \text{SiCl}_2(s) \quad p=0.2
\]
\[
\text{SiCl}_2(g) + \text{SiCl}_2(s) \rightarrow \text{(no reaction)}
\]
\[
\text{M}^+(g) + \text{SiCl}_2(s) \rightarrow \text{SiCl}(s) + \text{Cl}(g) \quad p=0.1
\]
\[
\text{M}^+(g) + \text{SiCl}_2(s) \rightarrow \text{SiCl}_2(g) + W(s) \quad p=0.8
\]

- Passivated walls effect reactivity of Cl.

\[
\text{Cl}(g) + W(s) \rightarrow \text{Cl}(s) \quad p=0.1
\]
\[
\text{Cl}(g) + \text{Cl}(a) \rightarrow \text{Cl}_2(g) + W(s) \quad p=0.1
\]
\[
\text{Cl}(g) + \text{SiCl}_2(s) \rightarrow \text{(no reaction)}
\]
Si ETCHING IN Ar/Cl$_2$

- Seasoning investigated for Si etch products in Ar/Cl$_2$.
- Base case:
  - Ar/Cl$_2$ = 90/10, 100 sccm
  - 15 mTorr, 300 W
  - 75 V bias at 5 MHz
- Silicon etching by chlorine is the source SiCl$_x$.
- Transport of SiCl$_x$ results in deposition (and further sputter/etch) on other surfaces.
Dominant ions are $\text{Ar}^+$ and $\text{Cl}^+$ due to dissociation of $\text{Cl}_2$.

Dominant neutrals are $\text{Cl}$, $\text{SiCl}_2^-$ and $\text{SiCl}_4$.

$\text{SiCl}_2^-$ is potentially reactive with surfaces; $\text{SiCl}_4$ is not.

$\text{Ar}/\text{Cl}_2 = 90/10$, 100 sccm, 15 mTorr, 300 W, 75 V at 5 MHz.
Ion energies on wafer are bimodal, typical of rf sinusoidal biases.

Ion energies on other surfaces peak at time averaged $\Phi_{\text{floating}}$ (38 V).

Quartz nearly always at $\Phi_{\text{floating}}$.

IEADs extend to higher energy on grounded walls (oscillation in $\Phi_{\text{plasma}}$).

Reactivity of wafer and walls differ due to differences in threshold energies and IEDs.

$\text{Ar/Cl}_2 = 90/10$, 100 sccm, 15 mTorr, 300 W, 75 V at 5 MHz.
SEASONING EFFECT: ETCH RATE

- Si etch for 3 min for each wafer.
- Etch rate in seasoned chamber decreases.
- Passivation of walls by SiCl$_2$ decreases further reactivity of SiCl$_2$ increasing density in plasma.
- SiCl$_2$ passivates wafer SiCl$_x$ sites forming Si$_2$Cl$_y$ etch blocks.

\[
\text{SiCl}_2(g) + \text{SiCl}_n(s) \rightarrow \text{Si}_2\text{Cl}_{n+2}(s)
\]
- Ions removes Si$_2$Cl$_y$ with no net contribution to etch rate.
- Rate of change of etch rate decreases with number of wafers; chamber wall conditions stabilize.

- Ar/Cl$_2$=90/10, 100 sccm, 10 mTorr, 300 W, 75 V at 5 MHz

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SEASONED CHAMBER ETCH RATE: VOLTAGE

- Si etch rates decrease with seasoning.
- With additional wafers etch rates stabilize as chamber seasons.
- Etch rate stabilizes sooner at higher voltages.
  - Higher etch rates and more etch products season chamber faster.
  - Larger ion energies remove overlying Si$_2$Cl$_n$ more rapidly.
- In spite of lower reactivity of Cl on walls (and larger Cl in plasma), etch rates decrease due to site blockage.

- Ar/Cl$_2$=90/10, 100 sccm, 10 mTorr, 300 W

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SURFACE COVERAGES: WAFER

- As additional wafers are etched:
  - Flux of etch products to wafer increases.
  - Coverage of etch block, \( \text{Si}_2\text{Cl}_y \) increases.
  - Ions remove etch block, exposing native Si.
  - Chlorination of native Si results in increasing coverage of Si.
- \( \text{Ar/Cl}_2=90/10 \), 100 sccm, 15 mTorr, 300 W.

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REMEDY TO SEASONING: REAL-TIME CONTROL

- Etch rate was controlled using a feedback control loop as the chamber seasons.
- Sensor: Etch rate monitor
  Actuator: Voltage
- Without control:
  - Re-deposition of etch product blocks sites…reduces etch rate.
- With proportional controller:
  - Voltage is generally increased to sputter re-deposition products.
  - Set-point etch rate is restored.

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Run-to-run control was achieved using a proportional controller.

- After each run, a new wafer is used, i.e. coverage of Si is 1.

Bias voltage is not reset to actuator setting from previous run(s).

- Chamber wall conditions lower initial etch rate.
- Initially, aggressive voltage change is required to restore set point etch rate.
- Ultimately, voltage is lowered as high etch rates are enabled by high bias voltage.

\[
\text{Ar/Cl}_2=90/10, 100 \text{ sccm}, 10 \text{ mTorr}, 300 \text{ W}, 100 \text{ V at 5 MHz.}
\]
RUN-TO-RUN CONTROL: ACTUATOR BIAS NOT RESET

• $\beta$ is the normalized rate of change of voltage during each control case.

• At high biases:
  • Aggressive voltage changes makes it difficult to achieve control.
  • High ion flux and low passivating radical flux.
  • Chemical etch transitions to physical etch.
  • Lower $\beta$ maintains Cl radical flux to a significant fraction of total radical flux.

- Ar/Cl$_2$=90/10, 100 sccm, 10 mTorr, 300 W.
RUN-TO-RUN CONTROL: ACTUATOR BIAS RESET

- Etch rate stability was achieved using run-to-run control as the chamber seasons.

- With proportional controller:
  - Bias voltage is reset to actuator setting from previous run.
  - Enables initial high etch rates → bias voltage is lowered
  - As chamber seasons, voltage increases to maintain set point etch rate.

- $\text{Ar}/\text{Cl}_2=90/10$, 100 sccm, 10 mTorr, 300 W, 75 V at 5 MHz.
CONCLUDING REMARKS

• Chamber seasoning was investigated in Si etch using Ar/Cl₂ plasmas.

• Etch rates decreased in a seasoned chamber.
  • Seasoned reactor increases SiCl₂ flux back to wafer.
  • Feedback of etch products (SiCl₂) from the plasma form Si₂Cl₅ etch blocks.
  • Removal of Si₂Cl₅ does not contribute to etch rate.

• Sensors and real-time control will be required to mitigate effects of seasoning.

• Proportional controller algorithm was used to maintain a constant etch rate in both real-time and run-to-run.
  • Sensor: Etch rate monitor
  • Actuator: Bias Voltage