SEASONING OF REACTORS: FEEDBACK CONTROL STRATEGIES TO COUNTER WAFER-TO-WAFER DRIFTS*

Ankur Agarwal\textsuperscript{a)} and Mark J. Kushner\textsuperscript{b)}

\textsuperscript{a)}Department of Chemical and Biomolecular Engineering
University of Illinois, Urbana, IL 61801, USA
aagarwl3@uiuc.edu

\textsuperscript{b)}Department of Electrical and Computer Engineering
Iowa State University, Ames, IA 50011, USA
mjk@iastate.edu

http://uigelz.ece.iastate.edu

60\textsuperscript{th} Gaseous Electronics Conference, October 2007

*Work supported by the SRC and NSF
AGENDA

- Seasoning of plasma reactors
- Approach and Methodology
  - Hybrid Plasma Equipment Model
  - Virtual Plasma Equipment Model
- Si etching in Ar/Cl$_2$
  - 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.

---

Iowa State University
Optical and Discharge Physics
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/Cl$_2$: WAFER SURFACE MECHANISM

- Cl adsorbs on forming SiCl$_x$ passivation layer.

$\text{Cl}(g) + \text{Si}(s) \rightarrow \text{SiCl}(s)$,

$\text{Cl}(g) + \text{SiCl}_n(s) \rightarrow \text{SiCl}_{n+1}(s)$

- Ions etch passivation.

$\text{Cl}^+(g) + \text{SiCl}(s) \rightarrow \text{SiCl}_2(g)$,

$\text{Cl}^+(g) + \text{SiCl}_3(s) \rightarrow \text{SiCl}_4(g)$,

$\text{M}^+(g) + \text{SiCl}_x(s) \rightarrow \text{SiCl}_x(g)$

- Etch products further passivates, creating etch blocks.

$\text{SiCl}_2(g) + \text{Si}(s) \rightarrow \text{Si}_2\text{Cl}_2(s)$

$\text{SiCl}_2(g) + \text{SiCl}_n(s) \rightarrow \text{Si}_2\text{Cl}_{n+2}$

Iowa State University
Optical and Discharge Physics
Si ETCHING IN Ar/Cl₂: WALL SURFACE MECHANISM

- On chamber walls

  \[ \text{SiCl}_2(g) + W(s) \rightarrow \text{SiCl}_2(s) \]
  \[ \text{SiCl}_2(g) + \text{SiCl}_2(s) \rightarrow \text{(no reaction)} \]
  \[ \text{M}^+(g) + \text{SiCl}_2(s) \rightarrow \text{SiCl}(s) + \text{Cl}(g) \]
  \[ \text{M}^+(g) + \text{SiCl}_2(s) \rightarrow \text{SiCl}_2(g) + W(s) \]

- Passivated walls effect reactivity of Cl.

  \[ \text{Cl}(g) + W(s) \rightarrow \text{Cl}(s) \]
  \[ \text{Cl}(g) + \text{Cl}(a) \rightarrow \text{Cl}_2(g) + W(s) \]
  \[ \text{Cl}(g) + \text{SiCl}_2(s) \rightarrow \text{(no reaction)} \]
Si ETCHING IN Ar/Cl₂

- Seasoning investigated for Si etch products in Ar/Cl₂.
- Base case:
  - Ar/Cl₂ = 90/10, 100 sccm
  - 15 mTorr, 300 W
  - 75 V bias at 5 MHz
- Silicon etching by chlorine is the source SiClₓ.
- Transport of SiClₓ results in deposition (and further sputter/etch) on other surfaces.

Iowa State University
Optical and Discharge Physics
Si ETCHING IN Ar/Cl₂: REACTANT FLUXES

- Dominant ions are Ar⁺ and Cl⁺ due to dissociation of Cl₂.
- Dominant neutrals are Cl, SiCl₂ and SiCl₄.
- SiCl₂ is potentially reactive with surfaces; SiCl₄ is not.
- Ar/Cl₂=90/10, 100 sccm, 15 mTorr, 300 W, 75 V at 5 MHz.

Iowa State University
Optical and Discharge Physics
Si ETCH: ION ENERGY ANGULAR DISTRIBUTIONS

- 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.
- 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 SiCl₂ decreases further reactivity of SiCl₂ increasing density in plasma.
- SiCl₂ passivates wafer SiClₓ sites forming Si₂Cl₂ etch blocks.

\[ \text{SiCl}_2(g) + \text{SiCl}_n(s) \rightarrow \text{Si}_2\text{Cl}_{n+2}(s) \]
- Ions removes Si₂Cl₂ with no net contribution to etch rate.
- Rate of change of etch rate decreases with number of wafers; chamber wall conditions stabilize.

- Ar/Cl₂=90/10, 100 sccm, 10 mTorr, 300 W, 75 V at 5 MHz

Iowa State University
Optical and Discharge Physics
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

Iowa State University
Optical and Discharge Physics
SURFACE COVERAGE:
WAFTER

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

Iowa State University
Optical and Discharge Physics
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.

Iowa State University
Optical and Discharge Physics
RUN-TO-RUN CONTROL: ACTUATOR BIAS NOT RESET

- 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.

- Ar/Cl₂ = 90/10, 100 sccm, 10 mTorr, 300 W, 100 V at 5 MHz.

---

Iowa State University
Optical and Discharge Physics
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.
- Ar/Cl₂=90/10, 100 sccm, 10 mTorr, 300 W, 75 V at 5 MHz.

Iowa State University
Optical and Discharge Physics
CONCLUDING REMARKS

- Chamber seasoning was investigated in Si etch using Ar/Cl\textsubscript{2} plasmas.
- Etch rates decreased in a seasoned chamber.
  - Seasoned reactor increases SiCl\textsubscript{2} flux back to wafer.
  - Feedback of etch products (SiCl\textsubscript{2}) from the plasma form Si\textsubscript{2}Cl\textsubscript{y} etch blocks.
  - Removal of Si\textsubscript{2}Cl\textsubscript{y} 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