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

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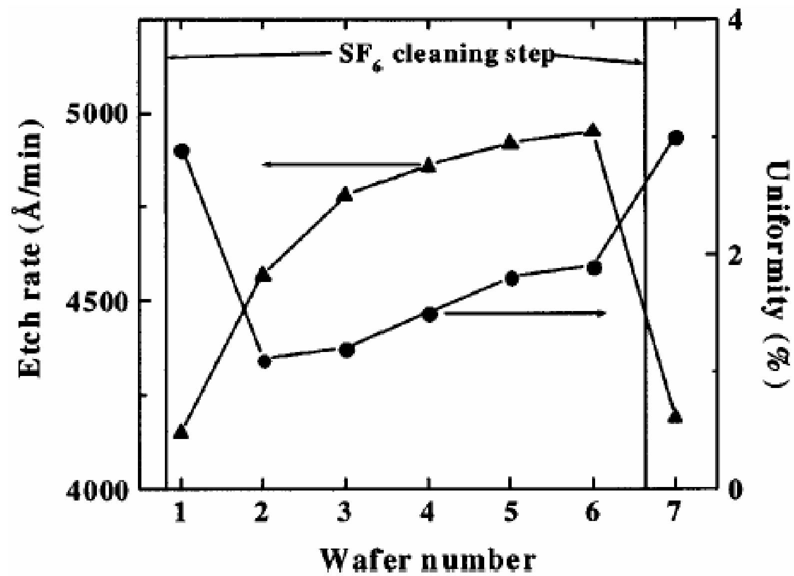
AGENDA

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

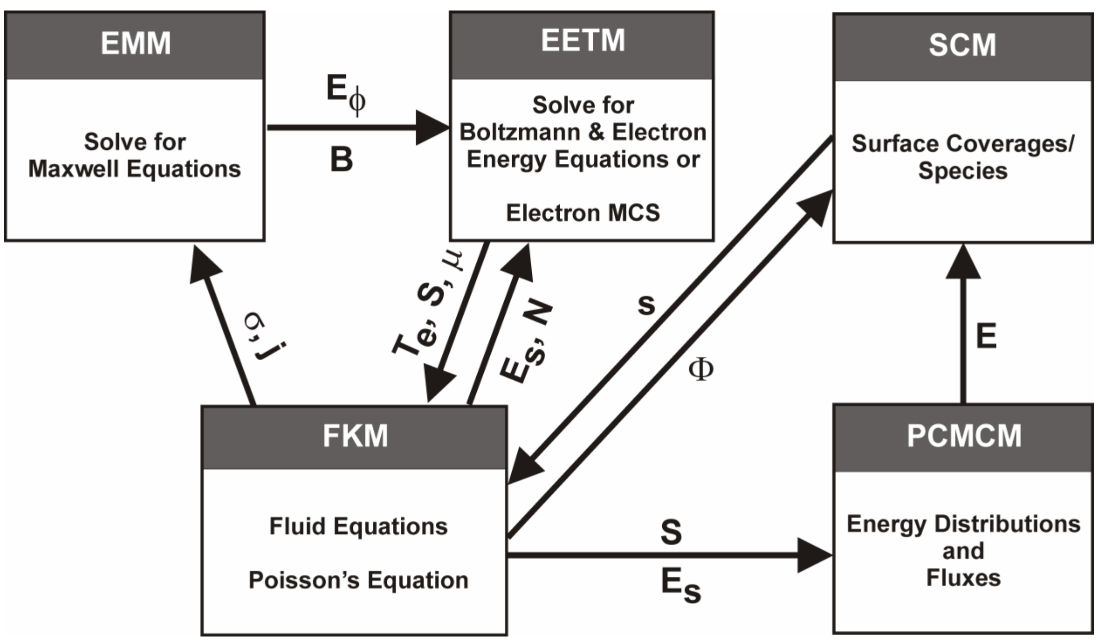


Ref: E.S. Aydil et al., JES 150, G418 (2003)

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

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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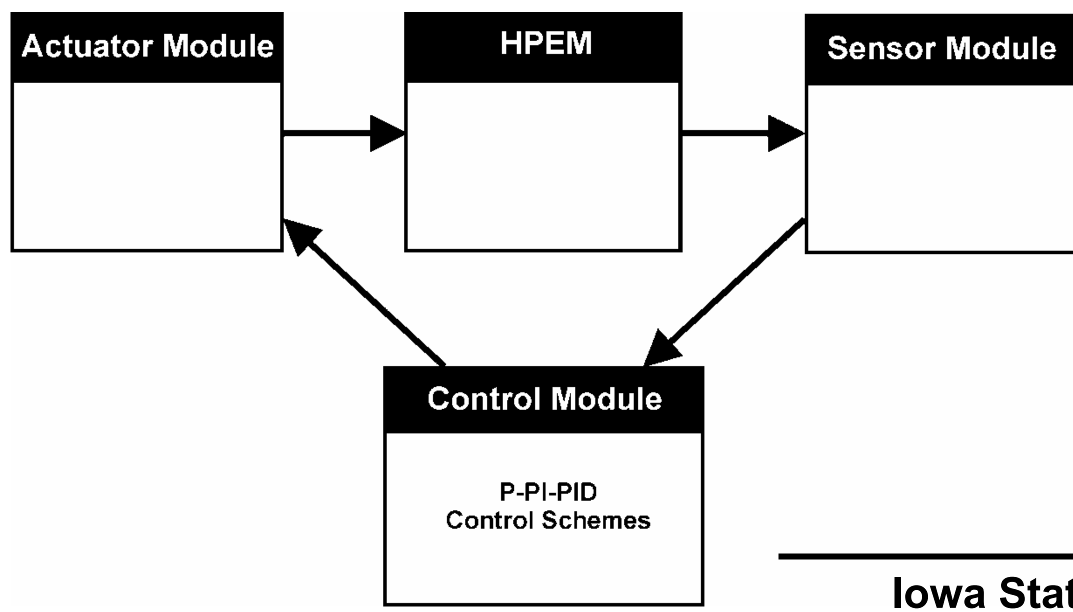
VIRTUAL PLASMA EQUIPMENT MODEL (VPEM)

- **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/Cl_2: WAFER SURFACE MECHANISM

- Cl adsorbs on forming $SiCl_x$ passivation layer.

$Cl(g) + Si(s) \rightarrow SiCl(s)$, p=0.99

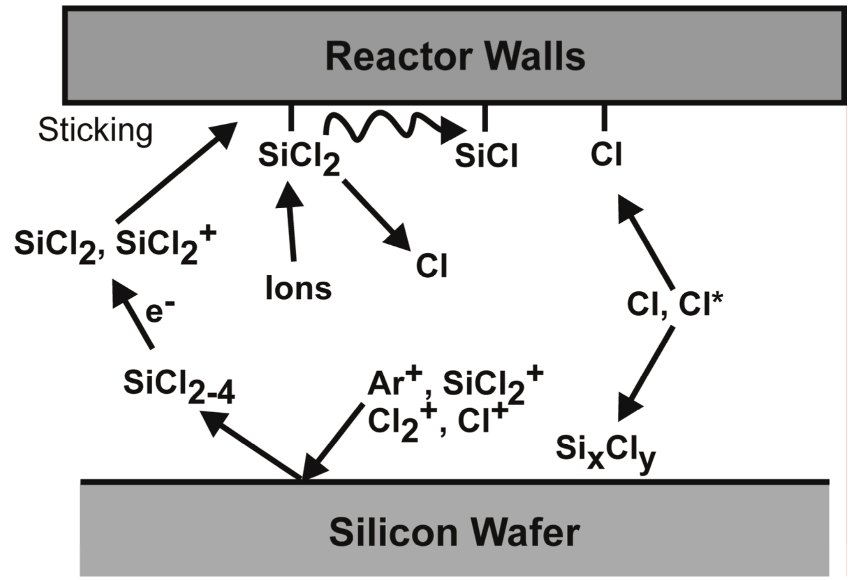
$Cl(g) + SiCl_n(s) \rightarrow SiCl_{n+1}(s)$ p=0.2

- Ions etch passivation (for 200 eV).

$Cl^+(g) + SiCl(s) \rightarrow SiCl_2(g)$, p=0.3

$Cl^+(g) + SiCl_3(s) \rightarrow SiCl_4(g)$, p=0.6

$M^+(g) + SiCl_x(s) \rightarrow SiCl_x(g)$ p=0.6



- Etch products further passivates, creating etch blocks.

$SiCl_2(g) + Si(s) \rightarrow Si_2Cl_2(s)$ p=0.3

$SiCl_2(g) + SiCl_n(s) \rightarrow Si_2Cl_{n+2}$ p=0.1-0.2

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Si ETCHING IN Ar/Cl_2: WALL SURFACE MECHANISM

- On chamber walls

$SiCl_2(g) + W(s) \rightarrow SiCl_2(s)$ p=0.2

$SiCl_2(g) + SiCl_2(s) \rightarrow$ (no reaction)

$M^+(g) + SiCl_2(s) \rightarrow SiCl(s) + Cl(g)$
p=0.1

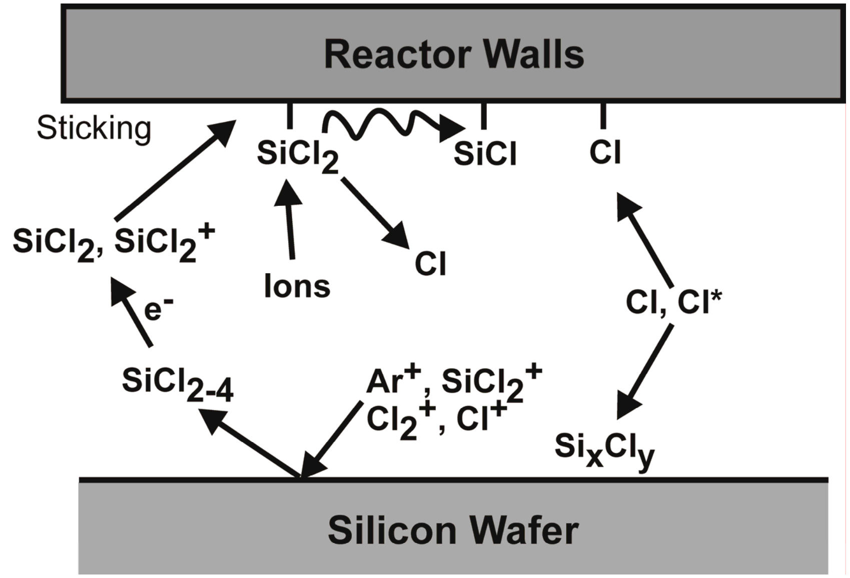
$M^+(g) + SiCl_2(s) \rightarrow SiCl_2(g) + W(s)$
p=0.8

- Passivated walls effect reactivity of Cl.

$Cl(g) + W(s) \rightarrow Cl(s)$ p=0.1

$Cl(g) + Cl(a) \rightarrow Cl_2(g) + W(s)$ p=0.1

$Cl(g) + SiCl_2(s) \rightarrow$ (no reaction)



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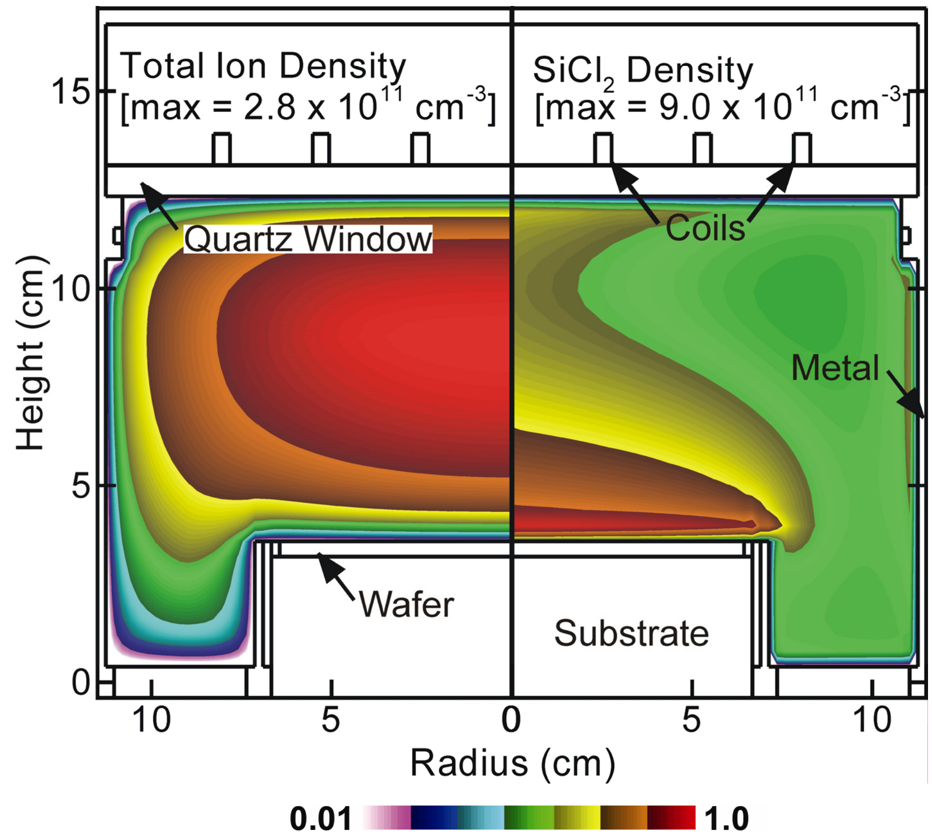
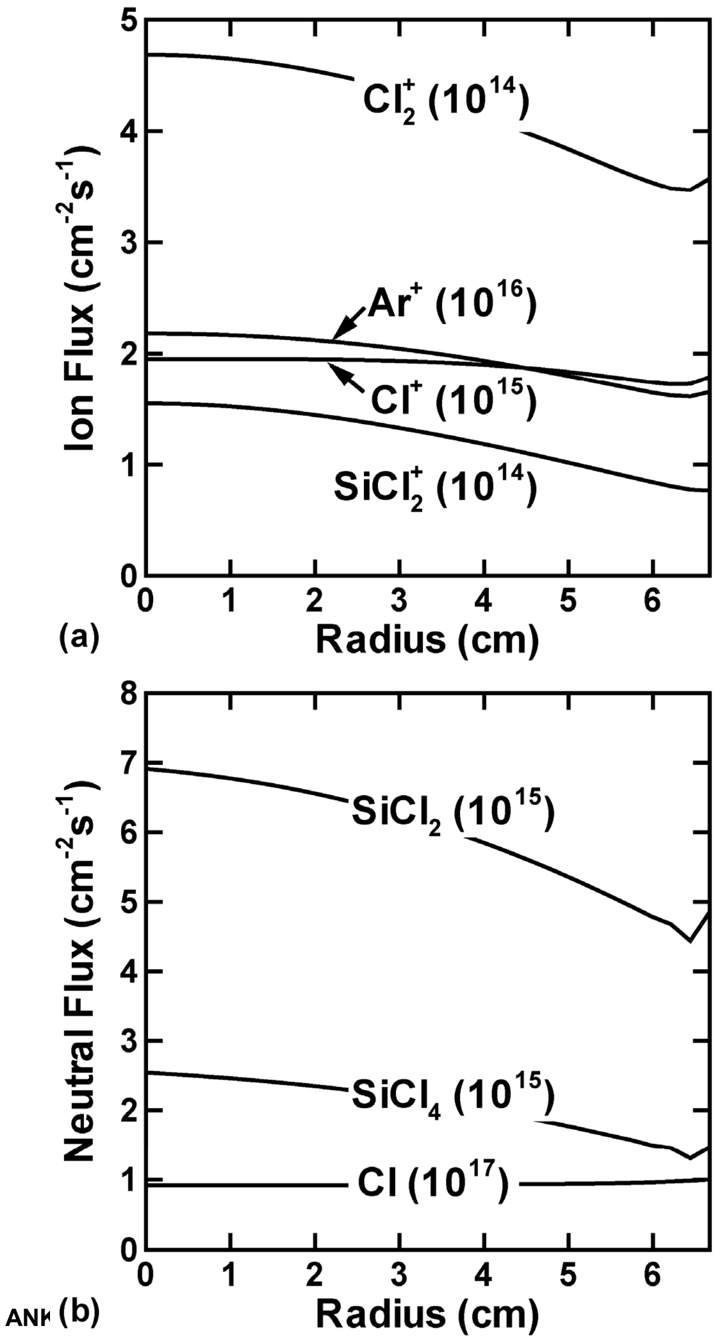
Si ETCHING IN Ar/Cl_2

- 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.



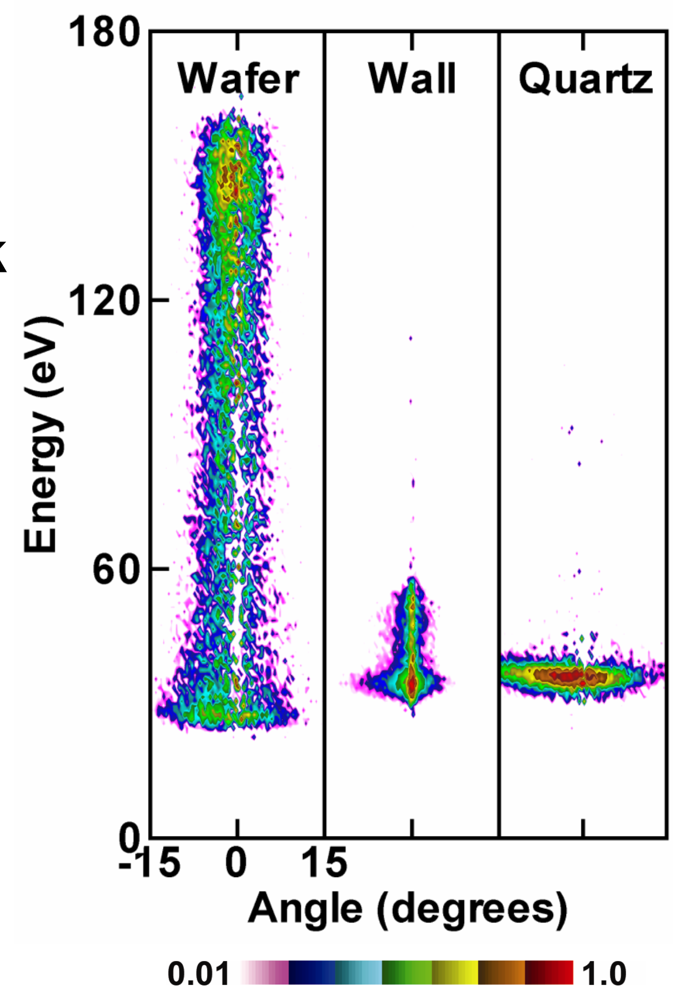


Si ETCHING IN Ar/Cl_2: REACTANT FLUXES

- Dominant ions are Ar^+ and Cl^+ due to dissociation of Cl_2.
- Dominant neutrals are Cl, $SiCl_2$ and $SiCl_4$.
- $SiCl_2$ is potentially reactive with surfaces; $SiCl_4$ is not.
- Ar/Cl_2=90/10, 100 sccm, 15 mTorr, 300 W, 75 V at 5 MHz.

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 $\Phi_{floating}$ (38 V).
- Quartz nearly always at $\Phi_{floating}$. IEADs extend to higher energy on grounded walls (oscillation in Φ_{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



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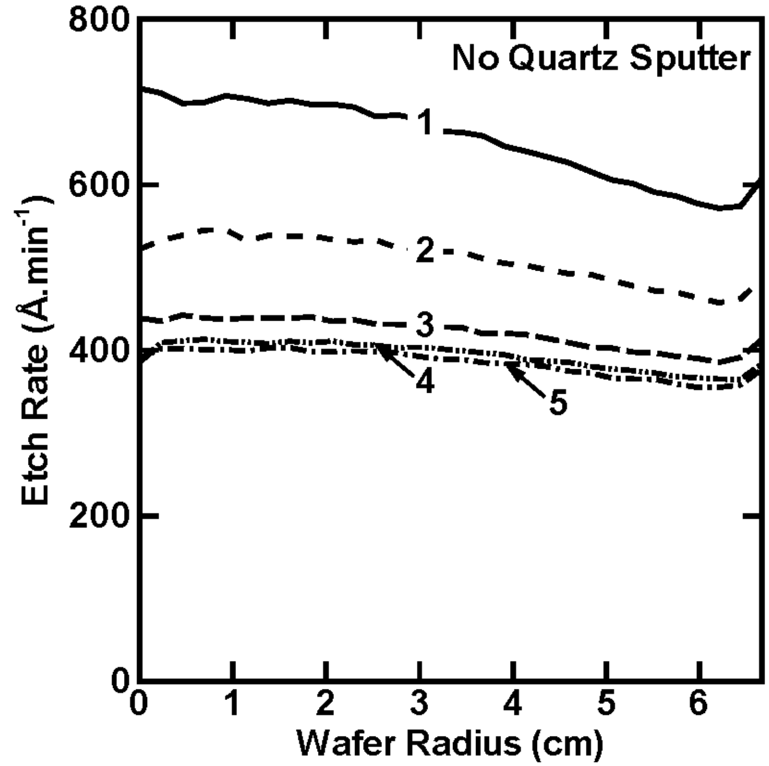
SEASONING EFFECT: ETCH RATE

- 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_2Cl_y etch blocks.

$$SiCl_2(g) + SiCl_n(s) \rightarrow Si_2Cl_{n+2}(s)$$

- Ions removes Si_2Cl_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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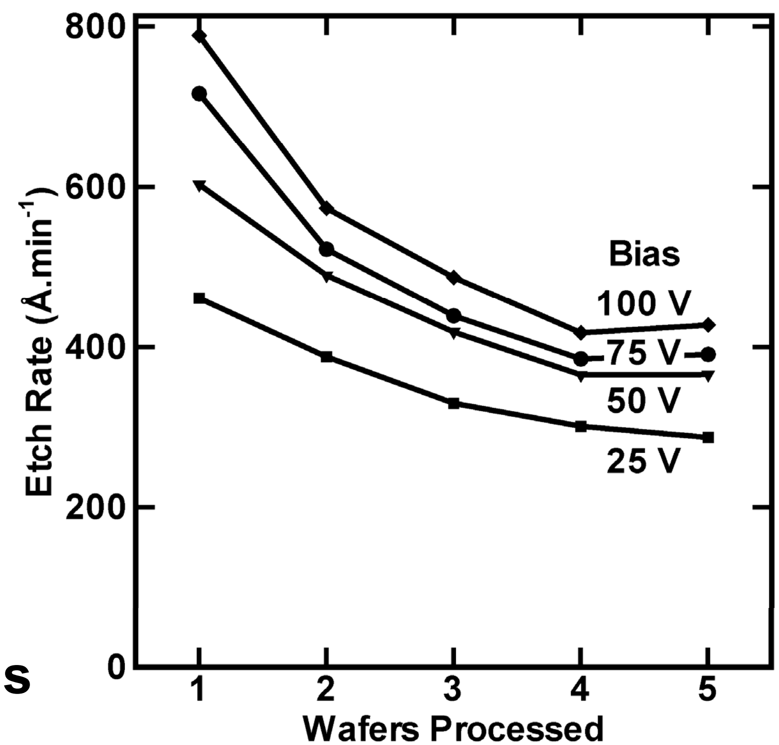
SEASONED CHAMBER ETCH RATE: VOLTAGE

- 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_2Cl_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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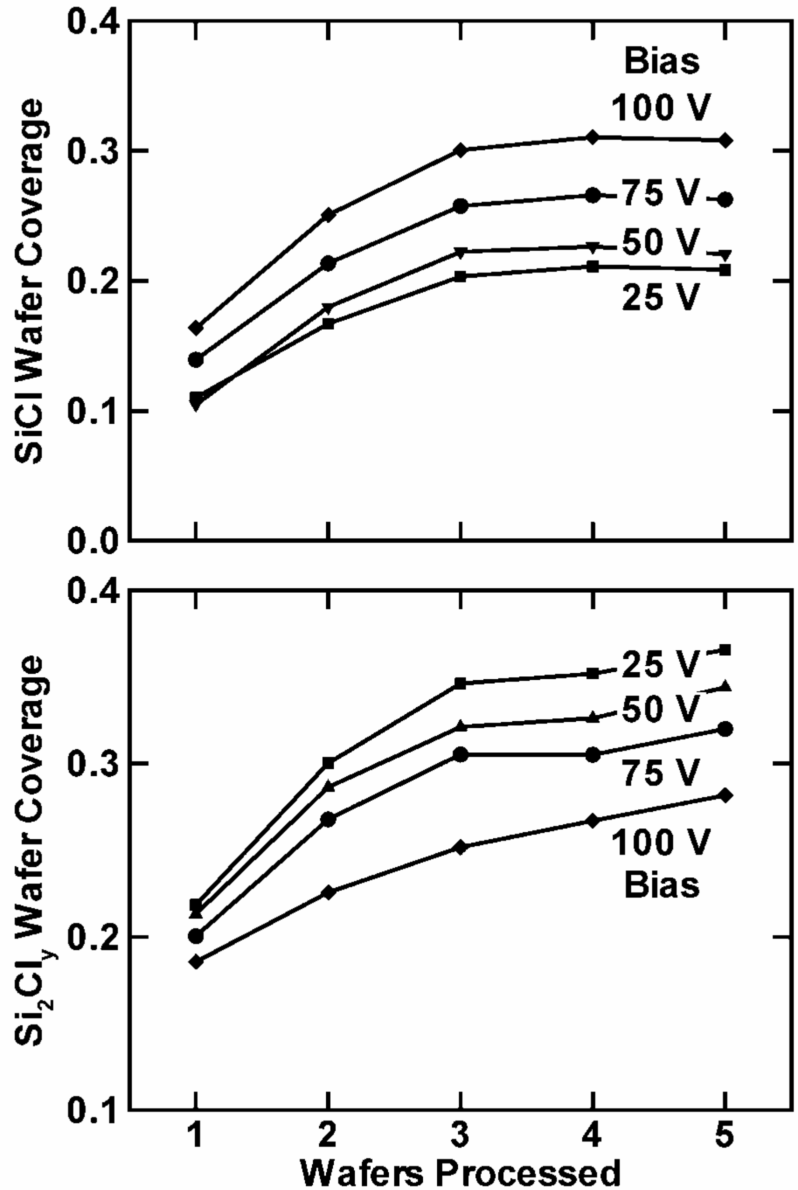

SURFACE COVERAGES: WAFER

- As additional wafers are etched:
  - Flux of etch products to wafer increases.
  - Coverage of etch block, Si_2Cl_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.

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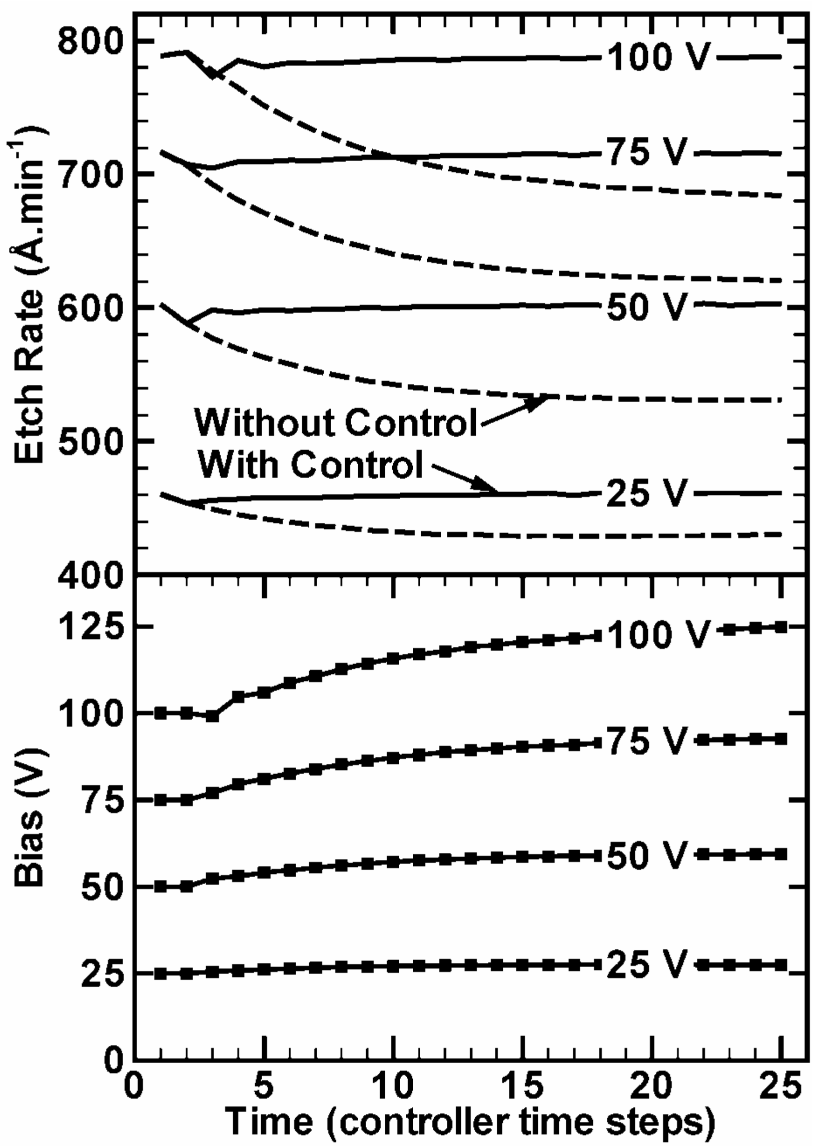

REMEDY TO SEASONING: REAL-TIME CONTROL

- 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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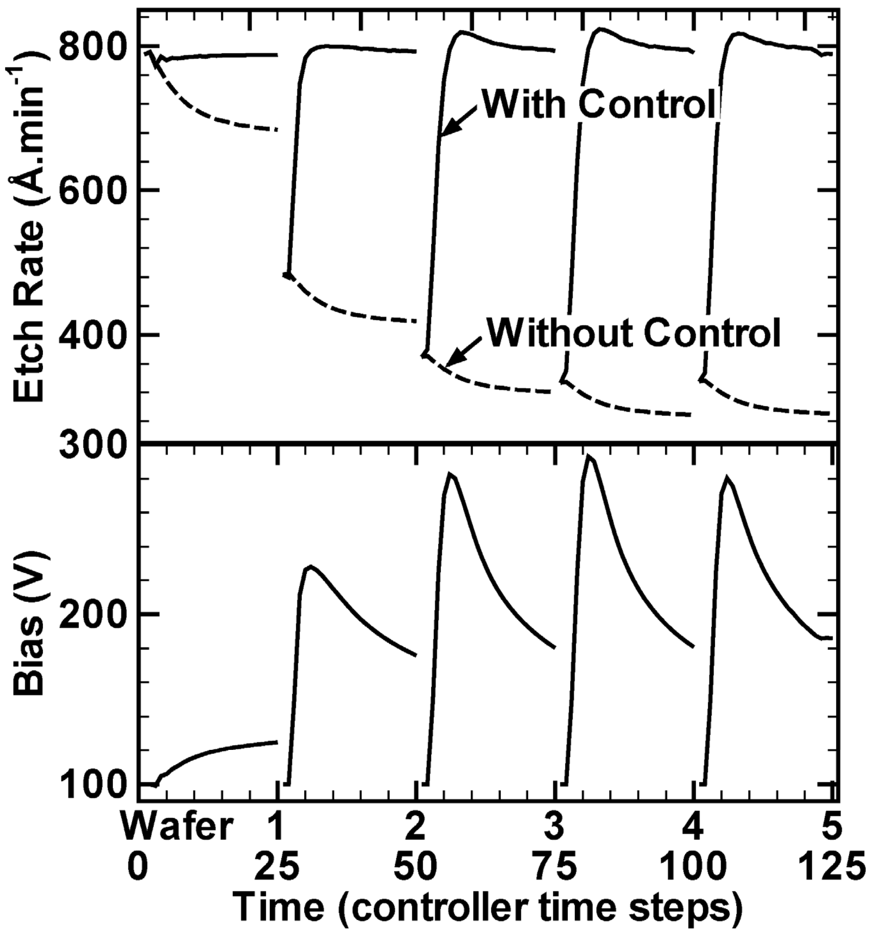
RUN-TO-RUN CONTROL: ACTUATOR BIAS NOT RESET



- Ar/Cl_2=90/10, 100 sccm, 10 mTorr, 300 W, 100 V at 5 MHz.

- 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.

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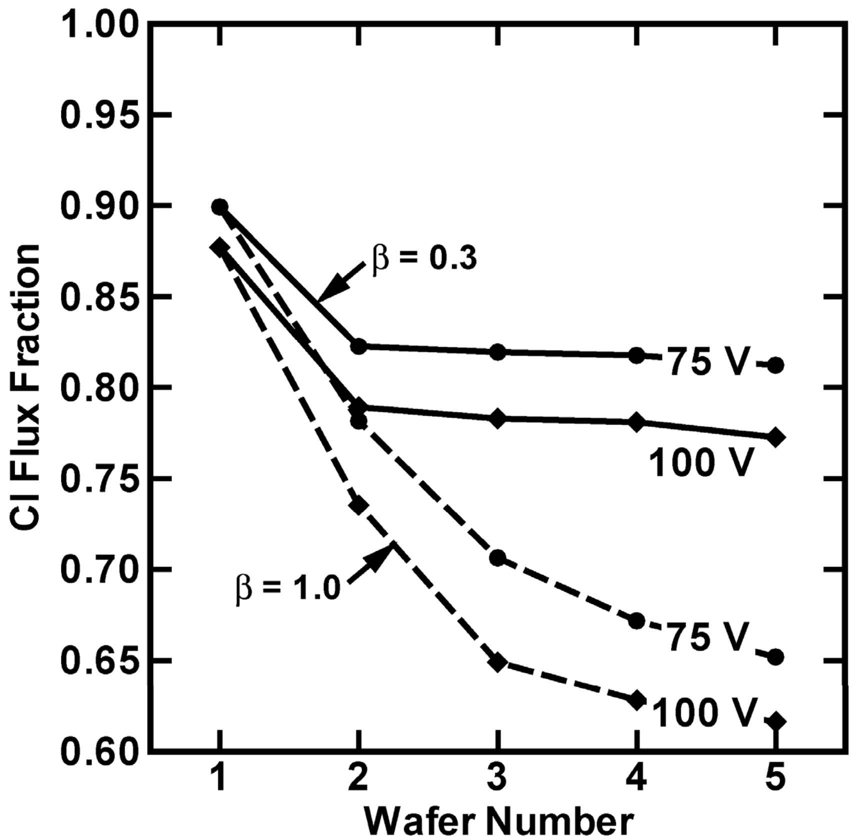
RUN-TO-RUN CONTROL: ACTUATOR BIAS NOT RESET



- Ar/Cl_2=90/10, 100 sccm, 10 mTorr, 300 W.

- β 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 β maintains Cl radical flux to a significant fraction of total radical flux.

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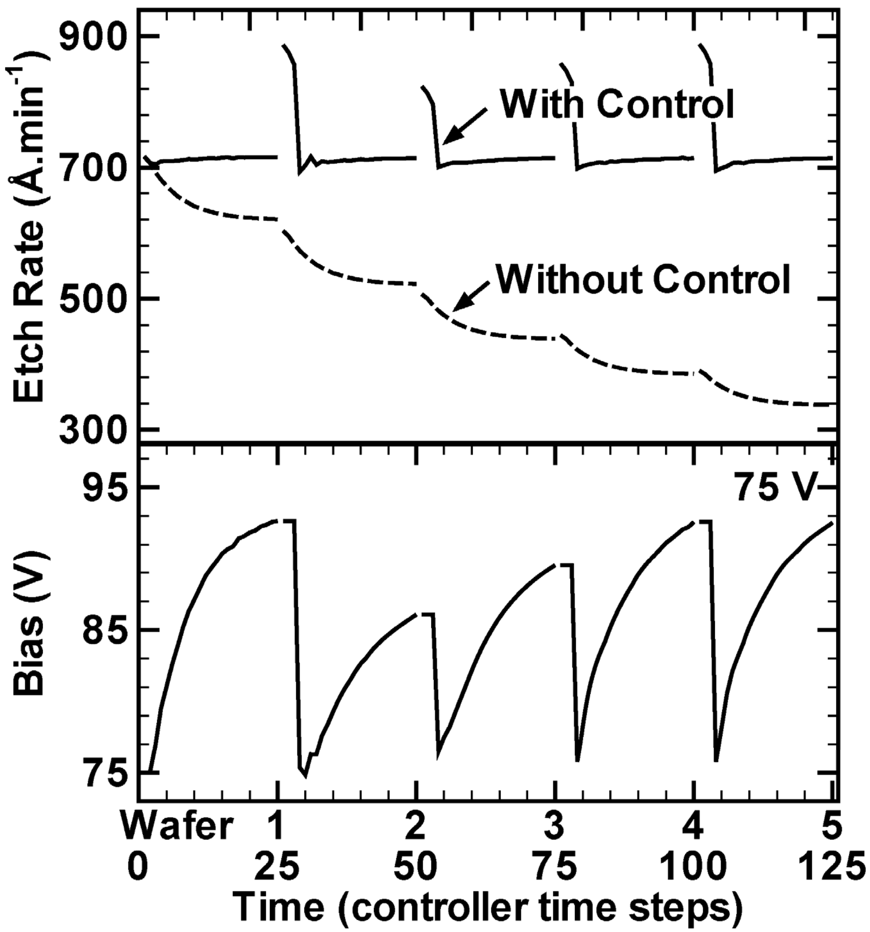
RUN-TO-RUN CONTROL: ACTUATOR BIAS RESET



- **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/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/Cl_2 plasmas.
- Etch rates decreased in a seasoned chamber.
  - Seasoned reactor increases $SiCl_2$ flux back to wafer.
  - Feedback of etch products ($SiCl_2$) from the plasma form Si_2Cl_y etch blocks.
  - Removal of Si_2Cl_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