REAL TIME CONTROL OF PLASMA TOOLS DURING RECIPE CHANGES AND TRANSIENTS*

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October 1999

* Work was supported by AFOSR/DARPA and SRC
AGENDA

• Introduction to modeling of RTC for plasma tools
• Description of the Virtual Plasma Equipment Model
• Control strategies through transients
  • Impurity injection
  • Actinometry as a sensor
  • Recipe changes
• Concluding Remarks
REAL TIME CONTROL OF PLASMA TOOLS

• Strategies are being developed for control of plasma tools with the goals of producing improvements in both real-time and run-to-run performance using increasingly more sophisticated diagnostics.

• Krogh et al have demonstrated multivariable real-time-control of PECVD of silicon nitride using multi-species mass spectroscopy.

• Khargonekar et al have investigated control of RIE using response-surface based controllers with OES and interferometry as sensors.

• Lee and Maynard demonstrated the use of multi-wavelength ellipsometry for real-time-control using patterned wafers.

In this paper, two topics in RTC will be addressed in the context of controlling transients in plasma tools.

• Can first principles modeling be used to optimally select sensors?
• Demonstration of advanced control strategies using gain scheduling.
The Virtual Plasma Equipment Model (VPEM) is a “shell” which supplies sensors, controllers and actuators to the HPEM.
The VPEM has been equipped with a variety of sensors and actuators.

**Sensors:**
- Spatially averaged densities
- Densities at points
- Optical emission through ports
- Electrical sensors (I-V)
- Actinometry
- Mass spectroscopy
- Fluxes to surfaces
- Bias power
- Langmuir probe
- Pressure

**Actuators:**
- Pressure
- Inductive power
- Coil currents
- Power supply frequency
- Flow rate/mole fractions
- Bias power
- Electrode voltage
RESPONSE SURFACE BASED CONTROLLERS

- The response surface is developed by performing a "S-DOE" (statistical design of experiments) using the commercial software package "E-CHIP".

- The response surface is constructed in the following manner:
  - Sensors, actuators and parameter are specified.
  - Using E-CHIP, a statistical model is specified, a set of "experimental" points are selected; and simulations run for those parameters.
  - A response surface is constructed from successive runs of the HPEM, and least mean square (LMS) polynomial coefficients are computed. In the case of a 2 sensor-2 actuator control scheme

\[
\begin{bmatrix}
    y_1 \\
    y_2 \\
\end{bmatrix} = \begin{bmatrix}
    a_1 \\
    a_2 \\
\end{bmatrix} + \begin{bmatrix}
    b_{11} & b_{12} \\
    b_{21} & b_{22} \\
\end{bmatrix} \begin{bmatrix}
    x_1 \\
    x_2 \\
\end{bmatrix} + \begin{bmatrix}
    c_{11} & c_{12} \\
    c_{21} & c_{22} \\
\end{bmatrix} \begin{bmatrix}
    x_1^2 \\
    x_2^2 \\
\end{bmatrix} + \begin{bmatrix}
    d_1 \\
    d_2 \\
\end{bmatrix} x_1 x_2
\]

- We assume that small perturbations do not significantly alter the response surface, and linearize the system.
The changes in sensor outputs resulting from small changes in actuator settings are then

\[
\begin{bmatrix}
\frac{dy_1}{dy_2}
\end{bmatrix} = \begin{bmatrix}
b_{11} + 2c_{11}x_1 + d_{11}x_2 \\
b_{21} + 2c_{21}x_1 + d_{21}x_2
\end{bmatrix} \begin{bmatrix}
\frac{dx_1}{dx_2}
\end{bmatrix} = A \begin{bmatrix}
\frac{dx_1}{dx_2}
\end{bmatrix}.
\]

Taking the inverse,

\[
\begin{bmatrix}
\frac{dx_1}{dx_2}
\end{bmatrix} = A^{-1} \begin{bmatrix}
\frac{dy_1}{dy_2}
\end{bmatrix}.
\]

To restore the system from a perturbed condition \((y_1', y_2')\) to desired a desired condition \((y_1, y_2)\) the actuators are changed by

\[
\begin{bmatrix}
\frac{dx_1}{dx_2}
\end{bmatrix} = gA^{-1} \begin{bmatrix}
(y_1 - y_1') \\
y_2 - y_2'
\end{bmatrix}
\]

where \(g\) is a specified gain.
A Proportional-Integral-Differential (PID) controller has been implemented in the VPEM.

- Proportional:

\[ \Delta A = A \cdot g \cdot \frac{\Delta S}{S}, \quad \Delta S = (S_o - S) = \text{Error Signal} \]

- PID

\[ A = g \cdot \left( \frac{\Delta S}{S} + \frac{1}{\tau_i} \int \frac{\Delta S}{S} dt + \tau_d \left( \frac{\Delta S}{S} \right) \right) + A_o \]

where:

\( \Delta S, S, S_o \) Error, current value and set point of sensor

\( \Delta A, A, A_o \) Change, current value and set point of actuator

\( g \) Gain of Controller

\( \tau_d, \tau_i \) Differential and integral time constants
An Inductively Coupled Plasma (ICP) reactor will be used to demonstrate control strategies during transients and recipe changes.

Sensors: Optical emission, mass spectroscopy, ion current, electron density
Actuators: Coils currents, power deposition, pressure
TYPICAL ICP DENSITIES

- Electric Field (8.8 V/cm)
- Power (0.5 W/cm³)

- \( \text{Ar/Cl}_2 = 98/2, \ 10 \text{ mTorr}, \ 200 \text{ W}, \ 250 \text{ sccm} \)

- \( \text{Cl}_2 \ (6.9 \times 10^{11} \ \text{cm}^{-3}) \)
- Ions \( (1.8 \times 10^{11} \ \text{cm}^{-3}) \)

- Optical Emission
CONTROL OF FACTORS THAT EFFECT ETCH RATE

• Etch rate in Cl2 chemistries is a function of:
  1. Ion flux to substrate,
  2. Cl flux to substrate,
  3. Ion energy.

• We consider polysilicon etching in an ICP reactor.

• Sensors:
  • Total ion flux at S1 (e.g., Sobolewski, APL 72, 1146 (1998)],
  • Cl* density using OES from S2.

• Actuators:
  • Inductive power (300-500 W),
  • Pressure (15-25 mTorr).

• Ar/Cl2 = 70/30, 150 sccm, no rf bias.
• Increase in power deposition causes more ionization and excitation, which enhances the $\text{Cl}^*$ density and total ion flux to the substrate.

• $\text{Cl}^*$ density increases slightly with pressure because the number of Cl that can be excited is larger.

• Since the plasma is more collisional at higher pressures, ion velocity and hence ion flux is smaller.

$\text{Ar/Cl}_2 = 70/30$, 150 sccm, no rf bias.
- At T=5, we artificially increase the Cl→Cl₂ sticking coefficient at the wall to simulate a change in wall conditions.
- This decreases the Cl⁺ density because of enhanced loss of Cl at the walls and decreases ion flux to substrate because the gas becomes more electronegative.
- The RS based controller increases the pressure and power until the sensors return to their original values.
The Mass Flow Controller (MFC) in an ICP plasma tool (Ar, 10 mTorr) malfunctions and injects a pulse of N\textsubscript{2} (25 sccm).

Due to the large inelastic electron impact cross sections of N\textsubscript{2}, the electron and ion densities decrease.

Ar, 10 mTorr, 250 sccm, 200 W
• Since etch rate depends on the total rate of radical production and ion bombardment on the wafer, choose electron density and ion flux as sensors.

• Since radical production scales with electron density and ion flux with pressure, choose power and pressure as actuators.

• Response surfaces obtained from DOE. Note weaker dependence on pressure implying need for lower gain.

- Ar, 10 mTorr, 250 sccm
- The electron (and ion) densities are only moderately well regulated against the perturbation by N$_2$ injection.
- The response surface was formulated using pure Ar, whereas the characteristics of the perturbed system differ significantly.
- As the N$_2$ density increases as the “pulse” moves through the reactor, larger actuator adjustments “in the future” are required than the controller suggests.

- Ar, 10 mTorr, 250 sccm, 200 W
ICP Ar PLASMA TOOL: N\textsubscript{2} INJECTION w/CONTROL (cont.)

- When the N\textsubscript{2} density increases, the controller underpredicts changes in actuator settings since the “future” conditions are always “worse”. When the N\textsubscript{2} density decreases, the controller overpredicts changes since future conditions are “better”.

- To address these issues, the controller requires knowledge of the “physics” of the disturbance or must cycle at a high enough frequency to negate poor knowledge of the future.

- Ar, 10 mTorr, 250 sccm, 200 W
With no apriori knowledge of the “physics” of the transient, one strategy is to increase the frequency of the controller so that lack of knowledge of future (or present) conditions is less of an issue.

- Ar w/N$_2$, 10 mTorr, 250 sccm, 200 W
Given the uncertainty and possible misguidance of response surface controllers during "unknown" transients, simpler PID controllers may fare better.

A "slower" proportional controller with high gain is competitive.

- Ar w/N$_2$, 10 mTorr, 250 sccm, 200 W
- P-controller gain = 0.75
The proper choice of sensor is critical to controlling through transients.

Sensors which are adequate for perturbations to the steady state may fail during a transient.

Example: Impulsively change the coefficient for \( \text{Cl} \rightarrow \text{Cl}_2 \) on walls while keeping the input flow rate and pressure constant.

Sensor: Actinometry of \( \text{Cl}^* \): \( S = [\text{Cl}^*]/[\text{Ar}^{**}] \)

The decrease in outflow resulting from more recombination increases the Ar density.

- 10 mTorr, 120 sccm, \( \text{Cl}_2/\text{Ar} = 95/5 \), 500 W

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As a result of the absolute increase in Ar density (and Ar* signal) resulting from the change in mole fractions, the actinometry signal decreases relative to the actual Cl density.

• Transients which change the mole fraction of the reference will complicate use of actinometry.
The response of the system is to increase power to recoup the actinometry signal which, during the transient, produces an unstable excursion in power and gas heating.
During a plasma etching process, it is not unusual for there to be 2-4 "recipe" changes.

Recipe changes are different values of, for example, power, pressure, flow rate or gas mixture to address beginning, middle and end of the etch.

Changes in recipes may produce unanticipated changes in plasma parameters such as uniformity or rate which may need to be controlled.
RECIPE CHANGE: Ar/Cl₂ p-Si ETCH TOOL

- An ICP reactor undergoes a recipe change during which the input flow rate changes from Ar/Cl₂ = 90/10 to 99/1. “Clearing” through the reactor produces an intermediate term transient which will be “controlled”.

- Electron impact processes deplete Cl₂, produce radicals, ions and excited states which radiate.

- 10 mTorr, 250 sccm, 200 W

Electron impact reactions:

\[
e + \text{Cl}_2 \rightarrow \text{Cl} + \text{Cl} \\
e + \text{Cl}_2 \rightarrow \text{Cl}_2^+ + 2e \\
e + \text{Cl} \rightarrow \text{Cl}^- + 2e \\
e + \text{Cl}^* \rightarrow \text{Cl}^+ + e \\
e + \text{Ar} \rightarrow \text{Ar}^* + e
\]
Although the power deposition remains constant through the recipe change, the decreasing Cl\(_2\) produces a decrease in electron loss rates and power transfer.

As a consequence, total electron and ion densities increase (which one may want to control...)

- 10 mTorr, 250 sccm, 200 W
Goal: Control uniformity of etching before and after recipe change. Prior studies have shown a close correlation between Cl* emission and local etch rate.

Sensors: Optical emission S(1)/S(2), S(3)/S(2)
Actuators: Coils currents I(1)/I(2), I(3)/I(2)

During the recipe change, the chlorine density changes from 10% to 1%, with there being commensurate changes in plasma properties.

In the absence of additional information, one must choose a chlorine density at which the response surface is developed and coefficients for the controller are derived.
RESPONSE SURFACES vs Ar/Cl\textsubscript{2} RATIO

- Response surfaces for uniformity of Cl* critically depend on the Ar/Cl\textsubscript{2} ratio.

Ar/Cl\textsubscript{2} = 90/10

Ar/Cl\textsubscript{2} = 99/1
Although the additional sensor data from the mass spec cannot be used directly by the (2 x 2) controller, it can be used to select coefficients for the controller which better represent the current conditions.

So interpolate between response surfaces developed for different Cl$_2$ flow rates based on mass spectrometer data.

$$f_{\text{eff}}(\text{Cl}_2) = 0.5 \, f(\text{Cl}) + f(\text{Cl}_2)$$
Ar/Cl\textsubscript{2} RECIPE CHANGE: SENSORS WITH 2 PLANE CONTROL

- In the absence of control, Cl* emission is peaked towards the center.
- With 2-plane control (Ar/Cl\textsubscript{2} = 90/10, 99/1), uniformity at large radii is significantly improved, leading to an overall improvement in uniformity.
- Control is lost half way through the transient when the control surfaces do not represent instantaneous reactor conditions well.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{chart.png}
\caption{Cl* emission and fraction Cl\textsubscript{2} in exhaust as a function of time.}
\end{figure}

- Ar/Cl\textsubscript{2}, 10 mTorr, 250 sccm, 200 W
Ar/Cl\textsubscript{2} RECIPE CHANGE: SENSORS WITH 3 PLANE CONTROL

- By adding an additional plane of response surfaces (Ar/Cl\textsubscript{2} = 90/10, 95/5, 99/1), the time of control is extended.
- Control is most difficult to maintain at low mole fractions of Cl\textsubscript{2} where the spatial distribution of the plasma is changing most rapidly.

- Ar/Cl\textsubscript{2}, 10 mTorr, 250 sccm, 200 W
The sensor readings can be quantified by weighting the local sensor signals by the relative underlying area of the wafer

$$\text{Uniformity} = \left(\frac{(S(\text{in})/S(\text{mid})-1)^2 A_{\text{in}}/A + (S(\text{out})/S(\text{mid})-1)^2 A_{\text{out}}/A)}{1/2}\right)$$

Increasing the number of “planes” of response surfaces enables the controller to maintain high uniformity for a longer period.

- Ar/Cl$_2$, 10 mTorr, 250 sccm, 200 W
CONCLUDING REMARKS

- A modeling hierarchy has been developed to evaluate control strategies in plasma tools.

- The applicability of actinometry and PID control have been discussed in the context of transients.

- Under conditions where mole fractions are changing, as during recipe changes or changes in wall conditions, the use of actinometry should be evaluated carefully.

- Examples of control strategies through transients were discussed.

- During "known" transients, such as recipe changes, gain scheduling is a viable control strategy.