NUMERICAL INVESTIGATION OF FEEDBACK CONTROL IN PLASMA PROCESSING REACTORS

Shahid Rauf and Mark J. Kushner
Department of Electrical and Computer Engineering
University of Illinois
1406 W. Green Street, Urbana, Illinois 61801

The continuously increasing complexity of fabricating microelectronics devices has made it necessary to consider utilizing feedback control during plasma processing steps. To investigate and optimally select control strategies, comprehensive plasma equipment models are required. This paper describes a versatile simulation tool, the Virtual Plasma Equipment Model (VPEM), that has been developed to computationally investigate feedback control in plasma processing equipment. The VPEM is an extension of a detailed plasma equipment model, which has been equipped with sensor, actuator and controller modules. The VPEM was used to investigate feedback control in inductively coupled plasmas using controllers based on a response surface methodology. The results from the VPEM suggest strategies whereby feedback control can be used to compensate for gas leaks, control drift in process parameters such as power and pressure, and nullify the effect of long term changes in wall conditions.

INTRODUCTION

As microelectronics device dimensions continue to shrink and wafers continue to increase in size, it is becoming necessary to have tighter tolerances during the fabrication process to maintain high yields. This is particularly true for plasma processing steps. Feedback control has, therefore, become an important issue in plasma processing equipment design. Theoretical and experimental research [1-3] has demonstrated the utility of feedback control in stabilizing plasma processes, control of external disturbances and improvement of important etching and deposition characteristics. To investigate and optimally select control strategies, comprehensive equipment models linked to control algorithms are required. In this paper, we report on a general plasma equipment simulation tool, the Virtual Plasma Equipment Model (VPEM), that has been developed to theoretically investigate feedback control in plasma processing equipment. The VPEM makes use of the Hybrid Plasma Equipment Model (HPEM) [4] to simulate the plasma. In the VPEM, the HPEM is connected to an external sensor module, actuator module and a programmable controller module in a feedback control loop.

We used the VPEM to study a number of feedback control related problems in inductively coupled plasmas (ICP) with Ar, Ar/N_2 and Ar/Cl_2 gas mixtures. In these studies, the controllers were designed using a response surface based methodology. Our results suggest means whereby controllers can be designed to stably control drifts in process parameters such as gas pressure and inductive power, compensate for gas leaks and nullify the effects of long term changes in wall conditions.

DESCRIPTION OF THE PLASMA MODEL

The general structure of the VPEM is illustrated in Fig. 1. The VPEM makes use of the HPEM for simulating the plasma. Since the HPEM has been described in detail in several previous publications [4-6], it is only briefly discussed here. The HPEM consists of three coupled modules. The first module computes the inductive electromagnetic fields. The second module simulates electron energy transport using either a Monte Carlo simulation or by solving the electron energy equation coupled with a solution of the Boltzmann equation for rate coefficients. The third module solves continuity and momentum equations for species densities, and computes the electrostatic fields. The HPEM iterates the three coupled modules until quasi-steady-state conditions are obtained.

To make the HPEM suitable for investigating feedback control problems, three modules were added. In the actuator module, process parameters including gas pressure, inductive power deposition, electrode voltages, gas flow rate and mole fraction of gases in the feed are adjusted. In the sensor module, the output of the HPEM is used to emulate quantities that are ideally measured by experimental sensors. These include point and spatially averaged densities, flux on the wafer, flux at a given location and ion energy flux at the wafer. The sensor and actuator modules are linked through a programmable controller.

In a typical VPEM simulation, the user sets up the HPEM simulation and, in addition, specifies the sensors, actuators and a desired set point. The HPEM computes the steady-state plasma conditions. This information is used by the sensor module to emulate sensor data, which is passed to the controller module. The controller module computes how much the actuators need to be adjusted to meet the set point, and passes this information to the actuator module. The actuator module adjusts process parameters and reruns the HPEM simulation. This process is repeated until the user-specified termination condition has been satisfied.

CONTROLLER DESIGN PROCEDURE

We used a response surface based methodology to design the controllers. The first step in the controller design is to specify the sensors, actuators and actuator parameter range that have to be used. Using this information, simulations are run at selected points within the actuator parameter range, and response surfaces of sensor output as a function of actuator settings are constructed. We used design of experiment techniques to minimize the number of simulations that must be performed. For controller design, the useful information that is extracted from these response surfaces are the least mean square polynomial approximations linking the sensors and actuators. In our studies, we found that quadratic polynomials were adequate for designing stable controllers. We will, therefore, restrict our attention to quadratic polynomials in the following discussion. For an n-actuator n-sensor system, these polynomials have the form

$$y_j = c_j + \sum_{k=1}^{n} a_{jk}(x_k - x_{k0}) + \sum_{k=1}^{n}\sum_{l=1}^{n} b_{jkl}(x_k - x_{k0})(x_l - x_{l0}), \tag{1}$$

where $j=1,2,\ldots,n$. y_j are the outputs (sensors), x_k are the inputs (actuators), x_{k0} are the center point within the range of x_j, and c_j, a_{jk} and b_{jkl} are constants obtained from the response surfaces.

The basic goal in the problems we studied was to adjust the actuators $\underline{X} = [x_1, x_2, \quad , x_n]^T$ so that the sensor signal $\underline{Y} = [y_1, y_2, \quad , y_n]^T$ can be made to approach a desired target $\underline{\mathrm{T}} = [t_1, t_2, \quad , t_n]^T$. To determine how much the actuators need to be adjusted in a given situation, we consider a small change δx_k in actuators in Eq. (1). This will modify the sensor outputs to $y_j + \delta y_j$. Assuming that $\delta x_k << x_k$, one can differentiate Eq. (1), linearize the resulting equation and write it in matrix form as

$$\delta \underline{X} = \underline{\underline{A}}^{-1}\ \delta \underline{Y}, \tag{2}$$

where $\delta \underline{Y} = [\delta y_1, \delta y_2, \quad , \delta y_n]^T$, $\delta \underline{X} = [\delta x_1, \delta x_2, \quad , \delta x_n]^T$ and $\underline{\underline{A}}$ is a $n \times n$ matrix with elements

$$A_{jk} = a_{jk} + \sum_{l=1}^{n} (b_{jkl} + b_{jlk})(x_l - x_{l0}). \tag{3}$$

Setting $\delta \underline{Y} = \underline{T} - \underline{Y}_m$ and $\delta \underline{X} = \underline{X}_{m+1} - \underline{X}_m$, where the subscript m denotes the current settings and $m+1$ denotes the new values, we can write Eq. (2) as

$$\underline{X}_{m+1} = \underline{X}_m + \underline{\underline{B}}\ \underline{\underline{A}}^{-1}\ (\underline{T} - \underline{Y}_m). \tag{4}$$

We multiplied $\underline{\underline{A}}^{-1}$ with a $n \times n$ diagonal matrix $\underline{\underline{B}}$ so that the actuator gains can be individually changed to improve stability. We used Eq. (4) for implementing the controllers.

FEEDBACK CONTROL OF PLASMAS

In this section, we describe two problems in which feedback controllers have been used to compensate for external disturbances. Both problems have been studied in the inductively coupled Gaseous Electronics Conference (GEC) reference cell [7]. In the first problem, we consider an Ar discharge (20 mTorr, 400 W), and design a 2-input 2-output controller which is meant to keep sensor outputs at given values. Gas pressure and inductive power deposition are the two actuators. Average electron density (as might be measured by a microwave interferometer) and total Ar^+ ion flux to the wafer (to emulate etch rate of an ion driven etch process) are the sensors. It was ascertained that this controller can stably control drifts in actuators. The problem we consider here examines the behavior of this controller in the presence of an unwanted leak of N_2 into the reactor (emulating an air leak). The results for this case are shown in Fig. 2. When N_2 is added into the reactor, both plasma density and Ar^+ ion flux to the wafer decrease. This is a consequence of the fact that some of the inductive power is now diverted towards non-ionizing collisions of electrons with N_2 molecules. For constant power deposition, less power is therefore available for ionization. To compensate for the decrease in sensor signals, the controller increased the inductive power and slightly decreased the gas pressure. This brought the sensor signals back to their original values. The small oscillation in the steady-state is a consequence of the fact that the controller is operating in a slightly different system (Ar/N_2) than the one it was designed for (Ar).

When reactive gases are used in plasma processing reactors, wall conditions may change over time due to passivation or polymer buildup. This change in wall conditions can appreciably modify the plasma characteristics by changing the sticking coefficient of radical species. A useful application of feedback controllers would be to compensate for these long term drifts. In the next example, whose results are shown in Fig. 3, we consider a 10% mixture of Cl_2 in argon (27 mTorr, 380 W). To design the 2-input 2-output controller, we chose inductive power and rf bias voltage as the actuators. The sensors were average electron density and total flux of Cl^+ ions to the wafer. To simulate a change in wall conditions, we modified the sticking coefficient of $Cl \rightarrow Cl_2$ at the reactor walls. When the sticking coefficient was increased, first from 0.0025 to 0.01 and then from 0.01 to 0.04, Cl_2 concentration in the reactor increased, which reduced the plasma density due to attachment and reduced the Cl atom density. With fewer electrons and Cl atoms available, Cl^+ density decreased. The controller responded to the change in sensor signals by increasing the inductive power and decreasing the rf bias voltage. This brought the sensor signals back to their original values.

CONCLUSIONS

In this paper, we described a general plasma equipment simulation tool, the Virtual Plasma Equipment Model (VPEM), that was used to study feedback control problems in ICP reactors. The VPEM uses the HPEM for simulating the plasma. The input and output of the HPEM are linked through a sensor, actuator and a programmable controller module. In the feedback control problems that were discussed, controllers were designed using a response surface based technique. These results demonstrate the viability of computationally designing controllers to stabilize drifts in process parameters such as pressure and power, compensate for gas leaks and nullify the effect of long term changes in wall conditions.

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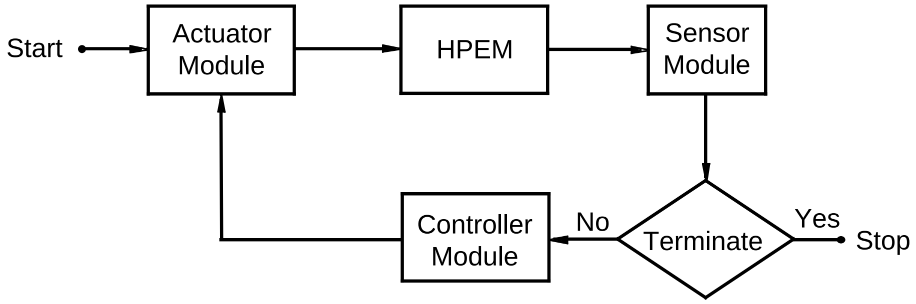

FIG. 1: A schematic of the Virtual Plasma Equipment Model (VPEM).

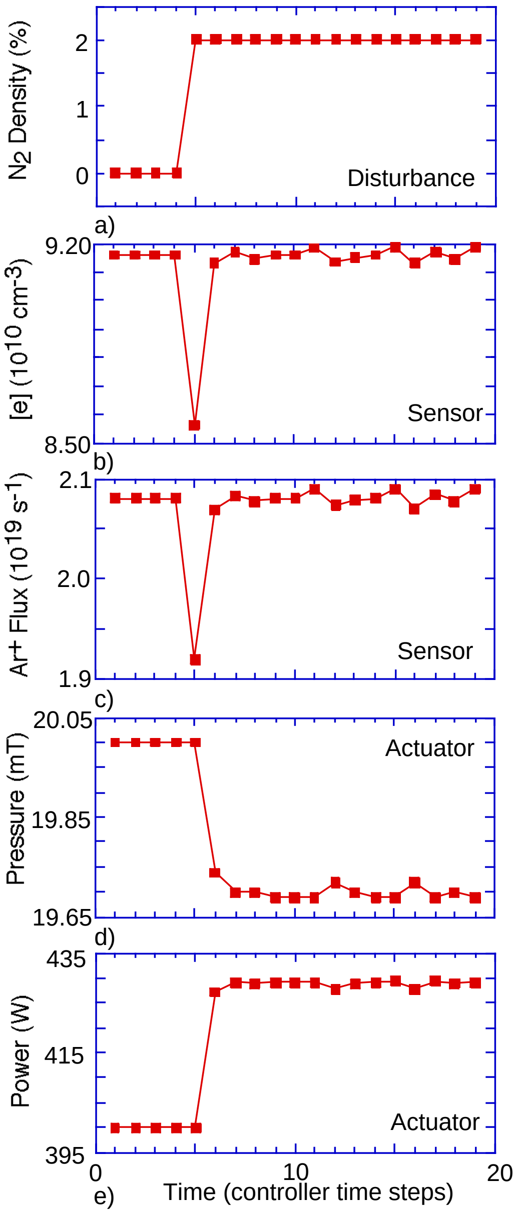

FIG. 2: Time history of a control case in which the controller compensates for a N_2 leak into the reactor.

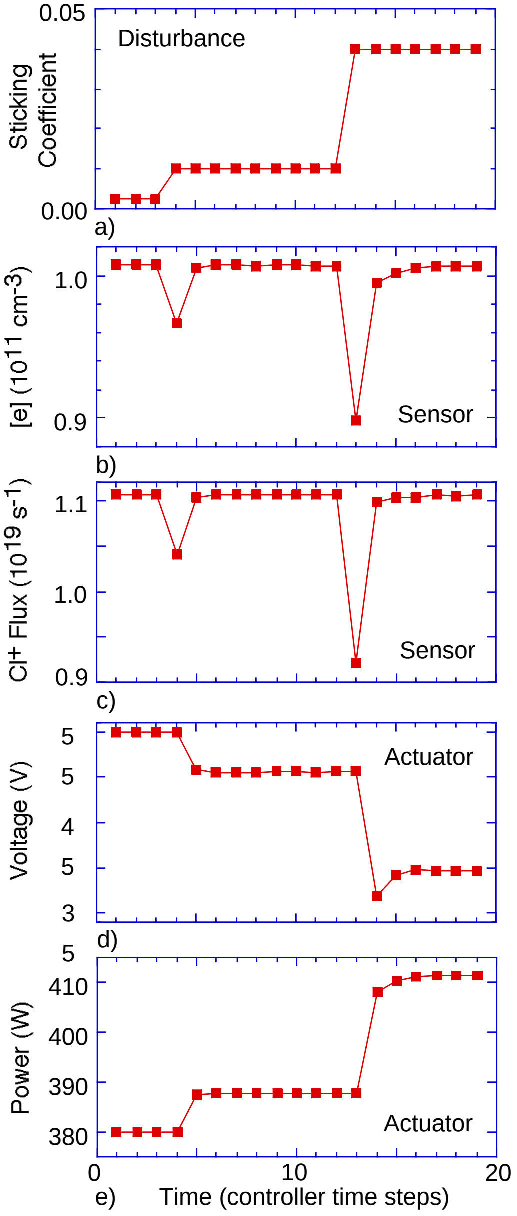

FIG. 3: Time history of a control case in which the controller compensates for a change in the sticking coefficient of $Cl \rightarrow Cl_2$ at the reactor walls.