Control of Semiconductor Manufacturing Equipment: Real-Time Feedback Control of a Reactive Ion Etcher

Brian A. Rashap, Michael E. Elta, *Member, IEEE*, Hossein Etemad, Jeffrey P. Fournier,
James S. Freudenberg, *Member, IEEE*, Martin D. Giles, *Member, IEEE*, Jessy W. Grizzle, *Senior Member, IEEE*,
Pierre T. Kabamba, *Member, IEEE*, Pramod P. Khargonekar, *Fellow, IEEE*, Stéphane Lafortune, *Member, IEEE*,
James R. Moyne, *Member, IEEE*, Demosthenis Teneketzis, *Member, IEEE*, and Fred L. Terry, Jr., *Member, IEEE*

Abstract—**This paper describes the development of real-time control technology for the improvement of manufacturing characteristics of reactive ion etchers. A general control strategy is presented. The principal ideas are to sense key plasma parameters, develop a dynamic input–output model for the subsystem connecting the equipment inputs to the key plasma variables, and design and implement a multivariable control system to control these variables. Experimental results show that this approach to closed-loop control leads to a much more stable etch rate in the presence of a variety of disturbances as compared to current industrial practice.**

I. INTRODUCTION

THIS paper is motivated by the fact that, at the present time, most semiconductor manufacturing equipment is designed to be operated in an open-loop mode. Due to this in-run open-loop operation, the manufacturing performance of this equipment is not as good as desired. The recent National Research Council Report on plasma processing of materials [17, p. 30] cites the lack of feedback control as one of the main problems facing the semiconductor manufacturing industry in general. In particular, this study notes that the lack of feedback control is a major impediment to reliable operation of low pressure reactive plasma systems.

This paper describes a part of a major interdisciplinary effort by the members of the Solid State Electronics Laboratory and the Control Systems Laboratory at the University of Michigan to improve the manufacturing characteristics of semiconductor processing equipment.

A. Research Objectives

Reactive ion etching (RIE) is a critical technology for modern VLSI circuit fabrication at many steps of the manufacturing process. We have chosen RIE as our initial research vehicle. At the present time, reactive ion etchers are typically supplied with a PID controller for regulating the chamber pressure. In addition, several of the actuators, such as the mass flow meters and the RF power generation unit, have internal controllers in order to make them less sensitive to variations in their operating environment. These actuators influence the actual etch process by affecting the plasma characteristics. At this time, the only plasma property which is stabilized using feedback control is pressure. It is commonly acknowledged that the RIE process is not very robust and requires frequent tuning to achieve acceptable yields. It is our contention that a major cause for this is the fact that this process is being operated essentially without feedback control.

Our research is directed toward the application of real-time control systems theory and technology to RIE. The aim is to develop sufficiently general methods and results that will allow the implementation of real-time feedback controllers on a large class of RIE machines with a minimal amount of tuning. We believe that the accomplishment of this goal will result, as a whole, in a substantial advancement of the state of the art in RIE material processing. Results in this paper provide some support for this belief.

The main thrusts of our current research program are as follows:

- control-oriented modeling and identification of the physicochemical processes involved in RIE,
- development, design, and implementation of a hierarchical controller for the RIE; experimental testing to determine improvements in accuracy and reliability of the etch process in terms of uniformity, anisotropy, and selectivity,
- extension of our ideas and approaches to other semiconductor manufacturing equipment, such as PECVD and sputter deposition.

From a control engineering viewpoint, the RIE process represents an interesting challenge in several different ways. A key issue is the fact that many of the crucial etch parameters that need to be controlled cannot, at present, be measured in real time. This necessitates an indirect control strategy wherein plasma parameters are used for feedback to achieve tight control of the etch characteristics. As control-oriented physics-based dynamic models are not currently available, the only way to check the efficacy of feedback control schemes is by doing experiments. An equally important issue is that the sensors are complex and are based on techniques used primarily for plasma science. In particular, they are not directly

Manuscript received February 27, 1994; revised January 15, 1995. This work was supported by the National Science Foundation under Grants EID 922041 and ECS-9312134, and the Semiconductor Research Corporation under Contract 93-MC-085.

B. Rashap, M. Elta, H. Etemad, J. Fournier, J. Freudenberg, J. Grizzle, P. Kabamba, P. Khargonekar, S. Lafortune, J. Moyne, D. Teneketzis, and F. Terry, Jr. are with the Electronics Manufacturing and Control Systems (EMACS) Group, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109-2122 USA.

M. Giles is with Intel Coporation, Santa Clara, CA, 95052–8119 USA.

IEEE Log Number 942779.

0894–6507/95$04.00 © 1995 IEEE

suitable for real-time dynamic feedback control. It is a challenge to relate the sensor measurements to plasma parameters of interest.

B. Summary of Results

In this paper, we demonstrate that real-time feedback control can significantly attenuate the deleterious effects of common RIE process disturbances on wafer etch performance. In Section II, we give a synthetic overview of the etch process and a description of our hardware and control platform. This is used in Section III to motivate a general control strategy for the RIE process. In Section IV, using input–output experiments, we develop a small-signal linear model for the plasma portion of the RIE and provide experimental results that confirm its fidelity. Based on the linear model, a linear time-invariant controller is designed and implemented. In Section V, this feedback controller is evaluated in terms of its ability to keep etch rate constant in the face of a number of representative process disturbances: 1) chamber wall contamination, 2) oxygen gas leak into the chamber, 3) matching network drift, and 4) wafer loading effects. The experiments show that real-time feedback control of certain key plasma characteristics leads to a significant attenuation of the effect of these disturbances on the etch rate.

Of course, etch rate is only one wafer parameter of interest. There are several other parameters of even greater interest such as anisotropy, selectivity, and uniformity, and these performance variables will be addressed as our research progresses. For now, let us note that etch rate, anisotropy, and selectivity each depend strongly on the chemical and physical components of the reactive ion etching process. Thus, demonstrating the ability of a feedback system to minimize variations in any one of these etch performance characteristics has important implications for the other two. In this work, we have focused on etch rate because it is the easiest wafer variable to dynamically measure while running an experiment. However, note that etch rate is not being used for feedback control.

C. Related Work

Sensor-based control of semiconductor manufacturing equipment is being investigated at a number of US universities and industrial research laboratories. A fairly complete survey of the various efforts along this direction may be found in [23]. Some representative works in the area of control of semiconductor manufacturing equipment are [2], [11], [22], [25], [26] and the references cited within. It is fair to say that at the present time, control-oriented modeling and real-time control of reactive ion etching is a open research problem. Considerable work has been done on the physical modeling of plasma based systems (see for example, [3]). Much of this work seems to be unsuitable for real-time control due to both extreme complexity and a large number of free unknown parameters. The classical method for developing empirical models in this area is known as *response surface methodology*. In this technique, statistically designed experiments are run to develop static steady-state nonlinear input–output models reflecting the relationship between equipment input variables—power, pressure, and flow—and plasma and wafer characteristics.

Recently, there have been a number of efforts to develop control-oriented models. Step input experiments have been used to empirical determine transfer functions for dynamic models relating equipment input variables to plasma parameters [4], [15]. Based on this system identification work, analysis of real-time controllers via relative gain arrays was carried out in [4]. In addition, phenomenological models for the chemical kinetics of the plasma are being developed in [24].

Our work has appeared as conference papers [8], [9], [19].

II. OVERVIEW OF AN RIE: PROCESS, EQUIPMENT, AND SYSTEM

In this section, we will give a brief description of the RIE process and equipment. This description is given from a control systems perspective. Thus, the emphasis is on the overall system behavior rather than individual physical/chemical processes. It is well known in the plasma community that the RIE process is highly nonlinear and multivariable. Existing plasma systems attempt to control the important wafer etch characteristics with the equipment input variables of pressure, applied power, and gas flow rates. However, there is no known way to use these inputs to predict the etch performance between different machines, between identical machines, or, in many cases, even for the same machine on two different runs. This is due to variations in plasma properties and various disturbances described later. Thus, there is necessarily a significant amount of uncertainty in any open-loop model of the RIE system. This is the main reason why we believe that real-time feedback will be of great potential benefit for the operation of reactive ion etchers.

A. The Process

Etching is the process through which a desired pattern is transferred to a silicon wafer by removing material, such as silicon (Si) or silicon dioxide (SiO_2), via the interaction of fluorine, or other chemicals such as chlorine or bromine with the wafer, and exhausting the reaction products. Some of the most important variables for determining the success of the etching process are: selectivity, uniformity, anisotropy, and etch depth. Selectivity refers to the ability to etch, for example, Si without etching either SiO_2 or photoresist; uniformity is the requirement that etching be spatially uniform across the wafer; anisotropy is the ability to etch vertically while minimizing horizontal etching, thus creating vertical walls. The importance of etch depth control lies in the ability to remove exactly a desired amount of material. Better control of these variables translates directly into improved yield, finer linewidths and hence higher device density, and higher throughput.

The physical and chemical mechanisms involved in reactive ion etching are very complex and are not fully understood at the present time. A detailed account of plasma etching can be found in [14]. Since the focus of this work is on the demonstration of the potential benefits of using feedback control systems (sensors, actuators, and control algorithms), an extremely simple plasma process is initially being used: a CF_4 gas system for the etching of unmasked wafers with a material stack of polysilicon/oxide/silicon substrate. This simple system has had the most complete scientific study with many known material parameters and reasonably advanced understanding of etch mechanisms and pathways. Normally, oxygen, hydrogen, or chlorine are added to enhance the selectivity and etch rate [29].

A reactive ion etcher is a low pressure, low temperature plasma system. The plasma is generated by capacitively coupling an RF (13.56 MHz) power source to one electrode, which has a smaller surface area then the grounded electrode. This leads to dissociation and ionization of the feed gas. Consequently, it generates a chemically active mixture of electrons, ions, and free radicals. To give a simple example, in a CF_4 gas system, the following reactions (among others) take place:

$$\begin{aligned}\mathrm{CF_4}+ e &\rightarrow \mathrm{CF_3^+} + \mathrm{F} + 2e,\\ \mathrm{CF_4}+ e &\rightarrow \mathrm{CF_3} + \mathrm{F} + e.\end{aligned}$$

References [3] and [7] list over 60 possible reactions in a $CF_4/O_2/H_2$ plasma. Due to electrons being more mobile than ions, a dc self bias voltage develops across the electrodes to achieve current continuity. This self bias voltage accelerates ions toward the surface of the wafer. The free radicals diffuse to the surface of the wafer where they react with the exposed silicon surface. The surface reactions are quite complicated and are not completely understood. However, in simple terms, the fluorine atoms react with silicon atoms and produce various volatile compounds such as SiF_4 and SiF_2. In addition, the impinging ions further enhance these etching processes. On the other hand, various polymers are formed as a result of chemical reactions between the radicals and the surface material. These inhibit the etching process. The polymers formed on the side walls (termed sidewall passivation) are largely unaffected by the ion bombardment and thus facilitate highly anisotropic etching. Polymers on the horizontal surface are removed by the impinging ions, provided the polymer film is not too thick and the ions have sufficient energy, and this allows the etching process to continue. The impinging ions can also physically sputter Si atoms, thereby etching the wafer surface, or cause surface activation, thereby speeding up the etch process.

It is thus useful to conceptualize reactive ion etching as consisting of two distinct but interacting mechanisms: chemical etching caused by radicals and physical etching caused/enhanced by ion bombardment. Etch characteristics can therefore be adjusted by carefully controlling the plasma species composition and ion energy, see for example, [29]. This will form the basis of the control strategy outlined later in this paper.

In summary, the key plasma parameters for the etching process are: the concentrations of the reactive radicals and ions, and the energy of the ions. The latter is strongly related to the dc self bias at low chamber pressures [3], [29], [30] because the ion mean free path length is greater than the sheath thickness. Important disturbances acting on the process are: wall recombination and outgassing, polymer buildup on reactor surfaces, loading of the plasma during etching, perturbations in gas flows, applied power drifts, etc.

B. Reactor

The experimental vehicle being used in our studies is an Applied Materials 8300 Hexode Reactive Ion Etcher. The reactor has a hexagonally shaped powered electrode (hexode) and bell jar shaped outer shell which serves as the ground plane [29, pp. 572–573]. The hexode has approximately half the surface area of the bell jar and allows ionic bombardment of the powered electrode while minimizing the bombardment of the ground electrode and other chamber surfaces. The process gases enter the chamber in a sprinkler fashion through vertical pipes across from each corner of the hexode. The gas reactants are removed by a turbomolecular pump with the exhaust conductance from the chamber regulated by a throttle valve. There are several viewports which allow the attachment of optical sensors for measuring plasma and wafer parameters. The wafers are placed on the powered electrode by opening the top of the bell jar; there is no load lock, which will have important consequences for the experiments reported later.

As is common with RIE machines, our reactor was instrumented only for steady-state process characterization and not for the purposes of dynamic system identification and real-time control. The first portion of our work was therefore dedicated to equipping the RIE with a data acquisition system, actuators, and sensors appropriate for real-time feedback control. This is described next.

C. Data Acquisition and Control Platform

A data acquisition and control platform has been developed for the collection of data during system identification experiments and for the implementation of real-time controllers on the RIE. The system is based on LabVIEW 2, which provides input–output board drivers, numerical manipulation, and a graphical user interface. Analog signals are used to collect real-time sensor data and send actuator commands. In addition, it has a number of digital channels and a GPIB interface for communication with other process instruments. State space linear controllers or general nonlinear controllers can be implemented directly in the LabVIEW programming language or through the inclusion of C language subroutines. The data acquisition and control system has been designed in a modular format which allows expandability within a generic environment.

D. Actuators

It was necessary to upgrade some of the actuators on the RIE in order to improve our ability to control the process. The existing throttle valve, which regulates the exhaust of reactant gases from the chamber, had several shortcomings from the point of view of dynamic control. These included a large leakage conductance when fully closed, an operating regime near saturation, hysteresis in the motion of the valve, and the lack of a sensor to determine actual valve position. The valve was replaced with an MKS Type 652A Throttle Valve and an MKS Type 653 Throttle Valve Controller. This valve was sized to be smaller, thus moving its operating region away from saturation. In addition, the valve has a low leakage conductance when fully closed, a good response time, and a measurement of actual valve position. The throttle valve controller allows either the specification of a pressure setpoint to be regulated by an internal PID loop or the direct control of throttle position. The RF power actuator includes a 2000 W, 13.56 MHz generation unit and matching network. During all of our experiments, the tuner in the matching network was left on. Gas flows are regulated by the MKS Type 2259C Mass Flow Controllers and are mixed in a manifold before entering the chamber.

E. Sensors

The dc bias voltage (V_{bias}) is measured through an inductive tap into the powered electrode. Pressure in the chamber is monitored by an MKS Type 127A Baratron Capacitance Manometer which is sensitive to pressures between 1 and 100 mtorr; 20 mtorr is a typical operating point for reactive ion etching in the Applied 8300. The fluorine concentration is estimated via optical emission spectroscopy using actinometry, with argon (5% of the total gas flow) as the calibration species. Optical emission from the plasma is modulated to 1 kHz using a mechanical chopper and is collected by two fused silica optical fiber bundles. The 703.7 nm and 750.4 nm wavelengths in the fluorine and argon spectra, respectively, are selected using two Oriel Multispec 125 mm monochromators with 1200 lines/mm holographic gratings with blaze wavelengths of 600 nm. The light is then converted into electrical signals using Oriel photomultiplier tubes and demodulated with Stanford Research SR850 DSP Lock-In Amplifiers with a low pass filter time constant of 30 ms.

The fundamental idea behind actinometry [10] is that for appropriately chosen spectral lines, $[\mathrm{F}]/[\mathrm{Ar}] = K_o I_{\mathrm{F}}/I_{\mathrm{Ar}}$, where I_{F} and I_{Ar} are the intensities of the particular fluorine and argon spectral lines, and K_o is the actinometry constant. In this work, the concentration of fluorine ([F]) in the plasma is estimated from the intensity of the emission lines by

$$[\mathrm{F}] = \frac{I_{\mathrm{F}}}{I_{\mathrm{Ar}}} P \qquad (1)$$

since the concentration of Ar is *roughly* proportional to pressure (P). This is still an uncalibrated measurement because it does not include the actinometry constant K_o. A more important omission is that $I_{\mathrm{F}}/I_{\mathrm{Ar}}\, P$ is not exactly proportional to [F] because it does not account for the dilution of Ar in the plasma due to the dissociation of $\mathrm{CF_4}$ into CF_x and F_y, nor does it take temperature into account. Work is proceeding on better dynamic, real-time estimates of [F] from actinometric data.

Etch rate is measured using the interference pattern of a He–Ne laser reflected at near normal incidence from the wafer. The laser light is modulated to 1 kHz by a mechanical chopper before entering the chamber and the reflected intensity is detected using a Thorlab PDA150 silicon photodiode detector. This signal is demodulated using a Stanford Research SR510 Lock-In Amplifier with a filter time constant of 1 s. The intensity of the detected signal varies as the strength of the interference between light reflected off the front and back of the polysilicon layer changes as material is etched. The time between a peak and a valley in the interference pattern corresponds to the etching of 417 Å of polysilicon. Thus, knowing the time elapsed between successive peak and valley, one can determine *average* etch rate during this time. To obtain an estimate of the actual etch rate, we fitted a smooth curve through these average etch rate measurements.

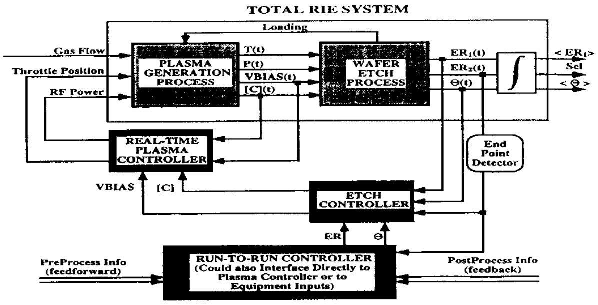


Fig. 1. Conceptual decomposition of an RIE system and control structure.

III. A CONTROL-ORIENTED RIE DECOMPOSITION AND CONTROL STRATEGY

The description of the etching process given in Section II naturally leads to a conceptual decomposition of the RIE system into two functional blocks, the plasma generation process (PGP) and the wafer etch process (WEP), as shown in Fig. 1. These sequential processes separate the generation of the important chemical and physical species from the action of etching the surface of the wafer. The inputs to the PGP are throttle position, gas flow rates, and applied power; its outputs are the key plasma parameters that are responsible for etching. Here V_{bias} represents an estimate of the mechanical energy of the impinging ions, [C] represents concentrations of the various chemical species involved in etching, and T represents thermal energy. The WEP is driven by the key plasma parameters and its outputs represent quantities crucial to etch performance. This decomposition actually represents a physical separation: the PGP represents the bulk plasma, the WEP represents the wafer surface phenomena, and the interface is the boundary layer. While this decomposition is based on sound physical principles, it is not completely accurate as there is a certain (small) amount of feedback coupling from the wafer surface reactions to the plasma.

The above decomposition of the RIE leads to our control structure. The key idea is to regulate the inputs to the WEP by precisely controlling the outputs of the PGP. This is accomplished by designing a real-time controller for the PGP as shown in Fig. 1. We expect to develop a controller around the WEP which will translate desired etch characteristics into setpoints for the PGP control system. Finally, the supervisory controller performs the high-level cell control functions that include on-line monitoring, diagnostics, and failure recovery as well as post-process analysis of the data for the purposes of sequential optimization, quality control, and so forth.

There are many merits to this approach.

- With existing sensor technology, it is very difficult to measure the key wafer etch parameters (selectivity, anisotropy, etc.) in real time during the etch process. (Some of these can be measured in near real time.) Therefore, for real-time feedback control, an indirect strategy is necessary.
- Modeling of the etch characteristics is the most difficult part of the problem. With this controller structure, the modeling task may become more tractable. The model for the PGP can be developed first, leading to the development of the real-time plasma controller. Then the modeling task for the WEP would involve relating the effects of the key plasma parameters on the etch performance, which is much more direct than trying to build a single model from the equipment inputs to the etch characteristics.
- The switch from specifying the process recipes in terms of [throttle position, flow, power] to (V_{bias}, pressure, [C]) is a significant change of viewpoint. As was seen earlier, these new setpoints are in many ways more directly connected to the overall etch performance, tightly regulating them should eliminate much of the variance seen in plasma systems. They will also facilitate the exchange of process recipes between different systems.

As stated above, it will be necessary to relate desired etch rate, selectivity and anisotropy to the key plasma parameters. This is the purpose of the etch controller. While this would also be a real-time controller, it would, perhaps, operate on a slower time scale than the plasma controller. At this time, the details of this second level etch controller are not completely clear. There are many reasons for this: real-time sensors for the wafer etch parameters are not readily available, the models for connecting plasma parameters to the wafer etch parameters are not well understood, etc. As a matter of fact, it is not even clear whether empirical small-signal models will be appropriate for the wafer etch process.

A primitive supervisory control platform has been developed and tested on the RIE. This high level system features a generic central control mechanism, a sequential statistical process optimization algorithm, standardized communications, and extensive *in-situ* monitoring and diagnostics capabilities [16]. The current focus is on the development of a generic supervisory control framework and dynamic/flexible implementations.

IV. SYSTEM IDENTIFICATION AND CONTROLLER DESIGN

A. System Identification

In order to build models for the plasma system, we have taken an experimental system identification approach. First, a region of operating points was delineated in the space of pressure, (CF_4) flow rate, and power corresponding to the reactive ion etching region of the plasma parameter space: the pressure from 8 to 30 mtorr, the flow rate from 15 to 40 sccm, and the power ranged from 800 to 1300 W. Based on this study, we chose 20 mtorr, 30 sccm, and 1000 W as the nominal operating point. The throttle position corresponding to these settings is 12.5% open. It turned out that the gas flow rate as a control input variable had weak control authority. Indeed, we have carried out experiments [9] to identify a model with inputs signals (throttle position, gas flow, applied RF power) and output signals (V_{bias}, pressure, and [F]). The resulting transfer matrix had an effective rank of two and not three as one may have hoped *a priori*. The physical reason for this is the following: input flow rate and throttle position primarily affect pressure, and then pressure in turn affects V_{bias} and [F]. Thus these two actuators are affecting the plasma through a single process variable, pressure, and thus are not independent. As a consequence, in steady state conditions, the transfer matrix becomes a real 3×3 matrix with numerical rank equal to two. From a control systems point of view, this means that *only two* of the model's outputs can be independently controlled since we only have two independent actuators: power and either flow or throttle. Further analysis revealed that throttle position was the most effective actuator, so the flow was simply held fixed at 30 sccm. Results in [9] show that (V_{bias} and [F]) seem to be the best choice for the two outputs to control. This makes physical sense since V_{bias} and [F] are more closely related, as compared to the pressure, to the physical and chemical components of etching. If we were to use a more complicated gas chemistry such as, CF_4/O_2, then we expect that we could actually control all three of (V_{bias}, pressure, and [F]) by using the percentage of O_2 as the third actuator.

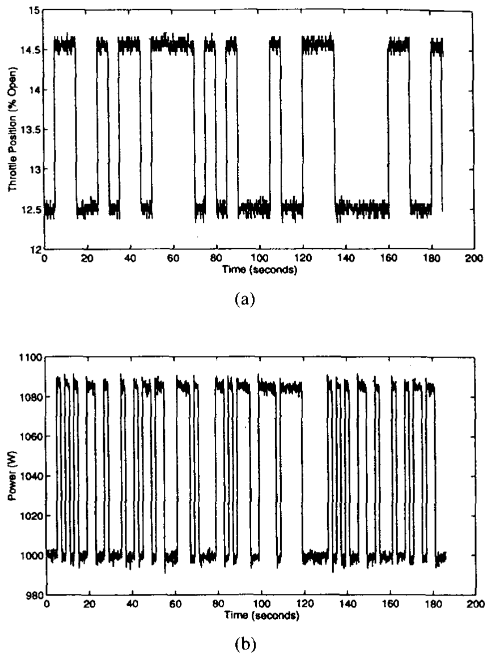
We performed small-signal experiments to build empirical dynamic model for the plasma subsystem. For this, we applied a 10% step increment on power, keeping the throttle angle constant, and measured the resulting V_{bias} and [F] time responses. This was followed by the application of a 16% step increment input on the throttle position, while keeping power constant, and measuring the resulting V_{bias} and [F] time responses. As the actual measurements are quite noisy, these experiments were repeated several times under identical conditions and the resulting measurements were averaged to reduce the noise.[1] From this step response data, using standard system identification algorithms, we computed a transfer function matrix relating small deviations in power and throttle position to the deviations in V_{bias} and [F] from their nominal values. The resulting transfer matrix was

$$\begin{bmatrix} V_{\text{bias}} \\ [\text{F}] \end{bmatrix} = \begin{bmatrix} \dfrac{2.72e^{-0.5s}}{s+0.17} & \dfrac{0.444}{s+1.25} \\ \dfrac{-0.43e^{-0.5s}}{(s+0.21)} & \dfrac{0.12}{s+4.93} \end{bmatrix} \begin{bmatrix} \text{Throttle} \\ \text{Power} \end{bmatrix}.$$

There are some differences between this identified model and the one reported in [8]. Most of these differences are related to the actinometry system described above. For example, the sign of the dc gain of the transfer function from throttle position to [F] is opposite to that reported in [8]. This is because the

---

[1] It is emphasized that averaging will NOT be done when the controller is implemented.



(a)

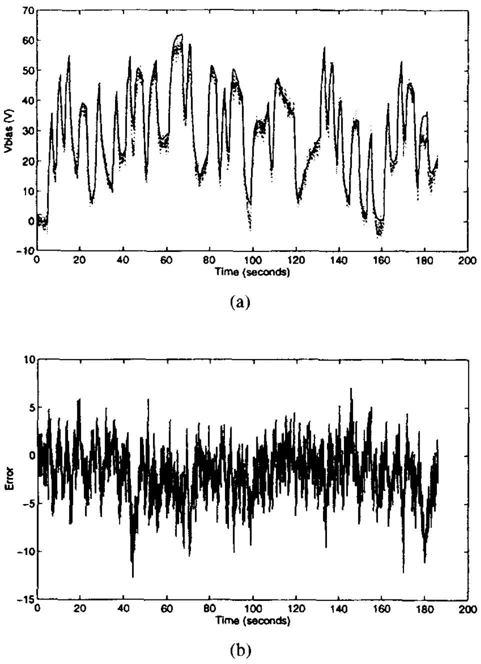
(b)

Fig. 2. PRBS applied in model validation experiment.

estimate for [F] now contains pressure which was not the case in [8]. An increase in throttle opening causes a decrease in pressure which in turn leads to the negative sign on the dc gain.

B. Model Validation

In order to determine if the 2 × 2 transfer function model represented a good approximation of the physical system, an experimental test was performed. The model was identified by exciting the system with only one actuator at a time; in the real system, it is of course possible to vary the throttle and power simultaneously. In principle, our linear model should predict the response to small simultaneous variations in the actuators with the same fidelity as it predicts the response to individual variations. In practice, however, the model may fail to accurately describe the system response due to neglected effects of nonlinearity. To test the fidelity of our model in describing simultaneous actuator variations, two simultaneous pseudo random binary signals (PRBS) were applied to the actuators; these are shown in Fig. 2. The PRBS applied to the throttle position was given a slower switching rate because the dynamics associated with the throttle are slower than those associated with the power input. The response of the model and the actual system, as well as the error between them, is plotted in Fig. 3 for the V_{bias} signal; the results are similar for [F]. As can be seen from the plot, except for a small bias in the response, the model accurately represents the dynamics of the system; a tentative explanation for this bias is that it is due to nonlinearity. Investigation of nonlinear variations of the system at different points of the operating regime is an ongoing part of our research.



(a)

(b)

Fig. 3. Comparison of actual and simulated responses to simultaneous PRBS inputs.

C. Controller Design

Based on this model, we designed a feedback controller for the plasma generation process. A key consideration limiting controller performance was the existence of bandwidth constraints. These arose from two sources. First, the optical emission spectroscopy based sensor for fluorine has a poor signal-to-noise ratio, and effectively limits the loop crossover frequency to be less than 1 rad/s. In addition, since the throttle is highly nonlinear, it is necessary to limit the overshoot in throttle response to step commands in V_{bias} and [F] to less than 5%. This further reduced the bandwidth to around 0.5 rad/s.

The compensator was designed using the following procedure. First, the inputs and outputs were scaled by their nominal values so that a unit deviation in one is equivalent to a unit deviation in another. Next, to achieve steady state rejection of step disturbances and tracking of step commands in V_{bias} and [F], integrators were augmented to the plant model. The time delays were represented by a second order Padé approximation. The LQG/LTR design procedure [6] at the plant input was applied to design an observer-based controller. Several iterations of the design were performed to achieve acceptable speed of command response, actuator overshoot, and noise rejection. The compensator was then reduced via the balanced realization procedure to obtain a fifth order controller. This controller contains the augmented integrators, plant scalings, and the nominal signal values that define the operating point at which the linearized plant model was obtained. Complete details are given in the Appendix. The controller was found to work satisfactorily in implementation despite process nonlinearities and model inaccuracy.

V. EXPERIMENTAL INVESTIGATION OF THE CLOSED-LOOP CONTROL SYSTEM

The principal aim of this paper is to explore the potential benefits of the plasma generation process controller, as measured by its ability to attenuate the effect of exogenous perturbations on the etch characteristics. As mentioned in the Introduction, our control strategy is indirect—we are controlling the plasma parameters V_{bias} and [F]—whereas we are really interested in the etch process. It is not clear *a priori* whether good control of V_{bias} and [F] will lead to stabilization and control of the etch characteristics. For our initial work and this paper, we have chosen the stability of the etch rate as the measure of performance. Etch rate data is collected in real time using the interference of laser light reflected off of the laser surface, as described in Section II.

A. Description of Experiments

To examine the ability of a control system based on V_{bias} and [F] to attenuate process variations, we designed a number of etch experiments around our experimental hardware. Since our reactor does not have a load lock, it must be opened to the ambient atmosphere when a wafer is loaded before each etch. As a result, water vapor adsorbs onto the inner walls of the reactor; the thickness of the film seems to vary with the degree of polymer buildup on the reactor's inner surfaces. The desorption of this moisture into the chamber acts as a "wall disturbance" to the etch process and is present in all of our experiments. This is a very large disturbance as our reactor has a large surface area. While in commercial practice there is always a load lock, one must still contend with contaminants that build up on the chamber walls over time. From our point of view, the wall disturbance makes for a very good test to demonstrate the power of feedback control.

The experiments we ran are described below.

1) Standard Practice, Open-loop Etch: In this process, we set the pressure, flow, and power, at the nominal values described earlier. This represents standard industrial practice. Note that there is a PID controller to regulate the chamber pressure, but V_{bias} and [F] are not regulated.

2) Base Line, Closed-loop Etch: In this case, we use the plasma generation process controller described in Section III to demonstrate the efficacy of closed-loop control in reducing the effect of the wall disturbance upon etch rate. In this experiment, the setpoints for (V_{bias}) and ([F]) were chosen to be 342 V and 47.1 (arbitrary units), respectively.

3) Loading Effect Experiment: The amount of exposed surface area to be etched will often vary from batch to batch. As the amount of exposed material in the chamber increases, so does the rate of consumption of the etchant. This may result in a decrease in etch rate, and is often termed a "loading effect" [29, p. 529]. To assess the effect of a loading disturbance upon etch rate, we ran etches with 2 wafers in the chamber, instead of just 1, therefore doubling the area of exposed silicon.

4) Oxygen Leak Experiment: The addition of small amounts of oxygen has been found empirically to cause a significant increase in the etch rate of polysilicon. It is believed that this is caused by reactions between CF_4 and O_2 which result in an increase in fluorine concentration [29 p. 549]. To emulate the effect of an O_2 disturbance upon etch rate, we introduced 1 sccm of O_2 in increments of $\frac{1}{2}$ sccm of O_2 applied at 600 and 1200 s into the etch.

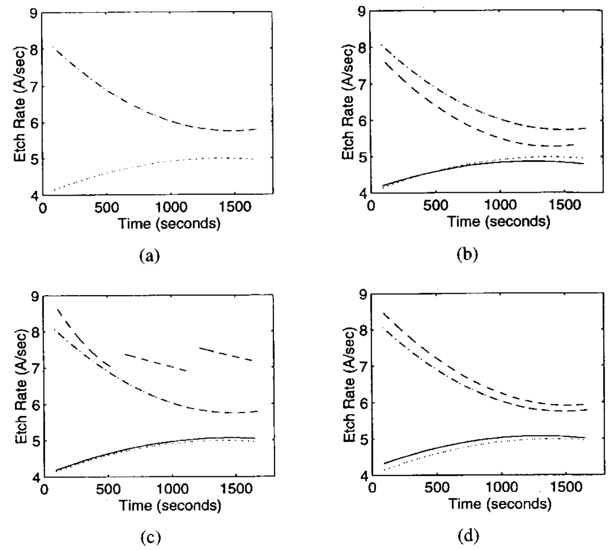
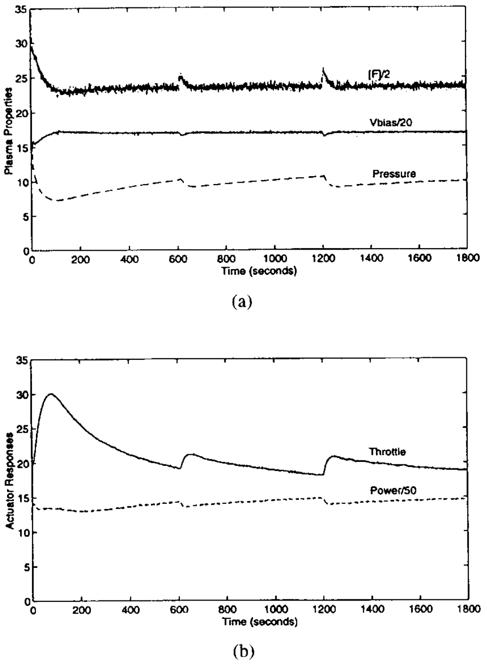


Fig. 4. Experimental results.

5) Power Mismatch Experiment: As mentioned previously, an RF matching network is used for impedance matching between the power source and the reactor load. To examine the impact of variations in the matching network or other variations in the power supply, we had the power supply respond with 2% more power than was commanded from it. In the open-loop case, this amounted to shifting the power from 1000 to 1020 W.

VI. RESULTS

In Fig. 4(a), the dash-dot curve is the etch rate under a standard practice open-loop etch. Notice that the etch rate decreases slowly over the length of the experiment. An explanation for this is that, during the initial phase of the etch, a significant amount of moisture is desorbed from the walls into the chamber. This moisture increases the etch rate by increasing the concentration of fluorine [18, p. 39]. The very high initial etch rate serves to demonstrate the fact that this is a very large disturbance. As the experiment progresses, the desorption of moisture decreases, as does the etch rate. The etch rate under the closed-loop conditions is shown by the dotted line. As one can see, the etch rate is much more constant under closed-loop conditions. The etch rates settle to different values because the setpoints under closed-loop control were different from the steady-state values of the plasma conditions in the open-loop experiment. It has been shown [8] that if the plasma setpoints are chosen to be the steady-state open-loop conditions, then the etch rates do indeed settle to the same rate. In this closed-loop experiment, as well as the others, the etch rate starts off below the steady-state value. However, the values of V_{bias} and [F] remain constant throughout the etch. One explanation is that while



(a)

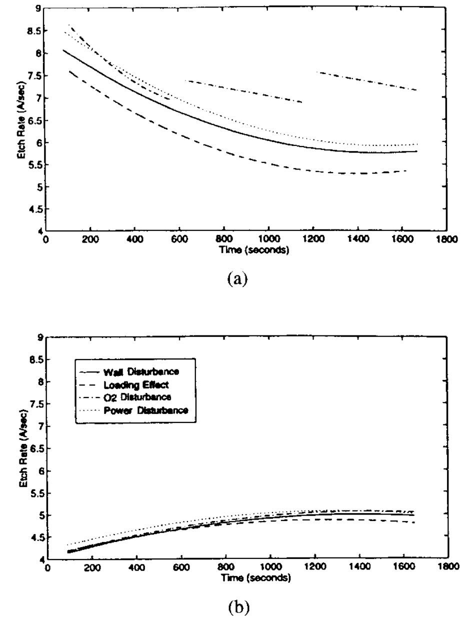
(b)

Fig. 5. Response of system during closed loop O_2 leak experiment.

the fluorine estimate, $(I_F/I_{Ar}\, P)$, is held constant, the actual concentration is not. Another reason is that there are factors other than V_{bias} and [F] which affect the etch rate. In other words, while regulating V_{bias} and [F] does reduce the impact of the disturbance substantially, it does not eliminate its effect. A full analysis of this phenomenon is a subject of our current research.

Fig. 4(b) shows the etch rates for the loading effect experiment. Here, the dashed curve represents the open-loop etch rate while the solid curve represents the closed-loop etch rate. The dash-dot and dotted lines from the wall disturbance experiments are included on this and the other plots to make comparisons easier. As expected, increased loading leads to a decrease in etch rate under open-loop conditions. However, comparison of the closed-loop data (the solid and dotted lines) shows that the impact of the loading on etch rate is greatly attenuated.

Etch rate data for the oxygen leak experiment is shown in Fig. 4(c). Notice that upon injection of oxygen, the etch rate goes up under open loop conditions, as expected. Under closed-loop conditions, the addition of oxygen makes virtually no difference to the etch rate. Notice that, despite very similar operating conditions, there is a difference in the open-loop experiment between the dashed curve and the dash-dot curve even before the injection of oxygen. An explanation for this phenomenon is that the amount of moisture absorbed on the walls varies from etch to etch depending upon the duration of the exposure to the atmosphere while loading the wafer and the condition of the chamber. The response of the V_{bias}, [F], and pressure signals for the oxygen leak experiment are shown in Fig. 5, along with the corresponding actuator responses.



(a)

(b)

Fig. 6. Comparison of the effects of the various disturbances under both (a) standard practice and (b) V_{bias} and [F] control.

Finally, the power disturbance results are shown in Fig. 4(d). As expected, an increase in power increases the etch rate under open-loop conditions. (Integrating this difference over the etch duration may be sufficient to break through to the next layer of material!) However, under closed-loop control, there is virtually no difference in the etch rate.

These results demonstrate that closed-loop control of the key plasma parameters, such as V_{bias} and [F], can result in a significant reduction in the deleterious effects of common disturbances as compared to the standard practice open-loop etches. This is certainly quite true for the loading effects, oxygen disturbance, and the power disturbance. This can be seen very clearly in Fig. 6 where results from the various disturbances using each control strategy are reshown. Even for the wall disturbance, we have achieved a significant reduction in the impact of the disturbance, but there is room for improvement.

C. Additional Results on Real-Time Control

Our initial efforts on real-time control have concentrated on feeding back plasma variables to attenuate the effects of process disturbances as illustrated in this paper. Additional results on two-input, two-output controllers which regulate estimated fluorine concentration and bias voltage are reported in [8], [9], [13], [19]; these references use controllers designed on the basis of dynamic linear models obtained from system ID methods. A higher fidelity nonlinear model obtained from system ID methods and a nonlinear controller are given in [28]. A real-time controller was fully integrated into an *a*-Si thin film transistor (TFT) fabrication process in [13]. The paper [9] explored the benefits of using multiple-input, multiple-output controllers versus several "independent" single-input, single-output PID controllers. A three-input, three-output controller

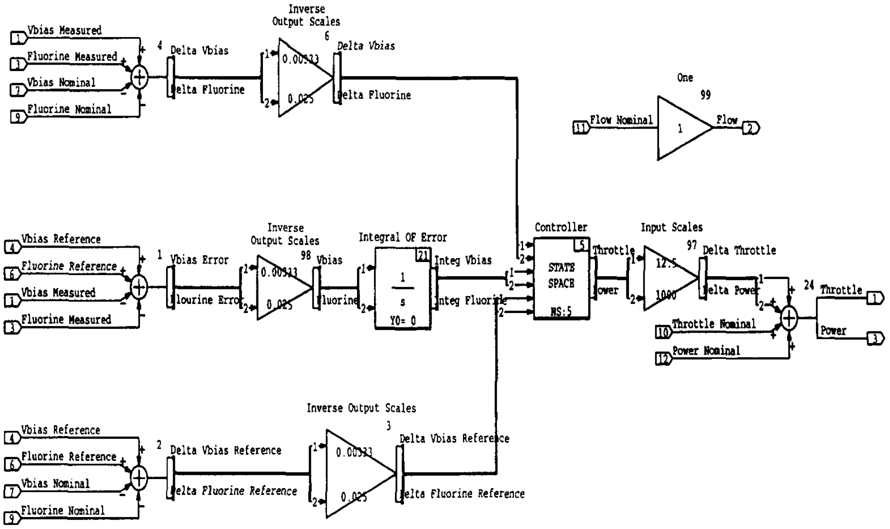


Fig. 7. Implementation of the controller.

which regulates estimated dc-bias voltage, pressure, and fluorine concentration, has been designed on the basis of a linear system ID model [20]; this paper also outlines our initial work on the etch controller. Initial development of an improved real-time fluorine estimator based on a phenomenological model can be found in [12]. A control-oriented phenomenological model of the plasma generation process was begun in [5].

VII. Conclusion

In this paper, we have developed a real-time feedback control system for an RIE machine for a relatively simple gas chemistry. The results demonstrate conclusively that the introduction of real-time feedback control leads to a much more stable etch rate as compared to the standard industrial practice of setting pressure, flow, and power. It is hoped that these efforts will be of use in obtaining significant improvements in the performance characteristics of semiconductor manufacturing equipment.

Appendix

The complete controller, including scalings and augmented integrators, is shown in Fig. 7. The Controller block represents

$$\begin{aligned}\dot{x} &= Ax + Bu,\\ y &= Cx + Du,\end{aligned}$$

where u are the inputs on the left and y are the outputs on the right and the A, B, C, and D matrices are given below:

$$A = \begin{bmatrix} -3.347 & -0.816 & -0.921 & -1.023 & 0.354 \\ 1.346 & -2.994 & 6.772 & 2.681 & 1.650 \\ 0.184 & 6.443 & -14.945 & -6.734 & -3.961 \\ -0.583 & 2.928 & -6.982 & -6.847 & -2.023 \\ 0.087 & 1.657 & -4.184 & -5.905 & -3.000 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & -0.0002 & 0.612 & -0.729 & -0.203 & 0.242 \\ 0 & 0.0007 & 0.482 & 0.554 & -0.160 & -0.184 \\ 0 & 0.0000 & -1.087 & -0.969 & 0.360 & 0.321 \\ 0 & -0.0003 & -0.239 & -0.326 & 0.079 & 0.108 \\ 0 & 0.0005 & -0.185 & -0.135 & 0.061 & 0.045 \end{bmatrix}$$

$$C = \begin{bmatrix} 0.997 & 0.074 & -0.047 & 0.116 & -0.080 \\ -0.112 & 0.770 & -1.533 & -0.410 & -0.227 \end{bmatrix}$$

$$D = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}.$$

References

[1] K. D. Allen, H. H. Sawin, M. T. Mocella, and M. W. Jenkins, "The plasma etching of polysilicon with CF_3Cl/Argon discharges: Part I, parametric modeling and impedance analysis," *Solid State Sci. Technol.*, vol. 133, pp. 2315–2325, 1986.

[2] S. Balemi, G. Hoffmann, R. Gyugyi, H. Wong-Toi, and G. Franklin, "Supervisory control of a rapid thermal multiprocessor," *IEEE Trans. Automat. Cont.*, vol. 38, pp. 1040–1059, 1993.

[3] S. W. Butler, "Etching and polymerization in fluorocarbon hydrogen plasmas: Mathematical modeling and experimental validation," Ph.D. dissertation, University of Texas at Austin, 1991.

[4] S. W. Butler, K. J. McLaughlin, T. F. Edgar, and I. Trachtenberg, *J. Electrochem. Soc.*, vol. 138, pp. 2727–2735, 1991.

[5] M. Chandhok, M. D. Giles, P. D. Hanish, and J. W. Grizzle, "Phenomenological modeling of plasma generation for real-time control of RIE systems," presented at the Workshop on Numerical Modeling of Processes and Devices for Integrated Circuits: NUPAD V, Hawaii, June 1994.

[6] J. C. Doyle and G. Stein, "Multivariable feedback design: Concepts for a classical/modern synthesis," *IEEE Trans. Automat. Cont.*, vol. AC-26, pp. 4–16, 1981.

[7] D. Edelson and D. L. Flamm, "Computer simulation of a CF_4 plasma etching silicon," *J. Appl. Phys.*, vol. 56, pp. 1522–1531, 1984.

[8] M. Elta, H. Etemad, J. S. Freudenberg, M. D. Giles, J. W. Grizzle, P. T. Kabamba, P. P. Khargonekar, S. Lafortune, S. M. Meerkov, J. R. Moyne, B. A. Rashap, D. Teneketzis, and F. L. Terry, Jr., "Applications of control to semiconductor manufacturing: Reactive ion etching," in *Automat. Cont. Conf.*, 1993, pp. 2990–2997.

[9] M. Elta, J. P. Fournier, J. S. Freudenberg, M. D. Giles, J. W. Grizzle, P. P. Khargonekar, B. A. Rashap, F. L. Terry, Jr., and T. Vincent, "Real-time feedback control of reactive ion etching," in *Proc. Microelectron. Processes, Sensors, Cont. Conf.*, 1993, pp. 438–451.

[10] R. A. Gottscho and V. M. Donnelly, "Optical emission actinometry and spectral line shapes in RF glow discharges," *J. Appl. Phys.*, vol. 56, pp. 245–250, 1984.

[11] R. Gyurcsik, T. Riley, and F. Sorrell, "A model for rapid thermal processing: Achieving uniformity through lamp control," *IEEE Trans. Semiconduct. Manufact.*, vol. 4, no. 1, pp. 9–13, 1991.

[12] P. D. Hanish, J. W. Grizzle, M. D. Giles, and F. Terry, Jr., "A model based technique for estimation of fluorine in a CF_4/Ar plasma," *JVST, A*, 1995.

[13] J. S. Herman, T. E. Benson, O. D. Patterson, C. Y. Chen, A. T. Demos, P. P. Khargonekar, F. L. Terry Jr., and M. E. Elta, "Real-time control of reactive ion etching of amorphous silicon for thin film transistor applications," in *Electrochem. Soc. 186th Meeting*, 1994.

[14] D. M. Manos and D. L. Flamm, Eds., *Plasma Etching: An Introduction.* New York Academic Press, 1989.

[15] K. J. McLaughlin, T. F. Edgar, and I. Trachtenberg, "Real-time monitoring and control in plasma etching," *IEEE Control Systems Magazine*, vol. 11, pp. 3–10, 1991.

[16] J. R. Moyne and L. C. McAfee, "A generic cell controller for the automated VLSI manufacturing facility," *IEEE Trans. Semiconduct. Manufact.*, vol. 5, no. 2, 1992.

[17] *Plasma Processing of Materials: Scientific Opportunities and Technological Challenges.* Plasma Science Committee, National Academy Press, 1991.

[18] M. L. Passow, "Microwave, RF, and hybrid reactor generated discharges for semiconductor processing," Doctoral dissertation, University of Michigan, 1991.

[19] B. A. Rashap, M. E. Elta, J. S. Freudenberg, J. W. Grizzle, P. P. Khargonekar, and F. L. Terry, Jr., "Real-time control of reactive ion etching: Identification and disturbance rejection," in *Proc. 32nd Conf. Decision Cont.*, 1993, pp. 3379–3385.

[20] B. A. Rashap, J. S. Freudenberg, and M. E. Elta, "Real-time feedback for sidewall profile control in reactive ion etching," *JVST, A*, 1994.

[21] E. Sachs, R. Guo, S. Ha, and A. Hu, "Process control system for VLSI fabrication," *IEEE Trans. Semiconduct. Manufact.*, vol. 4, no. 2, pp. 134–144, 1991.

[22] C. Schaper, T. Kailath, M. Moslehi, and K. Saraswat, "Modeling, identification, and control of rapid thermal processing systems," preprint, Dept. of Electrical Engineering, Stanford University.

[23] *Sematech Advanced Equipment Control Workshop,* Mesa, AZ, Mar. 3–5, 1992.

[24] V. Singh, A. E. Varnas, and R. Rhinehart, "Reaction kinetics of silicon dioxide in CF_4 and CF_4/O_2 plasmas in various reactor configurations," submitted to *Int. J. Chem. Kinet.*, preprint Aug. 1993.

[25] R. A. Soper, D. A. Mellichamp, and D. E. Seborg, "An adaptive nonlinear control strategy for photolithography," *IEEE Trans. Semiconduct. Manufact.*, pp. 2998–3002.

[26] C. J. Spanos, "Statistical process control in semiconductor manufacturing," *Proc. IEEE*, pp. 819–830, 1992.

[27] M. Wilcoxson and V. Manousiouthakis, "Glow discharge modeling," *AIChE Annual Meeting,* Miami Beach, FL, Nov. 1992, Paper 204c.

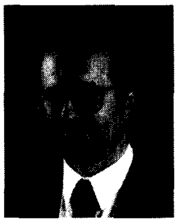
[28] T. L. Vincent, P. P. Khargonekar, B. A. Rashap, F. Terry, Jr., and M. E. Elta, "Nonlinear system identification and control of a reactive ion etcher," in *Proc. Amer. Cont. Conf.*, 1994, pp. 902–906.

[29] S. Wolf and R. N. Tauber, *Silicon Processing for the VLSI Era.* Sunset Beach, CA: Lattice Press, 1986.

[30] G. C. H. Zau, J. W. Butterbaugh, P. Rummel, and H. Sawin, "Monitoring and control of real power in RF plasma processing," *J. Electrochem. Soc.*, vol. 138, no. 3, pp. 872–873, 1991.

Brian A. Rashap received the B.S.E. degree in electrical engineering from the University of Michigan, Ann Arbor, MI, in 1990. In 1991, he received the M.S.E. degree in electrical engineering systems from the University of Michigan.

He has researched the control of large flexible space structures as a NASA Graduate Student Research Fellow; this work included the application of control strategies to an experimental space structure at the NASA Langley Research Center, Hampton, VA. Still at the University of Michigan, he is a Ph.D. candidate in Electrical Engineering Systems and a member of the Electronics Manufacturing and Control Systems Laboratory. In addition to his dissertation topic, Real-Time Feedback for Sidewall Profile Control in Reactive Ion Etching, his research interests include: empirical modeling of plasma processes, real-time control for microelectronic fabrication processes, computer simulations of etch profiles, sensors for *in-situ* process control, and implementation of software for real-time control. Later this year, he will be joining Intel, Albuquerque, NM, as a Senior Process Engineer for the Metal Etch group.



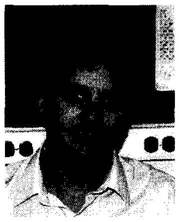
Michael E. Elta (S'78–M'78) received the B.S.E. degree in electrical engineering from the General Motors Institute, Flint, MI, in 1975, and the M.S.E. degree in electrical engineering from the University of Michigan, Ann Arbor, MI, in 1975. He received the Ph.D. degree in electrical engineering from the University of Michigan, in 1978. His doctoral work involved the numerical modeling of microwave transit-time devices.

From 1969 to 1973, he was a cooperative engineering student at AC Spark Plug, GMC, Flint, MI, and at The University of Michigan he was a Research Assistant in the Electron Physics Laboratory from 1975 to 1978. From 1978 to 1982, he was a member of the research staff, in the microelectronics group, at MIT Lincoln Laboratory, Lexington, MA. He has been at The University of Michigan, Ann Arbor, MI, since 1982. He is presently Executive Director of the Center for Display Technology and Manufacturing in the College of Engineering at The University of Michigan. He is a Research Scientist in the Electrical Engineering and Computer Science Department. His research activities are located in the Electronics Manufacturing and Control Systems (EMACS) Laboratory. His technical interests include flat panel display technology, sensor-based electronics manufacturing, plasma processing in microelectronics, plasma modeling, in-situ process diagnostic techniques, laser-based meteorology, and real-time equipment control.

Dr. Elta is a member of Tau Beta Pi, Sigma Xi, SID, and the American Vacuum Society.

Hossein Etemad received the B.S.E.E. degree from Seattle University in 1987 and the M.S.E.E. degree from The University of Michigan, Ann Arbor, in 1990.

From 1988 to 1990, he served as a Graduate Student Research Assistant at The University of Michigan. Since 1990, he has been employed as a Senior Research Associate in the Department of Electrical Engineering and Computer Science at The University of Michigan, Ann Arbor. His research topics include cell and run-to-run controller design, manufacturing automation, applications programming and statistical process control.

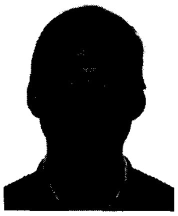


Jeffrey P. Fournier joined the Department of Electrical Engineering and Computer Science at the University of Michigan, Ann Arbor, in 1987, where he is currently a Project Manager in the area of flat panel displays. Prior to joining the University, he spent the previous eight years engaged in amorphous silicon photo voltaic research. Since joining the University, his work has included hardware and software development for vacuum process tools. His current research interests include control of semiconductor processes and equipment, plasma etch, and deposition processes.

James S. Freudenberg (S'80–M'84) was born in Gibson County, IN, in 1956. He received the B.S. degree in mathematics and physics from Rose-Hulman Institute of Technology, in 1978, and the M.S. and Ph.D. degrees in electrical engineering from the University of Illinois, in 1982 and 1984, respectively.

In 1984, he joined the Electrical Engineering and Computer Science Department at the University of Michigan, where he is currently an Associate Professor. From 1978 to 1979, he worked for the Navigation Systems Technology Group of Rockwell-Collins Avionics, Cedar Rapids, Iowa. He has consulted at the Honeywell Systems Research Center, Minneapolis. During the first six months of 1993, he was a visiting researcher at the University of Newcastle, Australia. His research interests are in robust multivariable control, sampled-data control, feedback design limitations, and applications to automotive, semiconductor manufacturing and aerospace problems.

Dr. Freudenberg received the Presidential Young Investigator Award in 1988.



Martin D. Giles (S'82–M'84) was born in London, England, in 1958. He received the B.A. and M.A. degrees in natural sciences from Cambridge University, England, in 1981 and 1985, and the M.S.E.E. and Ph.D. degrees from Stanford University, CA, in 1983 and 1984, respectively.

In 1984, he joined AT&T Bell Laboratories, Murray Hill, NJ, as a member of the VLSI device analysis and simulation group. There he developed and applied advanced process models for submicron silicon technology including defect-coupled diffusion, ion implantation, and sputter deposition. From 1990 to 1994, he was an assistant professor in the EECS department at the University of Michigan where he worked on silicon process modeling, plasma process equipment modeling, MEMS device modeling, and technology computer-aided design frameworks. He is currently a member of the Technology CAD department at Intel in Santa Clara, CA, where he is continuing his research interests in the modeling of process technology and process equipment, and the development of frameworks for technology computer-aided design.

Dr. Giles is a member of the Electrochemical Society.

Jessy W. Grizzle (S'79–M'83–SM'90) received the Ph.D. degree in electrical engineering from The University of Texas at Austin in 1983.

Since September 1987, he has been with The University of Michigan, Ann Arbor, where he is a Professor of Electrical Engineering and Computer Science. He has held visiting appointments at the Dipartimento di Informatica e Sistemsitica, L'Università di Roma, "La Sapienza," Rome, Italy, and the Laboratoire des Signaux et Systèmes, SUPELEC, CNRS-ESE, Gif-sur-Yvette, France. His major research interests include nonlinear system theory, automotive applications and control of electronics manufacturing equipment, and he is a past Associate Editor of the IEEE TRANSACTIONS ON AUTOMATIC CONTROL.

Dr. Grizzle was a Fulbright Grant awardee and a NATO Postdoctoral Fellow from January to December 1984. He received the Presidential Young Investigator Award in 1987 and the Henry Russell Award in 1993. In 1992, he received the Paper of the Year Award with K. L. Dobbins and J. A. Cook from the IEEE Vehicular Technology Society.

Pierre T. Kabamba (M'94) received the degree of "Ingénieur Civil en Mathématiques Appliquees" from the University of Louvain, Belgium, in 1977, and the Ph.D. degree in mechanical engineering from Columbia University, NY, in 1981.

In 1983, he joined the Aerospace Engineering Department of the University of Michigan, where he is currently a Professor. His current research interests are in sampled-data control, robust control, modeling, design, guidance, and navigation.

Pramod P. Khargonekar (M'81–SM'90–F'93) received the B.Tech. degree in electrical engineering from the Indian Institute of Technology, Bombay, in 1977, the M.S. degree in mathematics and the Ph.D. degree in electrical engineering from the University of Florida, in 1980 and 1981, respectively.

From 1981 to 1984, he was an Assistant Professor of Electrical Engineering at the University of Florida. In 1984, he joined the University of Minnesota as an Associate Professor, and in 1988 became a Professor of Electrical Engineering. He joined The University of Michigan, in 1989, where he is a Professor of EECS. His research and teaching interests are in control systems, analysis and design, robust control, system identification and modeling, and applications of control to electronics manufacturing systems. He served as the Vice-Chair for Invited Sessions for the 1992 American Automatic Control Conference. He was an associate editor of the IEEE TRANSACTIONS ON AUTOMATIC CONTROL, *SIAM Journal on Control and Optimization*, and *Systems and Control Letters*. He is currently an associate editor of *Mathematics of Control, Signals, and Systems, Mathematical Problems in Engineering*, and the *International Journal of Robust and Nonlinear Control.*

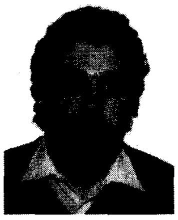
Dr. Khargonekar is a recipient of the American Automatic Control Council's (AACC) Donald Eckman award in 1989, the NSF Presidential Young Investigator award in 1985, 3 best paper awards including the 1991 IEEE W. R. G. Baker Prize Award, and the Japan Society for Promotion of Science Fellowship in 1992. At the University of Michigan, he received a teaching excellence award from the EECS department in 1991 and a research excellence award from the College of Engineering in 1994. He is a Fellow of IEEE.

Stéphane Lafortune (S'85–M'86) received the B.Eng. degree from the École Polytechnique de Montréal in 1980, the M.Eng. degree from McGill University in 1982, and the Ph.D. degree from the University of California, Berkeley, in 1986, all in electrical engineering.

Since 1986, he has been with the Department of Electrical Engineering and Computer Science at the University of Michigan, where he is an Associate Professor. His current research interests include discrete-event systems (modeling, on-line control, failure diagnosis, and applications), and intelligent vehicle-highway systems.

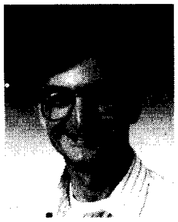
James R. Moyne (S'88–M'90) received the B.S.E.E. and B.S.E. degrees from The University of Michigan, Dearborn, in 1983, and the M.S.E.E. and Ph.D. degrees from The University of Michigan, Ann Arbor, in 1984 and 1990, respectively.

From 1987 to 1994, he served on the various committees of Semiconductor Equipment and Materials International, where he was the chief technical designer of both the SECS Message Service specification (which has been internationally adopted as a standard for semiconductor equipment communications) and a sensor bus specification (which is being reviewed for international standard adoption). He is currently an assistant research scientist in the Department of Electrical Engineering and Computer Science at The University of Michigan, Ann Arbor. His research topics include cell and run-to-run controller design, process control, manufacturing automation, networking, and database design and implementation. He has a background in local area networks, discrete control, solid-state circuits, mathematics, and databases, and has a patent pending on a generic cell controller design.



Demosthenis Teneketzis (M'87) received the B.S. degree in electrical engineering from the University of Patras, Patras, Greece, in 1974, and the M.S., E.E., and Ph.D. degrees in electrical engineering from the Massachusetts Institute of Technology, Cambridge, MA, in 1976, 1977, and 1979, respectively.

From 1979 to 1980, he worked for Systems Control Inc., Palo Alto, CA, and from 1980 to 1984, he was with Alphatech Inc., Burlington, MA. Since September 1984, he has been with the University of Michigan, Ann Arbor, where he is presently a Professor of Electrical Engineering and Computer Science. In the winter and spring of 1992, he was a visiting Professor at the Institute for Signal and Information Processing of the Swiss Federal Institute of Technology (ETH), Zurich, Switzerland. His current research interests include stochastic control, decentralized systems, queueing and communication networks, stochastic scheduling and resource allocation problems, and discrete event systems.



Fred L. Terry, Jr. (S'80–M'85) received the B.S. and M.S. degrees, and the Ph.D. degree from the Massachusetts Institute of Technology, Cambridge, all in electrical engineering, in 1981 and 1985, respectively.

His doctoral work involved the electronic properties of ammonia-annealed silicon dioxide films (nitrided oxides). After completing his education, he joined the Department of Electrical Engineering and Computer Science at the University of Michigan, Ann Arbor, where he is currently an Associate Professor. His current research interests include nondestructive and *in-situ* characterization techniques including spectroscopic ellipsometry and reflectometry, control of semiconductor processes and equipment, plasma etch and deposition processes, the physics and technology of insulated gate devices in crystalline and amorphous Si and III–V compound semiconductors, and materials problems in microfabrication.

Dr. Terry is a member of the American Physical Society, the Electrochemical Society, the Metallurgical Society of the AIME, the Electron Devices Society of the IEEE, and Sigma Xi.