ROBUST TWO-TIME SCALE CONTROL SYSTEM DESIGN FOR REACTIVE ION ETCHING SYSTEM

N. Tudoroiu, K. Khorasani and V. Yurkevich

Department of Electrical & Computer Engineering , Concordia University
1455 de Maisonneuve Blvd. W., Montreal, Quebec, Canada, H3G 1M8
e-mail: tnicolae@excite.com, kash@ece.concordia.ca, yurkev@mail.ru

Keywords: Control of reactive ion etching process.

Abstract

The problem of designing a robust controller to solve a tracking control problem for improving plasma characteristics in Reactive Ion Etching Systam is studied. The presented design methodology is based on the construction of a two-time scale motions of the closed-loop system. It has been shown that a sufficiently small perturbation parameter associated with the dynamical controller consisting of high order derivatives of the output signal, induces a two time-scale separation of the fast and slow modes in the closed-loop system. Stability conditions imposed on the fast and slow models can ensure that the full-order closed-loop system achieves the desired properties so that the output transient performances are insensitive to parameter variations and external disturbances.

1 Introduction

In order for the semiconductor industry improves its competitiveness, it is critical that its factories produce highly advanced products at very low costs. To achieve these goals, these factories must be equipped with processing systems which can perform their functions with very high accuracy and throughput but with low overall costs. Reactive Ion Etching (RIE) is a critical technology for modern VLSI circuit fabrication used in many stages of the manufacturing process [2]. Silicon dioxide films are of significant interest as an interlayer dielectric material for integrated circuits and multichip modules (MCM's). The patterning of these films is of crucial importance in semiconductor manufacturing. Reactive Ion Etching (RIE) in radiofrequency (RF) glow discharges is among the most used methods for forming via holes in between metal layers of an MCM and for achieving the level of detail necessary to define small features in films [4]. The lack of feedback control in these systems is generally considered as one of the main challenging problems facing the semiconductor manufacturing industry. This in particular is a major impediment in reliable operation of low pressure reactive plasma systems [2]. The principal motivation for introducing advanced control techniques in these systems is that by controlling appropriate plasma parameters (the concentrations of the reactive radicals and ions and ions energy) it is possible to improve the etch performance of the reactive ion etchers, namely their selectivity, uniformity, anisotropy and etch depth. The current state of knowledge in RIE does not yet allow for a definitive choice of the key plasma parameters to be controlled. For example in [1] four measured variables (namely $[F]$, $[CF_2]$, $[CO_x]$, and V_{bias}), four manipulated variables (namely $\%O_2$, $pressure$, $power$, and $flow\ rate$) and seven performance variables (namely $Si\ etch\ rate$, $SiO_2\ etch\ rate$, $Si/SiO_2\ selectivity$, $SiO_2\ anisotropy$, $Si\ uniformity$, $SiO_2\ uniformity$, and $Si\ anisotropy$) were considered for the RIE of silicon and silicon dioxide in CF_4/O_2 and CF_4/H_2 plasma. Furthermore, in [3, 6, 8] only two manipulated variables (namely $power$ and $throttle\ valve\ position$), two measured variables as the key plasma parameters to be controlled (namely V_{bias} and $[F]$) and four performance variables for RIE (namely $etch\ depth$, $selectivity$, $uniformity$ and $anisotropy$) were considered.

The development of real-time control techniques for improving the manufacturing characteristics of reactive ion etching process is well documented in [2]. The overall goal is to redesign the RIE machine for enhanced controllability and improved performance. The objective in [2] is to develop sufficiently general methods and results that allow implementation of real-time feedback control systems to a large class of RIE machines with a minimal amount of tuning. Based on a novel decomposition of the process the authors present a general strategy for the control of RIE. The principal idea is that by controlling appropriate key plasma parameters, it is possible to improve the etch performance of these machines. In [2, 3, 6, 8, 9] the *dc bias voltage*, V_{bias}, and *fluorine concentration* $[F]$ are used as the key plasma parameters to be controlled and *power* of RF generator and *throttle valve position* are selected as input variables. The most important variables for determining the success of the etching process are: *selectivity, uniformity, anisotropy,* and *etch depth*. The authors in [2] conceptualize RIE as consisting of two distinct but interacting mechanisms, namely (***i***) chemical etching caused by radicals, and (***ii***) physical etching caused by ion bombardment. Etch characteristics can therefore be adjusted by carefully controlling the plasma species composition and ion energy. Therefore, the key plasma parameters for the etching process are the concentrations of the reactive radicals and ions and ions energy. Based on the measured output data, and using standard identification algorithms, the authors in [2] have constructed a two input-two output model mapping small perturbations in *power* (Watts) and *throttle valve* (% opening) to the V_{bias} (Volts) and $[\ F]$ signals. The idea is very interesting and although the model is very simple and easy to manipulate, it may not be able to capture all the dynamic of the plasma. Specifically, the problem of representing the dynamics of wafer still remains unanswered. In [5] experimental results are presented on nonlinear models of the Hammerstein type for reactive ion etcher and a nonlinear tracking controller is implemented. This is motivated by the observation that the RIE exhibits significant nonlinear behavior. In [7] a simple nonlinear model structure is used that is an input static nonlinear block (polynomial of second degree) in series with a linear time-invariant system. The model is improved compared to a linear one because it takes into consideration the nonlinearity of the *throttle valve* actuator. However, the problem of capturing the dynamics of the wafer, and whether the model is capable of capturing all the dynamics of the plasma still needs to be investigated.

In this work the RIE system is decomposed in two functional blocks:

(*i*) the plasma generation process (PGP), and

(*ii*) the wafer etch process (WEP).

This decomposition suggests a suitable control structure for the RIE system. From a control engineering viewpoint, the RIE process represents an interesting challenge in several different ways. The key issue is the fact that many of the crucial etch parameters that need to be controlled cannot, at present time, be measured in real-time. This necessitates indirect control strategies wherein plasma parameters are used for feedback to achieve tight control of the etch characteristics.

2 Overview of the RIE Process

In this section a brief description of the RIE process is provided. This description is given from a control system perspective. The emphasis is on the overall system behaviour rather than on an individual physical/chemical processes. It is well known in the plasma community that RIE process is *highly nonlinear* and *multivariable* [2]. Existing plasma systems attempt to control the important wafer etch characteristics with the input variables *pressure*, applied *power*, and *gas flow rates*. However, there is no standard and known way to use these inputs to predict the etch performances in different machines or in identical machines, or even in the same machine on two different runs [2]. This is due to the variations in plasma properties and disturbances and the fact that there is a significant amount of uncertainty in the open-loop system. This is the main reason why we believe that the real-time robust based feedback control strategies developed in this paper will be of great potential benefit to the control of RIE process.

The plasma reactor that is used in this research is an Applied Materials 8300 Hexode Reactive Ion Etcher used at the Control Systems Laboratory of the University of Michigan. This reactor is equipped with a data acquisition system, actuators and sensors appropriate for real-time feedback control. The configuration of parallel plate Plasma Reactor Etching System type 1000TP is presented in Figure 1. The details about the system may be found in [2].

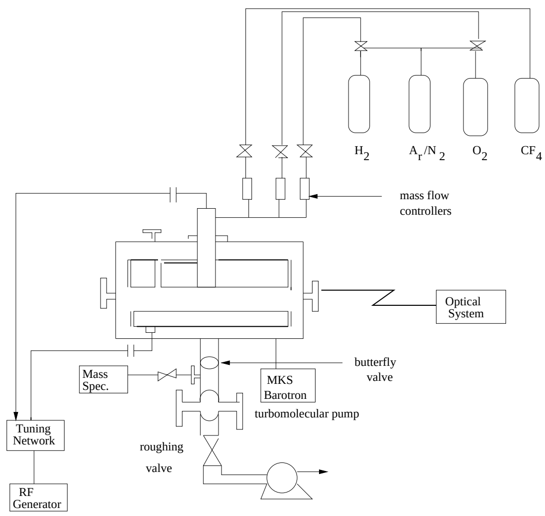

Figure 1: Plasma reactor etching system

2.1 RIE System: Decomposition and Control

The two inputs to the PGS are applied *power* and *throttle valve position* and the two outputs are the key plasma parameters, namely V_{bias} and *fluorine concentration* $[F]$. The above decomposition of the RIE system leads to our control structure shown in Figure 2. The key idea is to regulate the inputs to the WES by precisely controlling the outputs of the PGS [2]. With the existing sensor technology it is very difficult to measure the key wafer etch parameters, namely *selectivity, anisotropy*, etc., in real-time during the etch process. Therefore, for real-time feedback control, an indirect strategy is necessary. The decomposition of the etching process is very important because the modelling task for the WES would involve relating the effects of the key plasma parameters to the etch performance. This is much more direct than trying to build a single model from the equipment inputs to the etch characteristics.

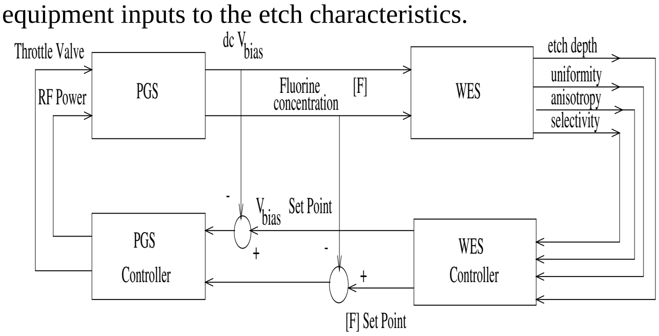

Figure 2: The decomposed structure of the RIE system

2.2 RIE System Modeling

In the PGS the control inputs are RF *power*, *throttle position*, and CF_4/Ar *flow*. The disturbances are *load* and *water vapours*. The state of the plasma system are the *fluorine concentration* $[F]$, and *dc bias voltage*, V_{bias}. The *fluorine* is the dominant etchant species and V_{bias} is used as a measure of the physical energy of the *impinging ions*. The models in [2, 3, 5, 6, 7, 8, 9], are simpler since they use only two independent input variables, namely *power* and *throttle valve* to control two independent output variables, namely V_{bias} and $[F]$. We also choose these variables since the plasma variables and [*F*] are more directly related to the *etch rate* and other output characteristics when compared to the *power* and *pressure*, which are held constant conventionally. The disturbances mostly affect the PGS and not WES, so by controlling the plasma variables, the effects of these disturbances can be mitigated.

3 Problem statement

3.1 Model of the plant

The nonlinear model of the reactive ion etching plant under consideration is given by

$$\dot{x} = f(\theta, x) + g(\theta, x)u \tag{1}$$

$$y = g(\theta, x) \tag{2}$$

which is essentially a generalized model considered in [5] where varying parameters and nonlinearities are included and x is the state vector, $x \in R^3$, θ is the vector of varying parameters, $y = [y_1, y_2]^T = [V_{bias}, Flourine]^T$ is the output available for measurement, $u = [u_1, u_2]^T = [Throttle\ Position, RF\ Power]^T$ is the control vector. The input–output description of (1) with the output described by (2) is then obtained by differentiating the output vector y with respect to time until the input vector appears, which is given by

$$\dot{y} = a(\theta, x) + \beta(\theta, x)u \tag{3}$$

where $y = [y_1, y_2]^T$ is the output available for measurement, $u = [u_1, u_2]^T$ is the control vector (Throttle position and RF Power in (3)). In other words, we have that the relative degree for both output variables equals to unity.

It accordance with the given parameters of the model (3) we need to have the following two assumptions satisfied.

Assumption 3.1 *Let* $\det \beta(\theta, x) \neq 0\ \forall x \in \Omega_x$ *and* $\forall \theta \in \Omega_\theta$ *where* Ω_x *is a specified region in the state space,* Ω_θ *is a specified region of varying parameters.*

Assumption 3.2 *The system (1)-(2) is internally stable (that is, the inverse dynamic is asymptotically stable).*

3.2 Output tracking control problem

Let us denote

$$e(t) = r(t) - y(t) \tag{4}$$

as the tracking error where $y(t)$ is the plant output and $r(t)$ is the reference input signal.

The control system is being designed to provide the following condition

$$\lim_{t \to \infty} e(t) = 0 \tag{5}$$

Moreover, the output transients $y(t)$ should have a desired behaviour which does not depend either on the external disturbances or on the varying parameters of the plant model (1), (2).

4 Control problem formulation

4.1 Desired dynamic equations

As the relative degree for both output variables equals unity then let us construct the model of desired output behavior of $y(t)$ in the form of the following vector differential equation

$$\dot{y} = F(y, r) \tag{6}$$

For example, (6) may have the form of a linear vector equation

$$\dot{y} = -A^d y + B^d r \tag{7}$$

By selecting A^d and B^d as diagonal matrices, then we require the decoupling of the control channels.

4.2 Insensitivity condition

Let us denote

$$e^F = F(y, r) - \dot{y} \tag{8}$$

where e^F is the realization error of the desired dynamics which is assigned by $F(y, r)$. Accordingly, if the condition

$$e^F = 0 \tag{9}$$

is held then the desired behavior of $y(t)$ with prescribed dynamics of (6) is fulfilled. The expression (9) is the insensitivity condition of the output transient performance with respect to the external disturbances and varying parameters of the plant model (1)-(2). In other words, the control design problem (5) has been reformulated as the requirement (9).

5 Control law structure

In accordance with the approach presented in [10, 11], in order to fulfil the requirement of (9) let us consider the control law as, for example, the following differential equation

$$\mu^2 \ddot{v} + \mu D_1 \dot{v} + D_0 v = K_1 e^F \tag{10}$$

where

$$u = K_0 v \tag{11}$$

Assume that D_1, D_0, K_1 are diagonal matrices, μ is a sufficiently small positive parameter, $\mu > 0$ and $K_1 = diag\{k_1, k_2\}$.

Consequently, when taken together, equations (7), (8), and (10), the dynamic control law (10) may be written in the form

$$\mu^2 \ddot{v} + \mu D_1 \dot{v} + D_0 v = K_1 \{-\dot{y} - A^d y + B^d r\} \tag{12}$$

6 Properties of the closed-loop system

The analysis below for the properties of the closed-loop system dynamics assumes that the state of the plant model x is bounded within an open set. This is also consistent with the assumption of internally stable dynamics of the plant model.

6.1 Fast-motion subsystem

The closed-loop input-output system equations have the following form

$$\dot{y} = a(\theta, x) + \beta(\theta, x)K_0 v \quad (13)$$

$$\mu^2\ddot{v} + \mu D_1\dot{v} + D_0 v = K_1 e^F \quad (14)$$

From (6), (8) it follows that the closed-loop system equations may be rewritten in the form

$$\dot{y} = a(\theta, x) + \beta(\theta, x)K_0 v \quad (15)$$

$$\mu^2\ddot{v} + \mu D_1\dot{v} + \{D_0 + K_1\beta(\theta, x)K_0\}v = K_1\{F(y, r) - a(\theta, x)\} \quad (16)$$

Let us assume that μ is small parameter ($\mu \to 0$) then the slow and fast motion dynamics take place in the closed-loop system (15), (16). Following the standard singular perturbation procedure we have that the fast-motion subsystem (FMS) is governed by

$$\mu^2\ddot{v} + \mu D_1\dot{v} + \{D_0 + K_1\beta(\theta, x)K_0\}v = K_1\{F(y, r) - a(\theta, x)\} \quad (17)$$

as $\mu \to 0$ where it is assumed that $y \approx const$, $r \approx const$ during the transients in the system (17).

Remark 6.1 *The asymptotic stability, desired behavior of transients and desired settling time of $v(t)$ can be achieved by a proper choice of the control law parameters.*

Remark 6.2 *In order to provide stability of the fast-motion subsystem (17) the matrix K_0 should be nonsingular such that $K_0\beta$ is positive definite (or e.g. if $K_0 \approx \beta^{-1}$.)*

6.2 Slow-motion subsystem

If the fast-motion subsystem (17) is asymptotically stable then by finding the limit $\mu \to 0$ in (15), (16). the slow-motion subsystem

$$\dot{y} = F(y, r) + K_1^{-1}D_0\{K_1^{-1}D_0 + \beta(\theta, x)K_0\}^{-1}\{a(\theta, x) - F\} \quad (18)$$

may be obtained.

Remark 6.3 *If $D_0 \neq 0$ and $k_i \gg 1 \; \forall \; i = \overline{1, n}$ then the slow-motion subsystem (18) approaches the form of (6). If $D_0 = 0$ and $k_i > 0 \; \forall \; i = \overline{1, n}$ then the slow-motion subsystem (18) is the same as (6). In this case an integral action is incorporated in the control loop and, accordingly, zero steady-state error of the reference input can be achieved.*

Remark 6.4 *If $\mu \to 0$ then from (15), (16) it follows that the behavior of $y(t)$ tends to the solution of reference model, and accordingly the controlled output transients in the closed-loop system meets the desired performance specifications after the FMS fast transients have vanished.*

7 Simulation results

In [5] nonlinear models of the Hammerstein type for reactive ion etcher is presented. This is motivated by the observation that the RIE exhibits significant nonlinear behavior. In [7] a simple nonlinear model structure is used that is an input static nonlinear block (polynomial of second degree) in series with a linear time-invariant system. In this section we present some preliminary results on the application of our proposed control technique to a linear time-varying model of the RIE process. We consider a model of the RIE process that has already been considered in the literature. It has been modified to capture the effects of rapidly changing parameters as follows:

$$\begin{aligned} \dot{x}_1 &= \{-0.17 + 0.1sin(0.7t)\}x_1 + 3.6u_1 \\ \dot{x}_2 &= \{-18 + 9sin(0.3t)\}x_2 + u_2 \\ \dot{x}_3 &= \{-1.5 + 0.8sin(0.2t)\}x_3 + u_2 \\ y_1 &= x_1 + x_2, \;\; y_2 = x_3. \end{aligned} \quad (19)$$

From (19) it follows that

$$\beta = \begin{bmatrix} 3.6 & 1 \\ 0 & 0.036 \end{bmatrix} \quad (20)$$

The condition for Assumption 3.1 is easily verified. Furthermore it is easy to show the boundedness of the internal dynamics of (1),(2) under condition (9) (Assumption 3.2).

Let us assume that $K_0 = \{k_{ij}\} \approx \beta^{-1}$ where $k_{11} = 0.28,\ k_{12} = -7.7,\ k_{21} = 0,\ k_{22} = 27.8$ Require that the desired controlled outputs $y_1(t)$, $y_2(t)$ behave as the solutions of the equations

$$\dot{y}_i = \frac{1}{T_i}(r_i - y_i) \quad (21)$$

As a result the controller (12) has the form

$$\mu_i^2\ddot{v}_i + \mu_i d_{i1}\dot{v}_i + d_{i0}v_i = k_i\{\frac{1}{T_i}(r_i - y_i) - \dot{y}_i\} \quad (22)$$

where $i = 1, 2$ and $k_1 = k_2 = 10$, $\mu_1 = \mu_2 = 0.3$, $d_{10} = d_{20} = 0$, $d_{11} = d_{21} = 3$, $T_1 = T_2 = 1$.

The simulation results of the system (19) controlled by the algorithm (22) are displayed in Figures 3–6 for the time interval $t \in [0, 25]$ sec.

The measure of plasma parameters, especially, based on optical emission spectroscopy, leads to the high frequency sensor noise being added to output variable

$$\hat{y}_1 = y_1 + n_1, \quad \hat{y}_2 = y_2 + n_2$$

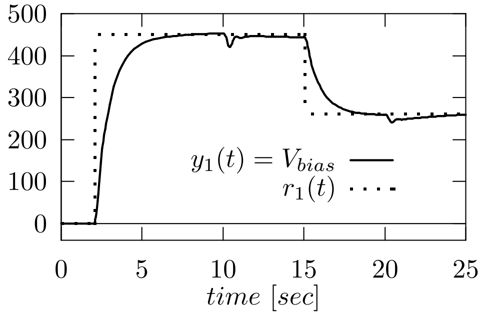

Figure 3: Response of $y_1 = V_{bias}\ [V]$ in the closed-loop system.

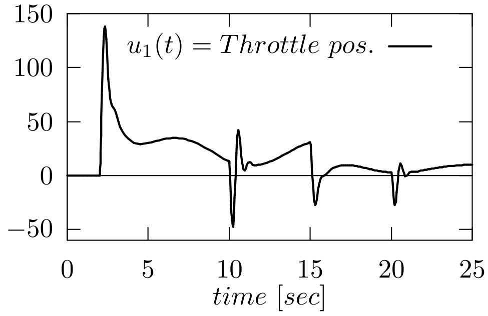

Figure 5: Behavior of the control variable u_1 = "$Throttle\ position$" $[\%]$ in the closed-loop system.

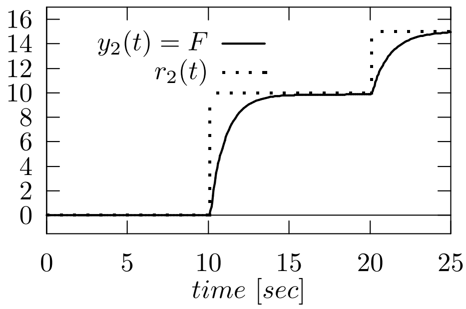

Figure 4: Response of $y_2 = Flourine\ [sccm]$ in the closed-loop system.

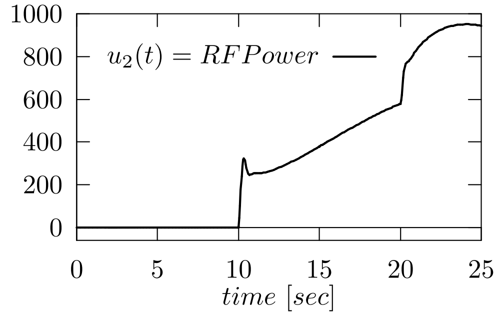

Figure 6: Behavior of the control variable u_2 = "$RF\ Power$" $[W]$ in the closed-loop system.

The susceptibility of the control system to high frequency sensor noise is an important question for implementation of the discussed controller in practice. In order to demonstration of the effect of sensor noise on the behavior of the discussed control system the simulation results of the system (19) controlled by the algorithm

$$\mu_i^2 \ddot{v}_i + \mu_i d_{i1} \dot{v}_i + d_{i0} v_i = k_i \{ \frac{1}{T_i}(r_i - \hat{y}_i) - \dot{\hat{y}}_i \} \qquad (23)$$

are displayed in Figures 7–10 where the noise is given by

$$n_1 = 10 \sin(20t), \quad n_2 = 2 \sin(30t)$$

and parameters of (23) are the same as in (22).

For short, the controller (23) may be considered as low pass filter for high frequency sensor noise and its parameters can be chosen such that the influence of the high frequency sensor noise n_i is suppressed.

8 Conclusions

The main result of this paper is development of a procedure of robust controller design which allows to provided desired output behavior for MIMO system in present of incomplete information about external disturbances and varying parameters of the system.

The resulting dynamical output feedback controller has a simple form consisting of low-order linear dynamical filters with small parameters μ_i. The proposed dynamical controller with the sufficiently small parameter induces the two-time-scale separation of the fast and slow modes in the closed-loop system where after damping of the stabilized fast transients the behavior of the output vector $y(t)$ is desired and insensitive to variation of parameters of the plant model and external disturbances.

The main advantage of the presented method is that the knowledge about the relative degrees and the matrix $\beta(\theta, x)$ are enough to controller design. Note that knowledge about the variation of parameters and external disturbances are not needed as well as the way they enter in the dynamics of the system.

Acknowledgements

This research was supported in part by Natural Science and Engineering Research Council of Canada (NSERC) under Grant RGPIN-42515. The authors would also like to express their thanks to Dr. Khargonekar for providing data on the RIE process.

References

[1] S. W. Butler, K. J. Mc Laughlin, T. F. Edgar, I. Trachtenberg. "Development of Techniques for Real-Time Monitoring and Contrrol in Plasma Etching - Multivariable Control System Analysis of Manipulated, Measured, and

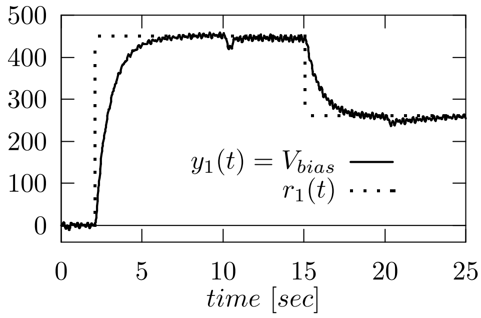

Figure 7: Response of $y_1 = V_{bias}$ $[V]$ in the closed-loop system with sensor noise.

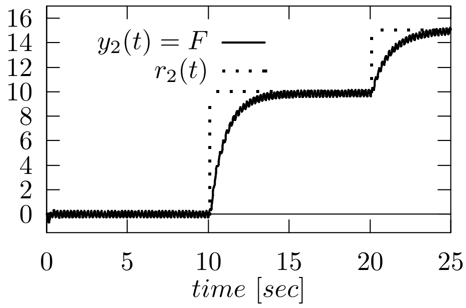

Figure 8: Response of $y_2 = Flourine$ $[sccm]$ in the closed-loop system with sensor noise.

Performance Variables", *Journal of Electrochemical Society*, **138**, No. 9, pp. 2727-2735, (1991).

[2] 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.T eneketzis, F. L. Terry. "Applications of control to Semiconductor Manufacturing: Reactive Ion Etching", *Proceeding of the American Control Conference*, San Francisco, California, pp. 2990-2995, (1993).

[3] E. S. Hamby, A. T. Demos, P. T. Kabamba, P. P. Khargonekar. "A Control Oriented Modeling Methodology for Plasma Enhanced Chemical Vapour Deposition Processes", *Proceedings of the American Control Conference*, Seattle, pp. 220-224, (1995).

[4] G. S. May, J. Huang, C. Spanos. "Statistical experimental design in plasma etch modeling", *IEEE Trans. Semiconduct. Manufact.*, **4**, pp. 83-98, (1991).

[5] O. D. Patterson, P. P. Khargonekar. "Reduction of Loading Effect in Reactive Ion Etching using Real-Time Closed-Loop Control", *Journal of Electrochemical Society*, **144**, No. 8, pp. 2865 - 2871, (1997).

[6] B. A. Rashap, M. E. Elta, H. Etemad, J. P. Fournier , J. S. Freudenberg, M. D. Giles, J. W. Grizzle, P. T. Kabamba, P. P. Khargonekar, S. Lafortune, J. R. Moyne, D. Teneketzis, F. L. Terry. "Control of Semiconductor Manufacturing Equipment : Real-Time Feedback Control of Reactive

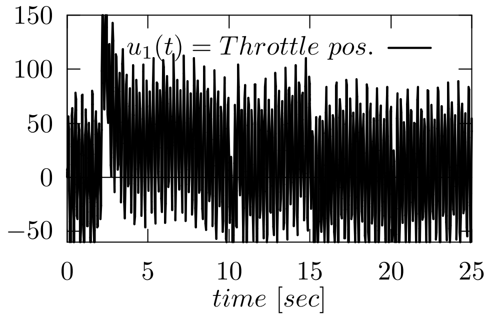

Figure 9: Behavior of the control variable u_1 = "$Throttle\ position$" $[\%]$ in the closed-loop system with sensor noise.

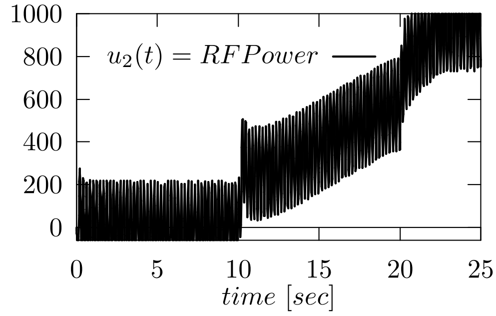

Figure 10: Behavior of the control variable u_2 = "$RF\ Power$" $[W]$ in the closed-loop system with sensor noise.

Ion Etcher", *IEEE Transactions on Semiconductor Manufacturing*, **8**, No. 3, pp. 286-297, (1995).

[7] T. L. Vincent, P. P. Khargonekar, B. A. Rashap, F. L. Terry, M. Elta. "Nonlinear System Identification and Control of a Reactive Ion Etcher", *Proceedings of the American Control Conference*, Baltimore, Maryland, pp. 902-906, (1994).

[8] T. L. Vincent, P. P. Khargonekar, F. L. Terry. "End Point and Etch Rate Control using Dual-Wavelength Laser Reflectometry with a Nonlinear Estimator", *Journal of Electrochemical Society*, **144**, No. 7, pp. 2467 - 2472,(1997).

[9] T. L. Vincent, P. P. Khargonekar, F. L. Terry. "An Extended Kalman Filter Based Method of Processing Reflectometry Data for Fast In-Situ Etch Rate Measurements", *IEEE Transactions on Semiconductor Manufacturing*, **10**, No. 1, pp. 42-51,(1997).

[10] V.D. Yurkevich. Control of uncertain systems: dynamic compaction method, *"Proc. of 9th Int. Conf. on Systems Engineering"*. University of Nevada. Las Vegas, pp.636-640, (1993).

[11] V.D. Yurkevich. "Decoupling of uncertain continuous systems: Dynamic Contraction Method", *Proc. of the 34-th IEEE Conf. on Decision and Control*, Evanston, **1**, pp.196-201, (1995).