Discrete-Time Control System Design for a Reactive Ion Etching (RIE) System

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Abstract

The problem of designing a robust controller to solve a tracking control problem for improving plasma characteristics in Reactive Ion Etching process 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 under discussed conditions the proposed dynamical controller 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 motions 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. Simulation results on a multivariable Auto Regressive Moving Average model of a RIE process are presented to demonstrate the utility of the proposed algorithm.

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 [1]. 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 [1]. 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 [3] four measured variables (namely $[F], [CF_2], [CO_2]$, 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 [2]-[3] 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 [1]. The overall goal is to redesign the RIE machine for enhanced controllability and improved performance. The objective in [1] 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 [1] and [2]-[3] 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 [1] conceptualize RIE as consisting of two distinct but interacting mechanisms, namely

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(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 [1] 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 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 [1]. 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 performance in different machines or in identical machines, or even in the same machine on two different runs [1]. 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 [1].

![Figure 1: Plasma reactor etching system](image)
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 [1], [2]-[3] 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 \( [F] \), 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 Linear Plasma Generation Subsystem Model

System Identification. In order to build a model for Plasma generation Subsystem (PGS) an experimental identification approach is needed.

Generally, a region of operating point is delineated in the space of pressure, \( [CF_4] \) flow rate, and RF Power corresponding to the RIR region of the plasma parameter space. Typical values of 1000 watts, 20 mTorr, and 30 sccm are selected as a nominal operating point. The model developed use only two independent input variables, namely RF Power and Throttle Position valve to control two independent output variables, namely \( V_{bias} \) and \( [F] \), more directly related to the etch rate. Using Matlab subroutines from Identification Toolbox and the available experimental input-output data set provided by Dr. P.P. Khargonekar and his group of the University of Michigan, we are able to develop a multivariable Auto Regressive Moving Average (ARMA) model of the first order given by

\[
y_k = A_1 y_{k-1} + B_1 u_{k-1} + B_2 u_{k-2} + G_1 w_{k-1}
\]

where \( k \) is the discrete time, \( k = 0, 1, \ldots \); \( y_k \) is the output available for measurement, \( y_k \in \mathbb{R}^p \); \( u_k \) is the control, \( u_k \in \mathbb{R}^p \); \( w_k \) is the external disturbances unavailable for measurement, \( w_k \in \mathbb{R}^p \). In particular, we have that \( p = 2 \) and \( y_k = [y_1(k), y_2(k)]^T = [V_{bias}(k), Fluorine(k)]^T \), \( u_k = [u_1(k), u_2(k)]^T = [Throttle Position(k), RF Power(k)]^T \). where

\[
A_1 = \begin{bmatrix}
0.9865 & 0 \\
0 & 0.9928
\end{bmatrix},
B_1 = \begin{bmatrix}
0.5975 & -0.0898 \\
-0.0001 & 0.0003
\end{bmatrix}
\]

\[
B_2 = \begin{bmatrix}
-0.3699 & 0.0921 \\
0.0010 & -0.0003
\end{bmatrix},
G_1 = \begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix}
\]

The open-loop simulations reveal that this model matches well with the experimental data. So the first order model is capable to capture well the dynamics of the PGS. The model is very simple and we could consider some of the coefficients of this model variable in a bounded range, giving us the possibility to prove the robustness of our control law strategy at these parameter variations of the system. The disturbances mostly affect the PGS and not WES, so by controlling the plasma variables the effects of these disturbances can be mitigated. It’s exactly which does our control law strategy developed in this paper.

It accordance with the approach to discrete-time control system design [5, 6] which will be used below, we need to make a check of that the following two assumptions are satisfied for given parameters of the model (2).

**Assumption 1** The roots of the characteristic polynomial of (1) lies in some neighborhood of 1.

**Assumption 2** The condition

\[
\text{det} \{B_1 + B_2\} \neq 0
\]

is fulfilled.

3.2 Output tracking control problem

Let us denote

\[
\lim_{k \to \infty} e_k = 0
\]

where \( e_k \) is the tracking error of the reference input realization; \( e_k = r_k - y_k \); \( r_k \) is the reference input, \( r_k \in \mathbb{R}^p \). Moreover, the output transients \( y_k \) should have a desired behavior which does not depend either on the external disturbances or on the varying parameters of the plant model (1).
4 Control problem formulation

4.1 Desired dynamic equations

Let us construct the model of desired output behavior of \( y_k \) in the form of the vector difference equation

\[
y_k = F^*(y_{k-1}, r_{k-1}) \quad (6)
\]

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

\[
y_k = A_1^d y_{k-1} + B_1^d r_{k-1} \quad (7)
\]

where

\[
I_p - A_1^d = B_1^d \quad \text{and} \quad \det B_1^d \neq 0.
\]

Here \( I_p \) is the unit matrix, \( I_p \in \mathbb{R}^{p \times p} \). Parameters of (7) are selected based on the required output transient performance indices. By selecting \( A_1^d \) and \( B_1^d \) as diagonal matrices and then we require the decoupling of the control channels. For example, let us select the following matrices of (7)

\[
A_1^d = \begin{bmatrix}
\frac{-\frac{\tau_2^f}{\tau_1^f}}{1 - \frac{\tau_2^f}{\tau_1^f}} & 0 \\
0 & \frac{1}{1 - \frac{\tau_2^f}{\tau_1^f}}
\end{bmatrix}, \quad B_1^d = \begin{bmatrix}
1 - \frac{\tau_2^f}{\tau_1^f} & 0 \\
\frac{\tau_2^f}{\tau_1^f} & 1 - \frac{\tau_2^f}{\tau_1^f}
\end{bmatrix}
\]

(8)

where the time constants \( \tau_1^f, \tau_2^f \) are selected based on the required settling time of output transient and \( T_0 \) is the sampling period.

4.2 Insensitivity condition

Let us denote

\[
e_k^f = F^*_i - y_k \quad (9)
\]

where \( e_k^f \) is the realization error of the desired dynamics assigned by \( F_i^* = F(y_{k-1}, r_{k-1}) \). Accordingly, if for all \( k = 0, 1, \ldots \), the condition

\[
e_k^f = 0 \quad (10)
\]

is held then the desired behavior of \( y_k \) with prescribed dynamics of (6) is fulfilled. The expression (10) is the insensitivity condition of the output transient performance with respect to the external disturbances and varying parameters of the plant model (1). In other words, the control design problem (5) has been reformulated as the requirement (10).

5 Control law structure

In accordance with [5, 6], to fulfill the requirement of (10) let us form the control law as, for example, the following difference equation

\[
u_k = D_1 u_{k-1} + D_2 u_{k-2} + \Lambda e_k^f \quad (11)
\]

where

\[
D_1 + D_2 = I_p \quad \text{and} \quad \det \Lambda \neq 0. \quad (12)
\]

From (12) it follows, that equilibrium of (11) correspond to the insensitivity condition (10).

6 Properties of the closed-loop system

6.1 Fast-motion subsystem

The closed-loop system equations have the following form

\[
y_k = A_1 y_{k-1} + B_1 u_{k-1} + B_2 u_{k-2} + G_1 w_{k-1} \quad (13)
\]

\[
u_k = D_1 u_{k-1} + D_2 u_{k-2} + \Lambda e_k^f \quad (14)
\]

In accordance with (7) and (9) the eqns. (13), (14) may be represented as the following equations

\[
y_k = A_1 y_{k-1} + \sum_{i=1}^{2} B_i u_{k-i} + G_1 w_{k-1} \quad (15)
\]

\[
u_k = \sum_{i=1}^{2} D_i u_{k-i} + \Lambda \{ A_1^d y_{k-1} + B_1^d r_{k-1} - y_k \} \quad (16)
\]

where the eqns. (15), (16) may be rewritten in the form

\[
y_k = A_1 y_{k-1} + B_1 u_{k-1} + B_2 u_{k-2} + G_1 w_{k-1} \quad (17)
\]

\[
u_k = [D_1 - \Lambda B_1] u_{k-1} + [D_2 - \Lambda B_2] u_{k-2} + \Lambda \{ A_1^d y_{k-1} + B_1^d r_{k-1} - G_1 w_{k-1} \} \quad (18)
\]

At first, note that the rate of the transients of \( u_k \) in (17), (18) depends on the controller parameters \( D, \Lambda \). At the same time, in accordance with the Assumption ??, we have slow rate of the transients of \( y_k \). So that under the proper choice of the controller parameters it is possible to induce two-time scale transients in the closed-loop system (17), (18) where the rate of the transients of \( y_k \) is much smaller than the rate of the transients of \( u_k \). Then in the asymptotic case from the closed-loop system (17), (18) follows that the fast-motion subsystem (FMS) is governed by

\[
u_k = [D_1 - \Lambda B_1] u_{k-1} + [D_2 - \Lambda B_2] u_{k-2} + \Lambda \{ A_1^d y_{k-1} + B_1^d r_{k-1} - G_1 w_{k-1} \} \quad (19)
\]

where \( y_k - y_{k-1} \approx 0 \forall i = 1, 2 \), i.e. \( y_k = \text{const} \) during the transients in the system (19). To ensure a stability and fastest transit processes of \( u_k \) let us choose the matrices \( \Lambda \) and \( D \) such that

\[
\Lambda = \{ B_1 + B_2 \}^{-1} \quad \text{and} \quad D_i = \Lambda B_i \quad \forall i = 1, 2 \quad \text{(20)}
\]

In this case the roots of the characteristic polynomial of eqn.(19) equal zero.

6.2 Slow-motion subsystem

At second, we assume that a steady state (or more exactly a quasi steady state) for the fast-motion subsystem (19) takes place, i.e. \( u_k - u_{k-1} = 0 \forall i = 1, 2 \). Then, from (12) it follows, that \( e_k^f = 0 \). Therefore, we have the slow-motion subsystem of (17), (18) is
the same as (6). Moreover, an integral action is incorporated in the control loop and, accordingly, zero steady-state error of the reference input is achieved.

Note that the required accuracy of the desired dynamics realization of (6) is provided and the control problem solution takes place under incomplete information about the disturbances and varying parameters of the system (1) if the sufficient degree of the fast and slow motion rate separation takes place. If the sufficient degree of the fast and slow motion rate separation takes place in the closed-loop system (17), (18) then the behavior of $y(t)$ tends to the solution of reference model, and accordingly the controlled output transients meets the desired performance specifications after the FMS fast transients have vanished.

6.3 Degree of time-scale separation

From (20) it follows that the characteristic polynomial of eqn. (19) is $z^m \tau^f s + 1)$, then the settling time of FMS equals $t^F_{s\, s} = 2pT_0$. In order to estimate the settling time $t^m_{s\, s}$ of SMS let us find the characteristic polynomial

$$
(\tau^f s + 1)(\tau^d s + 1)
$$

of the continuous-time counterpart of the reference model. Then we may evaluate:

$$
t^m_{s\, s} \approx \frac{4(\tau^d s + 1)^{1/2}}{\tau^f s + 1}
$$

The degree of time-scale separation between FMS and SMS may be calculated as the following ratio:

$$
\Theta_{s\, s} \approx \frac{t^m_{s\, s}}{t^F_{s\, s}}
$$

It is easy to see that the degree of time-scale separation between FMS and SMS increases as the both $\tau^f$ and $\tau^d$ increase. For example, assume that $\tau^f = \tau^d = 15$ and $T_0 = 1$ then for the given parameters of controller and reference model we have that $\Theta_{s\, s} = 15$.

We have that $(z - \zeta_1)(z - \zeta_2)$ is the characteristic polynomial of the open-loop system where $\zeta_1 = 0.9865, \zeta_2 = 0.9928$. Let us find the time constants $\tau_1, \tau_2$ are given by $\tau_j = [T_0/\ln(\|z_j\|)]$ where $j = 1, 2$. So far as $\|z_j\| \approx 1 \forall j$ then the degree of time-scale separation between rate of process in the open-loop system with respect to rate of process in FMS may be evaluated by the ratio $\Theta_{s\, s} \approx \frac{4(\tau_1 \tau_2)^{1/2}}{t^m_{s\, s}}$

For the given parameters of the plant model we have that $\Theta_{s\, s} \approx 100$.

7 Simulation results

The simulation results of the system in the form of the multivariable Auto Regressive Moving Average (ARMA) model (1), (2), (3) controlled by the given algorithm (11), (20) are displayed in Figures 3-7 where $\tau^d = 15$. The closed-loop simulations reveal that the response of the both output components matches well with the assigned desired behavior.

![Figure 3: Response of $V_{\text{in}}$ [V] in the closed-loop system.](image1)

![Figure 4: Response of Flourine [scm] in the closed-loop system.](image2)

8 Conclusions

The main result of this paper is development of a procedure of robust discrete-time 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. It has been shown that if the sufficient degree of the fast and slow motion rate separation are provided in the closed-loop system then the behavior of \( y_k \) tends to the solution of reference model, and accordingly the controlled output transients meets the desired performance specifications after the FMS fast transients have vanished.

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