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Run-to-run control of inductively coupled C_2F_6 plasma etching of SiO_2: Multivariable controller design and numerical application

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Abstract−A model-based run-to-run control method has been devised for an inductively coupled plasma etcher and applied to a numerical process for etching SiO_2 film with C_2F_6 plasmas. The controller was designed to minimize a quadratic cost of control error for the oxide etch rate and etch uniformity by run-wise integral action of the RF power, chamber pressure and RF bias voltage. Through numerical simulation, it was shown that the controller can truly minimize the cost even when the set point is given not to be reached by the process.

Key words: R2R Control, QILC, ICP Etcher, C_2F_6 Plasmas, SiO_2 Etching

INTRODUCTION

In the present micro-electronics industry, plasma processing is indispensable in various wafer fabrication steps such as etching, sputtering, chemical vapor deposition, photo-resist removal, equipment cleaning, etc. The plasmas used in micro-electronics fabrications are thermally non-equilibrium ones where the electron temperature is much higher than the ion and neutral temperature. The non-equilibrium plasma can be generated by different methods. At the present stage, however, inductively coupled plasma (ICP) is most popularly employed due to its capability to generate high density plasmas in a relatively simple system and also to independently manipulate the ion bombardment energy by a separate RF power applied to the wafer chuck.

Among various plasma processes, dry etching is considered to be most intricate, due to the complicated and poorly characterized surface reactions. Therefore, finding an appropriate operating condition of a dry etching system requires a number of trial runs by experienced people. As the 300 mm wafer becomes an industrial standard, the cost of a test run is greatly increased and reducing its number becomes an urgent issue. Due to the above-mentioned situation and also to meet the requirement of increasingly tighter within-wafer and wafer-to-wafer variations in the etching state, control of the plasma etcher has been a constant research subject during the past decade. In a recent review paper by Edgar et al. [2000] as well as in an early review paper by Badgwell et al. [1995], the plasma etcher was introduced as an important and challenging object for process control.

The plasma etcher control system is typically configured in two levels, run-to-run (R2R) control for the etching state in the upper level cascaded with real-time control of plasma state in the lower level. At present the etching state can be measured only after a processing. Therefore, only the run-wise information feedback is possible for etching state control. On the other hand, the plasma state can be monitored and controlled in real-time. However, plasma monitoring and control is expensive and sometimes unreliable, hence usually not practiced in commercial plasma etchers.

So far the study of the plasma etcher control has centered on R2R control of the etch rate. Sarfaty et al. [1997] proposed run-wise PID control combined with model-based feedforward compensation for etch rate control. They successfully applied the technique to poly-Si dry etching using the RF-bias voltage as the manipulated variable. This technique was further elaborated by Raul and Kushner [1999]. Hankinson et al. [1997] proposed an integrated real-time and R2R control method for etch depth control in reactive ion etching and evaluated the method experimentally. A R2R controller is rule-based and calculates improved set points for the bias voltage and fluorine concentration for a lower-level real-time controller after each cycle. Recently, Wang et al. [2005] have proposed an adaptive R2R control technique. It carries out model parameter update using the recursive least squares method after each cycle and computes the optimum EWMA (exponentially weighted moving average) control parameters. They applied the technique to etch rate control in a STI etch process. In addition to the above studies, neural network modeling of the response surface of a plasma etcher has been conducted for future R2R controller design [Kim et al., 2003]. To the authors' knowledge, most of the present plasma etcher control studies have focused on controlling only one variable, the etch rate, using one or two manipulated variables like the RF bias voltage with sometimes the concentration of a specific radical. Consequently, the R2R algorithm has been only for single-input single-output or multi-input single-output systems. The following two reasons are considered dominant for the above limitation. First, R2R control has been traditionally based on the EWMA-type algorithm which has been mostly for SISO systems. Secondly, wafer measurement is mostly performed off-line and it is inevitable that the metrology data is limited. Recently, integrated metrology has emerged as a new trend and the situation for metrology measurement is being improved greatly.

In this study, we have proposed a model-based MIMO (multi-input multi-output) R2R technique for the ICP etcher. Unlike the

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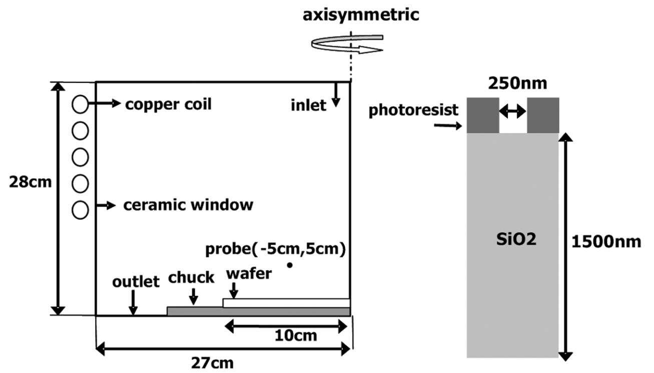

Fig. 1. Dimensions of the ICP etcher and etching pattern considered in the numerical model.

EWMA algorithms, the technique is devised such that the quadratic cost of the predicted control error in the next run is minimized. Through simple mathematical reasoning, it has been shown that the proposed technique can truly minimize the control error even when there is significant model uncertainty. The technique has been applied to a numerical ICP etcher that simulates SiO_2 dry etching with C_2F_6 plasmas, which was developed in the previous study [Seo et al., 2005] using a commercial CFD code called CFD-ACE+/TOPO. The average etch rate and etch non-uniformity over the radial direction have been chosen as the controlled variable, and the RF power, bias voltage, and chamber pressure have been chosen as the manipulated variables. The R2R controller was constructed by using a linear regression model that relates these two variables and was introduced in the accompanying previous paper.

DESCRIPTION OF THE NUMERICAL PROCESS

Fig. 1 shows a schematic diagram of the ICP chamber and the wafer pattern for feature scale simulation considered in this study. The chamber is made of dielectric material and has a five-turn RF coil around the wall, where 13.56 MHz RF power is applied to. Also a separate 13.56 MHz RF source is connected to the wafer chuck, for independent adjustment of ion bombardment. It is assumed that the chamber wall temperature is maintained at 300 K and the wafer temperature is regulated at 573 K. The wafer pattern is given to be parallel stripes with 250 nm of opening. It is assumed that the C_2F_6 flow rate is fixed at 50 sccm, and the chamber pressure, main RF power, and RF bias voltage are varied as operating variables.

A numerical model for the above process was constructed by using CFD-ACE+/TOPO, a commercial multi-physics simulator. The model was tuned to exhibit the characteristics of typical ICP etcher through extensive simulation study. The key parts we adjusted in the tuning process are the selection and parameter adjustment of the plasma and surface reactions. More details on the process and numerical modeling are described in the accompanying paper [Seo et al., 2005].

The final quality variables in an etching process can include the etch rate, spatial uniformity, anisotropy, ion bombardment damage, and so forth. However, as a continuum simulator, TOPO lacks the ability to predict bombardment damage. In addition, it does not seem to reliably predict the anisotropy aspects either. Under such restrictions, we took the etch rate and etch uniformity as the output of the process to regulate or optimize. It is assumed that the operating variables are not dynamically changing with time but kept constant during an etching period. Consequently, the process becomes a three-input two-output static process.

1. Linear Modeling

For controller design, a linear static model that relates the operating variables to the etch rate and uniformity was determined through linear regression. For this, simulation was conducted at 64 different points around the nominal operating condition. The etching state was measured at five different positions along the radial direction. The etch rate was defined as the average value and the uniformity was defined as the normalized standard deviation over the five monitoring points, which is actually a non-uniformity, such that

$$X(\mathrm{nm/min})=(x_1+x_2+x_3+x_4+x_5)/5 \tag{1}$$

$$\mathrm{NU}(\%)=\frac{\sigma}{X}\times 100,\quad \sigma=\sqrt{\frac{(x_1-X)^2+(x_2-X)^2+(x_3-X)^2+(x_4-X)^2+(x_5-X)^2}{4}} \tag{2}$$

Using the weighted least squares method, we obtained the following linear model:

$$\begin{bmatrix} X(\mathrm{nm/min}) \\ \mathrm{NU}(\%) \end{bmatrix}=\begin{bmatrix} 193.3632 & 20.1555 & 1.3352 \\ -0.3232 & 0.0460 & -0.0015 \end{bmatrix}\begin{bmatrix} \text{RF power (kW)} \\ \text{Pressure (mtorr)} \\ \text{RF bias (V)} \end{bmatrix}+\begin{bmatrix} -195.1989 \\ 1.2464 \end{bmatrix} \tag{3}$$

CONTROLLER DESIGN

Fig. 2 shows a block diagram for the R2R control system. After each batch run, the R2R controller takes the etch rate and etch uniformity measurements and calculates the RF power, chamber pressure and RF bias voltage for the next run.

The R2R controller proposed in this study is different from a conventional EWMA controller in that it is based on an integral action along the run index. This feature, just as in usual integral control, enables us to eliminate the offset against run-invariant set point and disturbance. To derive the R2R controller, let us represent the control error as e=r−y where r denotes the set point. Obviously, e is a function of the input, i.e., e(u). Now with the operation data at the k-1th run in hand, we compute the control input for the upcoming

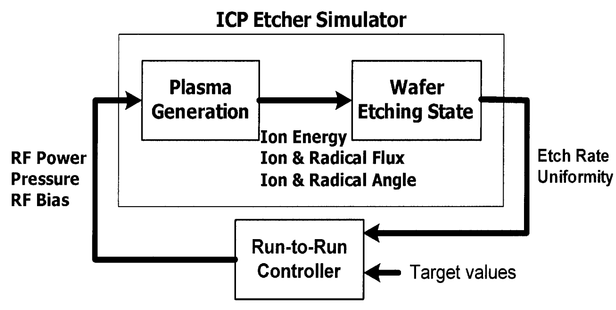

Fig. 2. Block diagram for the run-to-run control system.

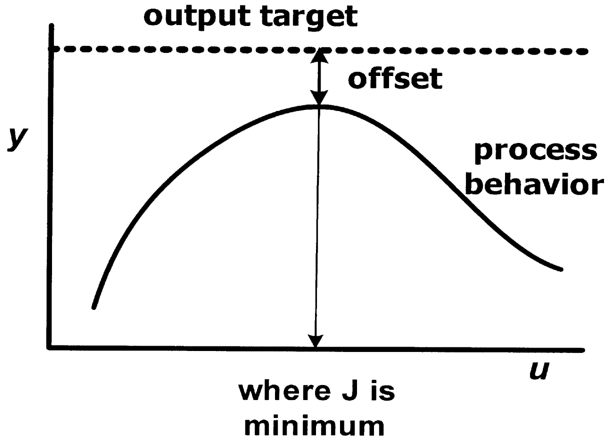

Fig. 3. Example of unattainable set point for a nonlinear process.

run such that

$$\min_u J(u)=\frac{1}{2}\{e(u)^T Qe(u)+(u-u_{k-1})^T R(u-u_{k-1})\} \tag{4}$$

Application of the Newton's method gives us the following updating equation for u:

$$u_k=u_{k-1}-(E_{k-1}^T QE_{k-1}+R)^{-1}E_{k-1}^T Qe_{k-1} \tag{5}$$

where $E_{k-1}=(\partial e/\partial u^T)_{k-1}$. In the above, $-E^TQe$ is the negative gradient of $(1/2)e^TQe$. Thus e^TQe can be decreased with k when u moves along the direction of −Me as long as the angle between −Me and $-E^TQe$ is less than 90°. Indeed, when J(u) is unimodal and the Newton's updating law (5) continuously decreases J until e^TQe reaches the minimum. When e is linear in u or when y=r is on a linear region in a nonlinear process, e can be zero for some u and J can be minimized down to zero. When e has an extremum with respect to u and an unreachable set point is given as in Fig. 3, J(u) can be minimized at the point where e is minimum. At this point, e has an offset; E vanishes; and u_k stops moving.

In our system, u and y are related by a linear regression model as in (3) for the controller design. If we write the nominal model as

$$y=G_m u+d \tag{6}$$

Then $e(u)=r-G_m u-d$ and $E=-G_m$. The resulting R2R algorithm becomes

$$u_k=u_{k-1}+(G_m^T QG_m+R)^{-1}G_m^T Qe_{k-1} \tag{7}$$

Under the above law, u_k keeps moving unless e is zero. For the case in Fig. 3, e cannot be zero and u_k moves continuously until it sticks to some constraints. To prevent such problem, we consider another law

$$u_k=u_{k-1}-(G_m^T QG_m+R)^{-1}\bar{E}_{k-1}^T Qe_{k-1} \tag{8}$$

where

$$\bar{E}_{k-1}=\begin{cases}[(e_{i,k-1}-e_{i,k-2})/(u_{j,k-1}-u_{j,k-2})] & \text{when } |u_{j,k-1}-u_{j,k-2}|\ge\varepsilon \\ [(e_{i,k-1}-e_{i,k-2})/\varepsilon\,\mathrm{sgn}(u_{j,k-1}-u_{j,k-2})] & \text{otherwise}\end{cases} \tag{9}$$

represents a numerical Jacobian matrix computed using the data from the previous two runs. Since the Jacobian may become singular as the minimum is approached, the denominator is set to $\varepsilon>0$ when the input change becomes too small. It can be seen that (9) can be used only after initial two runs. The two updating laws of (8) and (9) can be used switching from one to another in the R2R algorithm.

The above R2R technique is in fact a modification of the QILC (quadratic criterion-based iterative learning control) algorithm [Lee et al., 2000] for it to act as a true optimizing controller for nonlinear as well as linear input-output systems. More properties of QILC can be found in Lee et al. [2000] and also Kim et al. [2000].

SIMULATION CONDITIONS

We considered two cases of set point change, one that is physically achievable and the other unachievable, for investigation of the control performance. The process behavior is anticipated to be linear around the set point in the first case and to be nonlinear, perhaps similar to Fig. 3 for one of the two outputs, in the second case. In the first case, the input for the initial run was set at [1 kW 20 mtorr 150 V]. Under this condition, the etcher yielded $y_1=[556(\text{nm/min})\ 2.17\%]^T$. From this state, the set point was given as $r=[750(\text{nm/min})\ 1.2\%]^T$. The input updating law of (7) was used. In the second case, the initial run of the etcher was with $u_1=[2\text{ kW } 20\text{ mtorr } 250\text{ V}]^T$ from which $y_1=[1044(\text{nm/min})\ 1.23\%]^T$ was obtained. From this state, the output was required to reach $r=[750(\text{nm/min})\ 0\%]^T$, *i.e.*, to attain zero NU. Of course, zero NU is physically unattainable. What we truly wanted is that NU can be reduced as much as possible with zero target value. In the second case, the updating law of (7) was used for the first four runs and then switched to (8) from the fifth run.

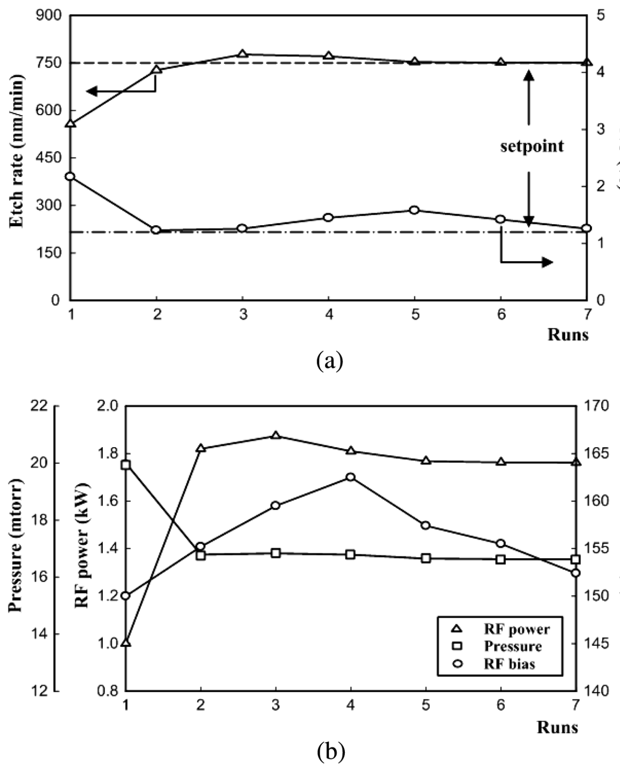

Fig. 4. Results of run-to-run control for an attainable set point.

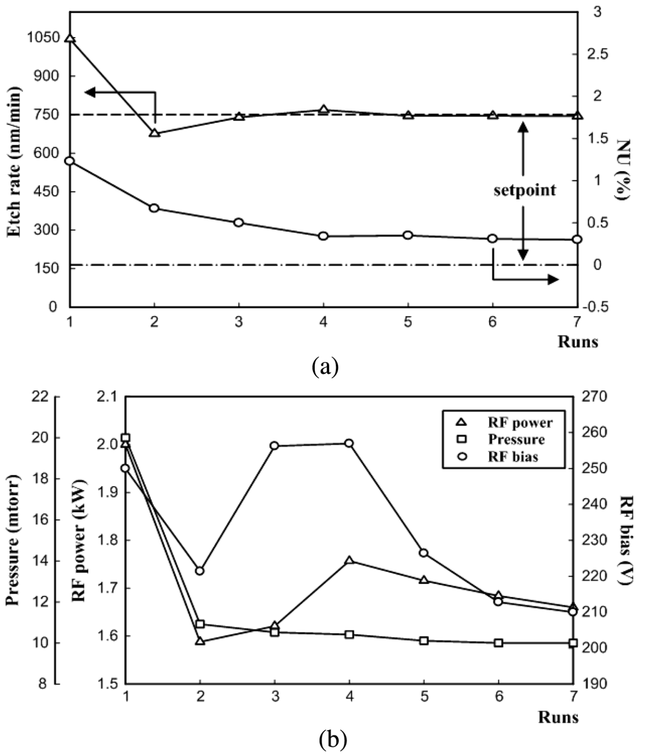

Fig. 5. Results of run-to-run control for an unattainable set point.

Input movements were constrained as

$$0.8 \leq RF(kW) \leq 3,\ 10 \leq Pressure(mtorr) \leq 30,\ 150 \leq Bias(V) \leq 400 \quad (9)$$

and we implemented the constraints by clipping the calculated input values. The quadratic weight Q was given as the output scaling matrix and R was given as a constant times the input scaling matrix. In this study, the following values were used:

$$Q = diag\{0.001, 1\},\ R = \lambda\, diag\{1, 0.5, 0.01\},\ \lambda = 0.1 \quad (10)$$

RESULTS AND DISCUSSION

In Fig. 4, responses of the average etch rate and etch non-uniformity to the first set point change are shown. Both outputs touch the respective set points only in one run and settle on the set points in five to seven runs. The input was initially at [1 kW 20 mtorr 150 V] and moved to [1.76 kW 16.6 mtorr 152 V] at the 7^{th} run.

In Fig. 5, the output response to the second set point is shown. It can be seen that NU was decreased down to 0.3%, a significant improvement from the initial state, while the etch rate is settled on its set point. The input was initially at [2 kW 20 mtorr 250 V] but settled at [2.66 kW 10 mtorr 210 V] in the 7^{th} run. This demonstrates the optimizing capability of the proposed R2R algorithm for nonlinear systems.

CONCLUSIONS

Through this study, an MIMO R2R control algorithm has been proposed for an ICP etcher and applied to a numerical process for etching SiO_2 film with C_2F_6 plasmas. It was assumed that the oxide etch rate and etch uniformity are controlled by manipulating the RF power, chamber pressure and RF bias voltage. The R2R algorithm has been devised to minimize a quadratic output error criterion using a linear regression model and a numerical Jacobian matrix. Through numerical simulation, it was shown that the proposed algorithm can truly minimize the quadratic error as the run number increases, which implies that the process can be steered to the best achievable state even when the set point is given to be physically unattainable.

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