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Design of optical emission spectroscopy based plasma parameter controller for real-time advanced equipment control

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ABSTRACT

With the advent of more than Moore's law era, control of plasma etch process is expected to become inevitable. Given that highly complex plasma is a medium of etch processes, plasma parameters are key factors to be controlled. In addition, highly interactive plasma characteristics require multivariate control schemes. In this paper, we design a multi-loop controller which controls effective plasma parameters in Ar plasma conditions. The effective plasma parameters obtained by optical emission spectroscopy are paired with plasma reactor instrumental variables through relative gain array and singular value decomposition. Each single input-single output (SISO) system based on the pairing result shows successful disturbance rejection performance but interactions between SISO controllers occur. In order to handle the interactions, 2 × 2 multiple input-multiple output (MIMO) controllers with and without decouplers are simulated to track set point change. Based on the simulations, a MIMO controller with decouplers is implemented in a capacitively coupled plasma reactor and show feasible control performance without interaction. Hopefully, the results introduced in this paper contribute to making progress in plasma parameter control.

1. Introduction

With the continual drive towards smaller feature size by Moore's law, semiconductor industry has considered quality control imperative. Plasma etching which is one of the most critical processes in semiconductor manufacturing has also followed this consideration. In plasma etching, it is inherently important to control plasma parameters like electron density (n_e), electron temperature (T_e), ion energy and so on. Thus, there have been some studies on control of plasma parameters (Chang et al., 2003; Lin et al., 2009; Lynn et al., 2012; Keville et al., 2013). Chang et al. reported a real-time controller of ion energy and ion density in an inductively coupled plasma reactor, where VI-probe and trace rate gases-optical emission spectroscopy (TRG-OES) were employed to estimate ion energy and ion density, respectively. Lin et al. addressed a feedback controller of electron density and ion energy in an inductively coupled plasma reactor, where VI-probe was employed to measure electron density and to calculate ion energy, respectively. Lynn et al. and Keville et al. showed the results of real-time control of electron density in a capacitively coupled plasma reactor, where Harpin probe was employed to measure electron density.

Even though those studies show excellent results, it is difficult to directly apply them to semiconductor manufacturing environment because the employed plasma diagnostic tools are invasive to process and are also required to modify current plasma reactors for installation. In addition, controllers shown in these studies have single input single output (SISO) schemes where a counter change of another plasma parameter during a SISO control action might occur due to the highly interactive plasma characteristics. Thus, a plasma controller using non-invasive diagnostic tools and enabling consideration of interactions among plasma parameters should be re-developed in semiconductor industry.

This paper introduces an optical emission spectroscopy (OES) based multiple input multiple output (MIMO) plasma parameter controller. Since OES is a default plasma diagnostic tool for every plasma reactor, there is no concern about invasiveness toward process and about installation. In order to estimate plasma parameters such as effective electron density and effective electron temper-

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ature, line-ratio techniques based on the popular corona model are employed for our plasma conditions (Boffard et al., 2004; Zhu and Pu, 2010). With these parameters treated as controlled variables (CVs), a MIMO plasma parameter controller is designed in a capacitively coupled plasma reactor.

This paper is organized as follows. In Section 2, the employed plasma reactor and the test conditions are explained briefly. In Section 3, theoretical backgrounds are introduced. Those are estimation of plasma parameters from OES, interaction analysis for optimum pairings and several multi-loop control schemes. In Section 4, results of pairings between CVs and manipulated variables (MVs) and their disturbance rejection performances are illustrated. Additionally, multi-loop control schemes are proposed so as to reduce interactions between plasma parameters based on simulation results. Finally, the designed controller is adjusted according to the experimental environment and conducts a MIMO set point tracking test. In Section 5, future works to be continued after this paper are described. Hopefully, the results in this paper can contribute to making progress in plasma parameter control in a non-invasive way for more than Moore's law era.

2. Experimental

Fig. 1 shows a schematic of a plasma etching reactor employed in this paper. It is a capacitively coupled plasma reactor that can carries 300 mm wafers. The reactor is powered by three radio frequency (RF) generators (each frequency is 60 MHz on top electrode, 13.56 MHz and 2 MHz on bottom electrode) and the gap between top and bottom electrodes is 25 mm. The OES can measure light ranging from 200 nm to 1100 nm wavelengths with 0.4 nm spectral resolution. Details about the experimental set-up is described in our previous paper (Ha et al., 2016).

The reference plasma condition is 20 mT of pressure, 200 W of 60 MHz RF power, 100 W of 2 MHz RF power and 400 sccm of Ar flow rate. With the regard to this reference plasma condition, 60 MHz RF power, 2 MHz RF power, Ar flow rate or pressure is changed independently by +/−10% and wait until plasma reaches steady-state. The steady-state gain of each MV (RF powers, Ar flow rate and pressure) is then calculated. The obtained steady-state gain is utilized in analyzing an interaction among variables through the relative gain array (RGA) or the singular value decomposition (SVD) technique. In addition, pseudo random binary sequence (PRBS) tests are done in order to consider time constant of the system.

To evaluate performance of the designed controller, two kinds of tests are conducted. O_2 gas is intentionally flown in the chamber to check how the controllers reject disturbance in terms of plasma parameters. Then, a set point tracking test for controlled variables is conducted.

3. Theoretical background

3.1. Estimation of effective plasma parameters from OES

OES is a non-invasive and default plasma sensor under semiconductor manufacturing environment. It measures emission in plasmas via an optical fiber which is attached on the viewport of chambers. Emission in plasmas is generated by a process where an excited particle is converted from its higher energy quantum state to a lower energy quantum state. Excitation of a particle is usually done by electron-particle or particle–particle collisions.

In corona equilibrium, the excited state is formed solely by electron impact excitation and the electron excitation rate and the photon decay rate are equal (Boffard et al., 2004; Zhu and Pu, 2010). An emission intensity from a particular p_{th} state to k_{th} state is described as Eq. (1).

$$\Phi_{pk} = n_0 n_e \int_{E_{thr}}^{\infty} \sigma_{pk}(E) \left(\frac{2E}{m_e}\right)^{\frac{1}{2}} f(E)\, dE, \tag{1}$$

where n_0 is the number density of ground state atoms, n_e is the electron density, $\sigma_{pk}(E)$ is the excitation cross section from level p into level k as a function of electron energy E, $f(E)$ is the electron energy distribution function (EEDF), m_e is the electron mass (Boffard et al., 2004).

In practice EEDF, $f(E)$, is assumed as one of the several standard functional forms, which is an one-parameter Maxwellian distribution described by an electron temperature, T_e, like that shown in Eq. (2),

$$f(E, T_e) = \frac{2\sqrt{E}}{\sqrt{\pi}(kT_e)^{3/2}} \exp\left(\frac{-E}{kT_e}\right), \tag{2}$$

where k is Boltzmann constant. In order to utilize OES for measuring plasma parameters, so-called line-ratio techniques have been utilized so far (Boffard et al., 2004; Zhu and Pu, 2010). For instance, ratio of measured two emission lines from different excited states can be described in Eq. (3) from Eqs. (1) and (2).

$$\frac{\Phi_{pk}}{\Phi_{ij}} = \frac{\int_{E_1}^{\infty} \sigma_{pk}(E) \exp\left[-\frac{E}{kT_e}\right] EdE}{\int_{E_2}^{\infty} \sigma_{ij}(E) \exp\left[-\frac{E}{kT_e}\right] EdE} \tag{3}$$

This is only dependent on the electron temperature. Of course, the two emission lines must be from different excited states with different energy thresholds, E_1 and E_2.

In addition to a line ratio measurement of the electron temperature, it would be useful to have a separate line-ratio measurement that is only a function of the electron density. Boffard et al. found that the 357.2 nm ($5p_5$)/425·9nm($3p_1$) line ratio serves this purpose. This line ratio is essentially independent of electron temperature, but highly dependent on electron density.

In a similar way, our study utilizes several Ar emission lines to estimate effective electron density and the effective electron temperature.

3.2. Singular value decomposition (SVD) and condition number (CN)

Singular value analysis (SVA) and its extensions such as Singular Value Decomposition (SVD) are powerful analytical techniques that can be helpful in solving important control problems such as selection of MVs and CVs and quantification of multivariable directionality (Seborg et al., 2004; Skogestad and Postlethwaite, 2005; Baek et al., 2013). If G is a constant $l \times m$ matrix, any matrix G can be decomposed into its singular value decomposition like Eq. (4),

$$G = U\Sigma V^T, \tag{4}$$

where $\sum$ is a diagonal $l \times m$ matrix with non-negative singular values, σ_i, arranged in a descending order along its main diagonal. In addition, U is an orthonormal $l \times l$ matrix of output singular vectors, u_i, and V is an orthonormal $m \times m$ matrix of input singular vectors, v_i.

That is, the original vector is decomposed into two directional vectors (u_i and v_i) and one stretching vector (σ_i). These characteristics of SVD can be utilized in analyzing a controller which is operated in a linear system model between input and output variables. If we consider a 2×2 linear controller with a steady-state gain K in Eq. (5), K can be decomposed like that shown in Eq. (6).

$$Y = KU + D, \tag{5}$$