ON THE MODELLING AND CLOSED LOOP CONTROL OF AN INDUCTIVELY COUPLED PLASMA CHAMBER

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Abstract: As a first step towards real time, multivariable control of an argon/oxygen plasma, the implementation of real time control of ion flux in an inductively coupled argon plasma through modulation of the RF power is described. It is demonstrated that an elementary PID controller does not guarantee stable control of ion flux over a range of operating points and hence that more elaborate control strategies must be considered. The design and testing of control algorithms is facilitated by suitable dynamical models of a process. A model of the inductively coupled plasma chamber which is suitable for control simulations is described. Ongoing and future work are discussed.

Keywords: semiconductor manufacturing, plasma process, etching, closed loop control

1. INTRODUCTION: DESCRIPTION OF THE CONTROL PROBLEM

Real time feedback control of plasma-assisted semiconductor manufacturing processes such as etching could yield greatly improved performance. A strategy to reduce the effect of disturbances, which has received some attention in recent years, has been to control plasma variables such as the electron density rather than to attempt to implement feedback control of a variable such as etch rate directly , as shown schematically in Fig. 1 (McLaughlin *et al.*, 1991; Rashap *et al.*, 1995). Successful implementation of this control strategy would enable etch recipes to be specified in terms of plasma variables as opposed to input variables such as RF power and gas flow rates.

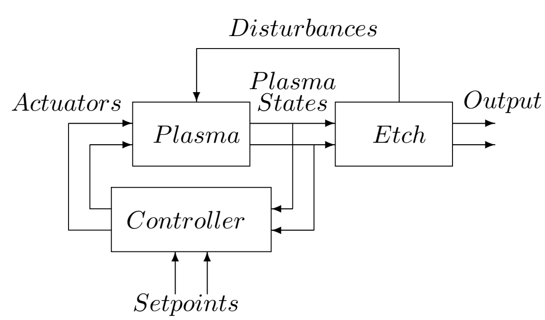

Fig. 1. Plasma control strategy

In this paper, the implementation of closed loop control of an inductively coupled plasma chamber with internal coil geometry is described. The chamber geometry is not suitable for an industrial application such as etching and the plasma chemistries have not been chosen with any particular application in mind. However, the simplicity of the configuration lends itself to experimentation and rapid adaptation, and the aim of the study is to demonstrate a principle rather than to develop a control algorithm for an industrially-based process at this stage. It is intended to transfer any results to a more complex, industrially-based system at a later date.

Before the control objectives are stated, a brief description of the system from a control point of view is required. From an electrical perspective, the power delivery system and plasma chamber may be represented as shown Fig. 2.

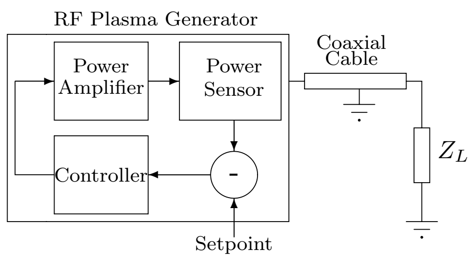

Fig. 2. Simplified schematic of RF delivery system and load

Power is supplied to the chamber from an ENI ACG-10B-07 RF plasma generator which regulates forward power, P_{for}, via a coaxial cable with characteristic impedance $Z_0 = 50\Omega$ and an RFPP AM20 automatic impedance matching box (IMB). The IMB consists of the load and tune capacitors, C_L and C_T, respectively, connected in a conventional configuration, which transform the antenna impedance, $Z_{ch} = R_{ch} + j\omega L_{ch}$, to the impedance Z_L, where

$$Z_L^{-1} = j\omega C_L + \left[R_{ch} + j\left(\omega L_{ch} - \frac{1}{\omega C_T}\right)\right]^{-1}. \quad (1)$$

C_L and C_T are adjusted by an automatic impedance matching algorithm. Assuming the matching box and coaxial cable are lossless, the power delivered to the plasma is given by

$$P = \frac{(1 - |\Gamma|^2)R_{plas}}{R_{plas} + R_{vac}} P_{for}. \quad (2)$$

Here, $\Gamma = (Z_L - Z_0)(Z_L + Z_0)^{-1}$ is the reflection coefficient, and R_{vac} and R_{plas} are the real parts of the vacuum impedance, Z_{vac}, and of the impedance, Z_{plas}, in the antenna due to the plasma, respectively.

Z_{plas} is a nonlinear function of plasma variables, which are, in turn, dependent on the power deposited in the plasma. It is clear from (2) that the power deposited in the plasma is dependent on Z_{plas} and the capacitance values C_L and C_T. In low pressure, low power regimes in particular, interactions between the load-dependent power delivery system, the automatic match circuit and the power-dependent load can lead to instabilities which result in unrepeatable variations in plasma parameters (Brouk and Heckman, 2004). Instabilities have been observed in inductive discharges with electronegative gases, an example of which is oxygen; see, for example, (Chabert *et al.*, 2001). The same process in the same reactor can be either stable or unstable depending on the RF power supply, which is, however, inherently stable when supplying a linear load (Brouk and Heckman, 2004). Hence, from the point of view of stability, one must consider the RF generator, the match circuit and the chamber impedance as a single system. In addition, it should be noted that, since gas density affects the plasma conductivity through the collision frequency and power deposition in the plasma affects the pressure through gas temperature, control of pressure should not be considered separately, but as part of the larger, multivariable problem.

The main objective of this research is the multivariable control of ion flux, atomic oxygen and pressure in an argon/oxygen plasma using RF power, gate valve position, and the flow rates of argon and oxygen as actuators. As a first step towards this, the control of ion flux in an argon plasma through modulation of the RF power is considered here. The basic experimental setup is described in the section 2, while the adaptation of the experimental setup in order to implement closed loop control is described in section 3. Here, it is shown that, due to system nonlinearities, an elementary PID controller does not guarantee stability outside of a small neighbourhood of any nominal operating point indicting that model-based control strategies should be considered. A first-principles approach to he development of a model for such a purpose is described in section 4. Finally, ongoing and future work is described in section 5.

2. DESCRIPTION AND SET-UP OF THE BARIS SYSTEM

BARIS (BAsic Radiofrequency Inductive System) is is an inductively coupled plasma chamber with an internal antenna. The discharge chamber consists of a cylindrical, stainless steel vacuum vessel of internal diameter 20cm and length 90cm, shown in Fig. 3. A water cooled copper antenna with 11 turns, positioned along the axis of a 30cm long quartz tube, is inserted into a 5cm diameter port at one end of the chamber. The antenna is 10cm long, 4cm in diameter is surrounded in the quartz tube by air at atmospheric pressure and has no direct contact with the plasma.

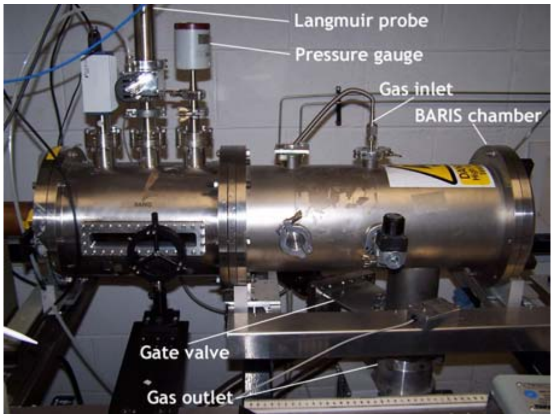

Fig. 3. BARIS Plasma Chamber

Three 70mm vacuum ports for diagnostic purposes are situated above the antenna. The middle port is situated directly over the middle turn of the antenna and is used for Langmuir probe, hairpin probe and B-dot probe measurements. Either of the other two ports may be used for pressure measurement employing a sensor with an interface for computer-based monitoring. The chamber is also equipped for laser induced fluorescence (LIF), optical emission spectroscopy (OES), and mass spectroscopy. Argon and oxygen flow into the chamber is regulated by two mass flow controllers. The chamber is evacuated through a pumping port by a turbomolecular pump backed by a rotary pump and pressure is regulated by means of a gate valve. Actuation and data collection are centralised in an Intel Pentium 4-based PC with the following three PCI boards: Measurement and Computing analog output card PCI-DDA08/16; National Instruments analog input card PCI-6031E; and Quatech 8 port RS232 serial interface ESC-100. A schematic of the chamber and experimental set up is shown in figure 4 below.

3. PID CONTROL

3.1 Real-time platform for implementation

LabView is widely used for data acquisition and monitoring in the world of plasma processing and has been used to implement real-time control (Rashap *et al.*, 1995), but is not, however, suitable for the implementation of advanced controller designs. Furthermore, for the implementation of even a simple PI controller in LabView, the sample rate may be limited to an unacceptably low rate, which suggests that a lower level implementation may be preferable (Chang *et al.*, 2001). In this study, the xPC Target toolbox in MATLAB was selected to implement PID control of ion flux using RF power in an argon plasma. xPC Target is a high performance, host-target environment which enables the connection of Simulink models to physical systems and their execution in real-time on PC-compatible hardware (The Mathworks Inc., 2002). The hardware setup is shown schematically in Fig. 5. Simulink models with input and output blocks are created on the host PC, executable code is then created with the Real-time workshop and a C/C++ compiler and this is then downloaded to the target PC running the xPC Target real-time kernel. A Simulink block diagram of the model used for PID control of the argon plasma in BARIS is shown in fig. 6. Special blocks are designed to convert the analog set points for valve position and RF power level into RS232 command sequences. Model variables may be observed on the target and host PCs via xPC target scopes. The gain blocks in the Simulink model and the parameters of the PID controller may be tuned from the host PC via a GUI. The *sampling time* for this design was set at 100ms. However, the *execution time* for the model was about 210μs per sample, so higher sample rates and/or much more complex models may be catered for.

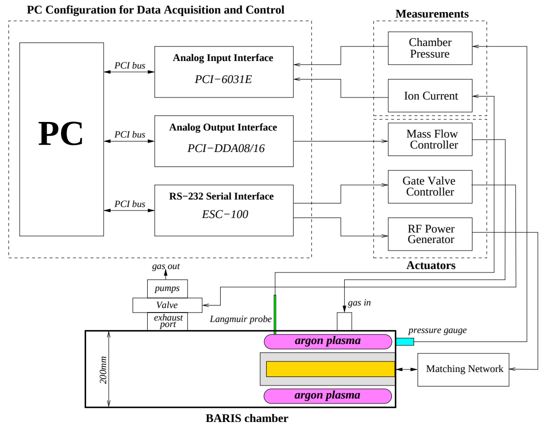

Fig. 4. Experimental setup for BARIS

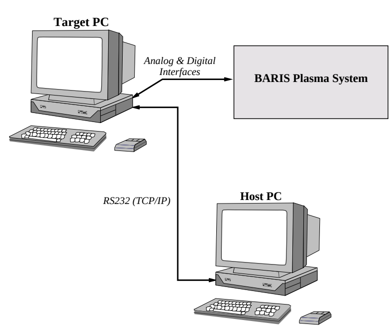

Fig. 5. xPC Target hardware configuration

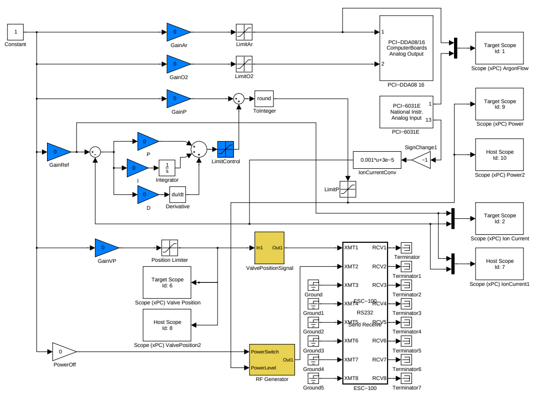

Fig. 6. Simulink model for PID control of Baris

3.2 *PID results*

The PID controller was tuned empirically at a nominal operating point and the closed-loop response to a step input is shown in Fig. 7 At a

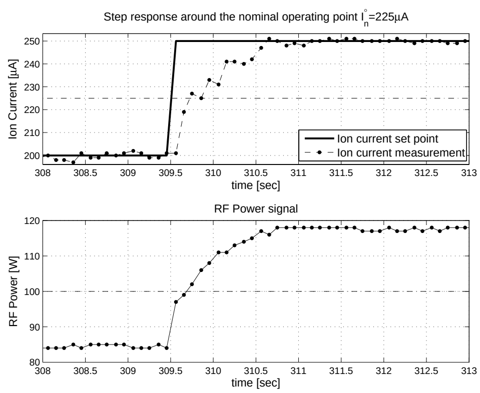

Fig. 7. Step response at a nominal operating point

slightly different operating point, the closed loop response with the same controller shown in Fig. 8 exhibits instability and poor set point tracking. Clearly, PID control is insufficient for such a

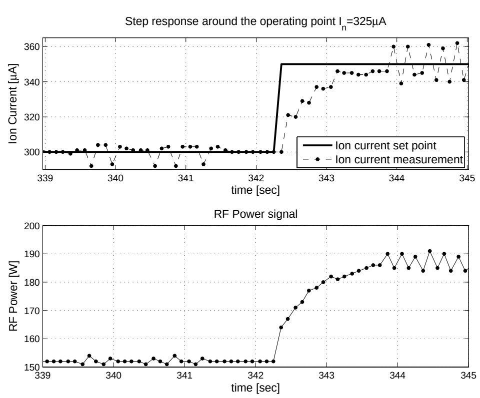

Fig. 8. Step response at a new operating point

complex, nonlinear process and control strategies which account for process variations must be considered. Suitable, control-oriented process models facilitate the the design and testing of control algorithms as well as providing a basis for model-based control. In the case of plasma processes, physically-based models are preferable to data-based models as these are specific to a particular chamber whose characteristics may change markedly over time. A physically-based model for the BARIS chamber is described in the following section.

4. PROCESS MODEL

The process model for control simulation consists of a global model of the argon plasma chemistry, the inputs to which are the mass flow rates from the mass flow controllers, the chamber residence time from the gate valve model, and the power deposited in the plasma, which is derived from an impedance model coupled to a model of the impedance matching unit. In addition, the impedance matching unit including its controller are described briefly.

4.1 *Global model*

The global model used is based on that due to Lieberman (Lieberman and Lichtenberg, 1994). Assuming all electrons generated by ionisation in the plasma migrate to the radial chamber wall where they recombine with ions, the charged particle density in the plsma bulk is given by

$$\frac{dn}{dt} = \left(\frac{1}{\tau_i} - \frac{1}{\tau_{rec}}\right)n, \tag{3}$$

where τ_i and τ_{rec} are ionisation and recombination time constants, respectively. Here, $\tau_i = 1/(k_i N)$, where k_i is the ionisation rate constant, and N represents the neutral gas density. The recombination time constant is given by

$$\tau_{rec} = \frac{1}{u_B}\frac{V_{plas}}{A_{plas}}, \tag{4}$$

where u_B is the Bohm velocity, V_{plas} is the plasma volume, and A_{plas} is an effective radial interface area between the plasma and the outer radial surface which takes into account the presence of the sheath.

If the ionisation fraction is small, N is determined by the difference in flow into and out of the chamber, ie

$$\frac{dN}{dt} = \frac{F_{Ar}}{V_{ch}} - \frac{N}{\tau_{res}}, \tag{5}$$

where F_{Ar} is the mass flow rate of argon into the chamber, V_{ch} is the chamber volume, and τ_{res} is the chamber residence time.

The global model is coupled to the impedance model via the power, P, deposited in the plasma, which is included in the balance equation for electron temperature, T_e. The global model is completed by a balance equation for the gas temperature, T. Outputs from the global model include the electron density and collision frequency which determine the plasma conductivity,

$$\sigma = \frac{\epsilon_0 \omega_p^2}{\nu + j\omega}, \tag{6}$$

where ω_p is the plasma frequency, ω the supply frequency, and ν the collision frequency. The chamber pressure, p, is also determined from global model variables according to the universal gas law:

$$p = k_B N T + k_B n T_e, \tag{7}$$

where k_B is Boltzmann's constant.

4.2 Impedance model

The vacuum impedance, $Z_{vac} = R_{vac} + j\omega L_{vac}$, may be determined by measurement. An expression for Z_{plas} as a function of chamber geometry and plasma variables may be determined by solving the wave equation for the induced electric field intensity, $\mathbf{E_i}$, in the chamber. In particular, the coil current density is denoted by $\mathbf{J_c}$, then

$$Z_{plas} = -\frac{1}{|i_c|^2} \int_{V_c} \mathbf{E_i} \cdot \mathbf{J_c^* dV}, \tag{8}$$

where V_c is the volume of the antenna. Given a number of assumptions - in particular, that the chamber exhibits azimuthal symmetry, that the plasma is perfectly cylindrical and bounded radially and at both ends by grounded surfaces, and that the antenna current is uniformly distributed on the surface of the antenna - an expression for the induced electric field intensity as a function of electron density and collision frequency may be derived. There is insufficient space to provide further information here, but details are contained in a forthcoming publication (Keville, 2006). Z_{plas} may be written in the form

$$Z_{plas} = R_{plas} - j\omega \Delta L_{plas}, \tag{9}$$

where R_{plas} is the increase in the antenna resistance due to the plasma and ΔL_{plas} is the decrease in the inductance seen in the antenna due to the presence of the plasma. R_{plas} and ΔL_{plas} are plotted in Figs. 9 and 10, respectively.

4.3 Mass flow controller

The mass flow controller (MFC) was modelled as a linear system with a transfer function

$$G_m(s) = \frac{e^{-s\tau_m}}{T^2 s^2 + 2\zeta s + 1}. \tag{10}$$

The model parameters $\tau_m = 0.119s, T = 0.107s, \zeta = 0.903$ were chosen to minimise the least squared difference between the response of the model and the response of the MFC to excitation by a PRBS (pseudo-random binary sequence) at a number of operating points. The two responses are compared in Fig. 11

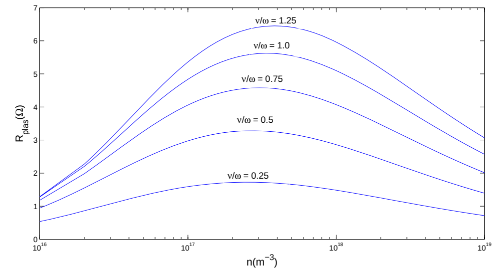

Fig. 9. R_{plas} as a function of electron density and collision frequency

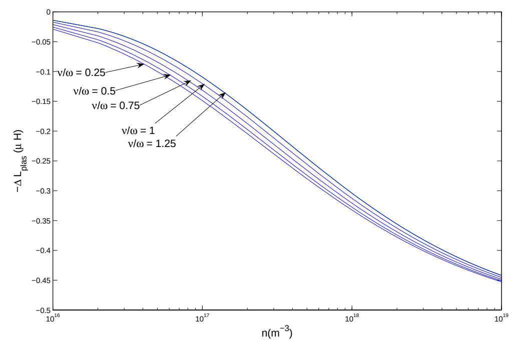

Fig. 10. $-\Delta L_{plas}$ as a function of electron density and collision frequency

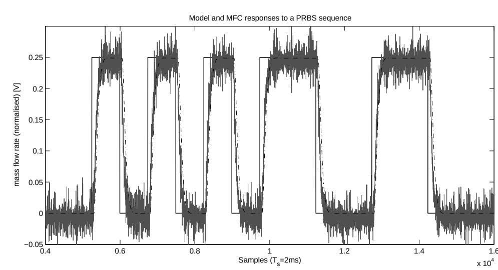

Fig. 11. Responses of the MFC(solid) and the identified model (dash-dot) to the PRBS sequence

4.4 Gate valve and controller

The gate valve is actuated by a stepper motor in open loop mode. The position of the motor is indicated on a scale from 1 - fully closed - to 1000 - fully open. The model of the gate valve consists of two components: A static characteristic relating the chamber residence time to the position of the gate valve, and a model of the gate valve controller relating the actual gate valve position to the position set point at the controller input.

The static characteristic is determined empirically. If the RF power is set to zero, so that no heating occurs, equations (5) and (7) yield

$$\frac{dp}{dt} = \frac{Q_{ar}}{V_{ch}} - \frac{p}{\tau_{res}}, \qquad (11)$$

where $Q_{ar} = k_B T F_{ar}$ is the throughput. Equation (11) is that of a first order, linear dynamical system. The time constant of the pressure sensor is, in general, substantially less then the residence time and hence may be neglected (Fisher, 2002). The residence time may hence be determined by considering the pressure response to perturbations of the flow rate in a way similar to that used in the determination of the transfer function of the mass flow controller. Residence time as a function of gate valve position is plotted for three different flow rates, 100, 150 and 200 sccm, in fig. 12.

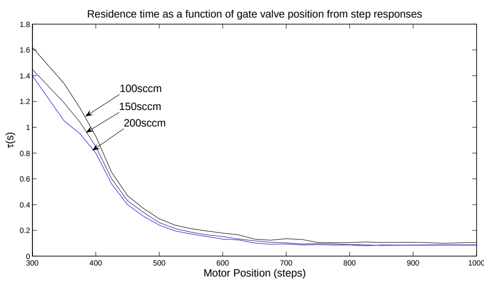

Fig. 12. Residence time as a function of stepper motor position

5. ONGOING AND FUTURE WORK

Validation of the global model of the plasma chemistry and the impedance model is proceeding. A model of the IMB requires the relationship between load and tune capacitor positions and the values C_L and C_T, respectively. In addition, the stray impedances and the characteristic of the phase and magnitude detector (PMD) must be determined (Cottee and Duncan, 2003). Match circuit settings and an accurate model of the impedance-matching circuit may facilitate an accurate estimate of the plasma impedance which may be used in feedback control or, given a suitable plasma model, for state estimation (Cottee, 1996). Future work in this area also includes the design of a model-based impedance-matching controller (Cottee and Duncan, 2003). Given that the model structure, if not the model parameters, has been established, design of a control algorithm for ion flux in an argon plasma has begun. Later work will include the addition of oxygen to the chemistry global model, control design and simulation for the argon/oxygen plasma and the investigation of process models for inferential sensing of plasma states.

REFERENCES

Brouk, V. and R. Heckman (2004). Stabilizing *RF* generator and plasma interactions. In: *47th Annual Technical Conference Proceedings of the Society of Vacuum Coaters*. Dallas, TX, USA. pp. 49–54.

Chabert, P., A. J. Lichtenberg, M. A. Lieberman and A. M. Marakhtanov (2001). Instabilities in low pressure inductive electronegative discharges. *Plasma Sources Science and Technology* **10**, 478–489.

Chang, C.-H., K.-C. Leou and C. Lin (2001). Real-time feedback of electron density in inductively coupled plasmas. *Journal of Vacuum Science and Technology A* **19**(3), 750–756.

Cottee, C. J. (1996). *Inferential sensing and control of radio frequency heating*. PhD Thesis, Control Systems Centre, UMIST. Manchester, UK.

Cottee, C. J. and S. R. Duncan (2003). Design of matching circuit controllers for radio-frequency heating. *IEEE Transactions on Control Systems Technology* **11**(1), 91–100.

Fisher, R (2002). Downstream pressure control: Calculation of the transfer function and optimization of control parameters leading to a new controller design. *Journal of Vacuum Science and Technology* **A 4(3)**, 314–316.

Keville, B. (2006). A transformer model for an inductively coupled plasma source with internal coil geometry. *In preparation for submission to Plasma Sources Science and Technology.*

Lieberman, M. and A. Lichtenberg (1994). *Principles of Plasma Discharges and Materials Processing*. Wiley. New York.

McLaughlin, K.J., T.F. Edgar and I. Trachtenberg (1991). Real-time monitoring and control in plasma etching. In: *Proceedings of American Control Conference*. San Diego, California. pp. 3–10.

Rashap, B. A., M. E. Elta, H. Eternad, 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 and F. L. Terry Jr. (1995). Control of semiconductor manufacturing equipment: Real-time feedback control of a reactive ion etcher. *IEEE Transactions on Semiconductor Manufacturing* **8**(3), 286–297.

The Mathworks Inc. (2002). *xPC Target for use with real-time workshop, User's Guide*. The Mathworks Inc. Natick, MA, USA.