PI Controller for Electron Density Control in Low Pressure Plasma [★]

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Abstract: This paper reports a PID control application for real-time feedback control of electron density, n_e, in a low pressure, capacitively coupled plasma chamber. Experimental results are presented which demonstrate that a PI controller enables effective control of electron density when radio frequency power is used as an actuator. A hairpin resonator probe is used to measure the electron density, when the resonator is placed in plasma, its characteristic resonance frequency in vacuum shifts to a higher value. From the frequency shifts, electron density can be easily determined. Actuation and data acquisition are briefly outlined.

Keywords: PID control, real-time, feedback control, low pressure plasma, hairpin probe, and electron desity.

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1. INTRODUCTION

Low-pressure plasmas are commonly used in semiconductor fabrication. Plasma-assisted etching is a major manufacturing activity in semiconductor production. Etch processes are generally operated in open loop, see Fig. 1. However, fixed recipe (process inputs) cannot guarantee fixed product outputs. Plasma parameters are sensitive to process disturbances, such as wall effects, wafer loading effects and actuator drifts. Disturbances to key plasma parameters may affect process metrics such as etch depth and anisotropy and result in a significant degradation in device yield and performance.

Real-time feedback control has the potential to enhance performance by reducing sensitivity to real-time disturbances. A general approach is to develop a real-time feedback control system to keep the key plasma parameters constant at wafer level. Rashap *et al.* (1993; 1995) developed a real-time feedback controller to achieve a desired sidewall profile. Electron density is one of key parameters, which is an indicator of how rf power is coupled into the wafer. Equation (10.2.15) from Lieberman's book (2005) indicates a direct relationship between rf power and electron density. A number of groups have investigated real time control of electron density in low pressure plasma discharges using rf power as actuator. In particular, Klimecky *et al.* (2003) describe real-time control of electron density using a novel microwave cavity resonance technique called broadband rf as a sensor. Cheng-Huang Chang *et al.* (2001) report on real-time control using a heterodyne interferometer as an electron density sensor. This paper considers the real-time control of electron density in a low pressure argon plasma where rf power is used as an actuator and electron density is measured with a hairpin resonance probe. Fig. 2 shows the closed loop block diagram of electron density control with PI controller in a RIE process. Experimental results are presented, which demonstrate that a PI controller delivers effective set-point tracking and disturbance rejection.

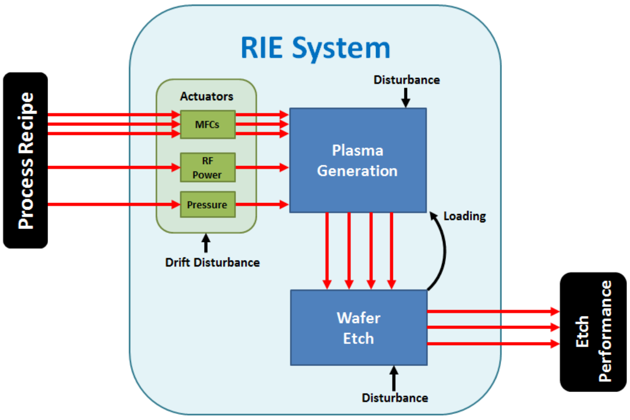

Fig. 1. Block diagram of Reactive-ion etching (RIE) process

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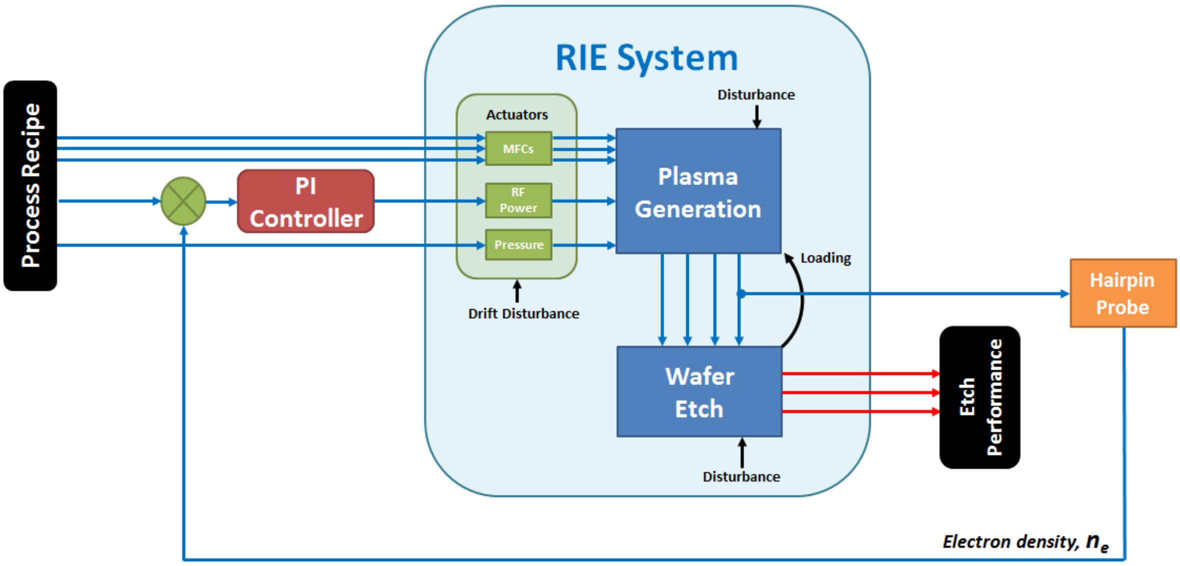

Fig. 2. Closed loop block diagram of electron density control

The remainder of this paper is structured as follows: the experimental setup and operating principles are described in Section 2. Section 3 contains the controller design technique and the experimental results. Section 4 consists of our conclusions and comments on future work.

2. EXPERIMENTAL SETUP

Fig. 3 illustrates the experimental set up for electron density control with hairpin probe. This capacitively coupled plasma chamber is a refurbished DP80 (1988). Hairpin resonance probe, digital oscilloscope (TDS3032) and microwave source (HP 8350B) are indicated.

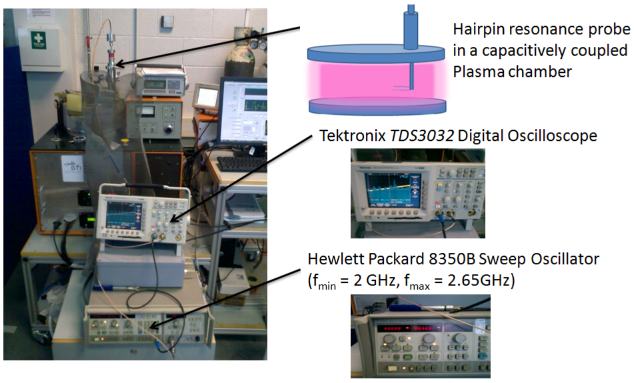

Fig. 3. Plasma chamber and electron density measurement setup

2.1 Hairpin Probe

The concept of using a microwave resonator probe to measure electron density in a low pressure plasma was initialised in the mid 1970s by Stenzel (1976). Due to the hairpin shape, the probe is now commonly referred to as “Hairpin” probe. Piejak *et al.* (2004; 2005) revisited this technique and redesigned Stenzels probe. Their results show hairpin probe reproducibility is excellent, and it appears to be an electron density diagnostic that is accurate, easy to interpret, and inexpensive to implement. This technique is most suitable for low-pressure plasma, with an electron density in the range of 10^9 to $10^{12} cm^{-3}$. The hairpin probe we use in this experiment was developed by Karkari *et al.* (2007) at National Centre for Plasma Science and Technology, Dublin City University.

The operating principle of the hairpin probe is based on measuring the plasma dielectric constant, ε, using a microwave resonant structure. When the resonator is placed in plasma, its resonant frequency shifts from the characteristic resonance frequency in vacuum. Electron density is easily determined from the frequency shifts. The simplest microwave resonator probe is a quarter-wavelength parallel transmission line, which has one end short-circuited and the other end open.

The resonance frequency of the hairpin is a function of length L and the dielectric constant, ε, of the medium surrounding the hairpin. We choose $L = \lambda/4$, where λ is the wavelength corresponding to the microwave frequency f_r. The resonance frequency of the hairpin is given by

$$f_r = \frac{c}{4L\sqrt{\varepsilon}}, \qquad (1)$$

where c is the speed of light ($3{\times}10^8 ms^{-1}$) and ε is the relative dielectric constant of the medium surrounding the probe. In vacuum, the hairpin has a fundamental resonance at a frequency given by $f_o = c/4L$. In a low pressure, weakly magnetized plasma, the resonance frequency and relative permittivity are related by

$$\varepsilon = 1 - \frac{f_p^2}{f_r^2}, \qquad (2)$$

where $f_p = \sqrt{ne^2/m\varepsilon_o}/2\pi$, is plasma frequency, e and m are the electron charge and mass, respectively, and n is the plasma density. Thus, in a plasma the resonant frequency is given by

$$f_r = \frac{f_o}{\sqrt{1 - f_p^2/f_r^2}}, \qquad (3)$$

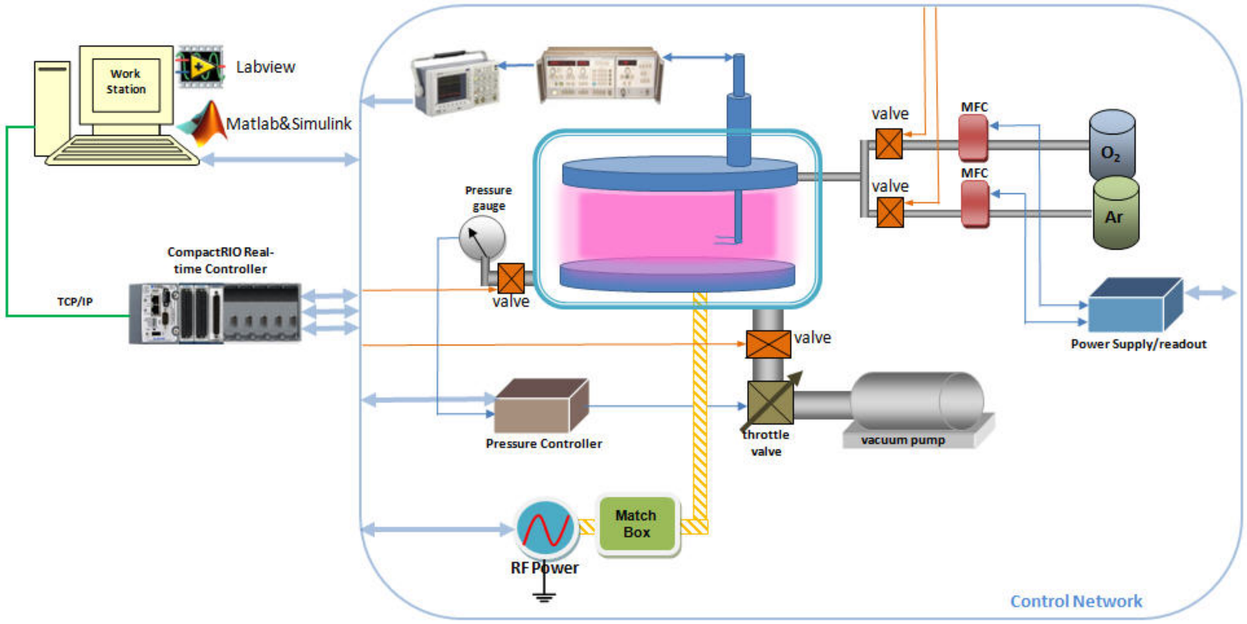

Fig. 4. Real-time plasma process control system configuration

which rearranges to

$$f_r^2 = f_o^2 + f_p^2. \tag{4}$$

Therefore, the electron density is then simply related to the frequency shift between resonances with and without plasma, as summarized in the following equation.

$$n(10^{10}cm^{-3}) = \frac{f_r^2 - f_o^2}{0.81}. \tag{5}$$

where f_r and f_o are expressed in GHz.

2.2 Labview User Interface

A schematic of the real-time feedback control of plasma process is shown in Fig. 4. Control and data acquisition system software is designed in LabVIEW. The sampling time of the hairpin probe for electron density measurement via Labview program is 0.5 second, mainly due to the waveform download and process from the digital oscilloscope. This particular configuration utilizes a NI cRIO-9024 (see CompactRIO user manual 2010) combined with various C-series modules for low pressure plasma control I/O. Fig. 5 shows the front panel of LabVIEW program that displays the frequency shift between f_r and f_o.

The National Instruments CompactRIO programmable automation controller is a reconfigurable control and acquisition system designed for applications that require high performance and reliability. CompactRIO hardware has a number of features which make it particularly suitable for the development of a real-time control system. Among these features is the facility to program a miniaturized computer with a real-time operating system and an onboard FPGA that interfaces to various analog and digital input-output modules.

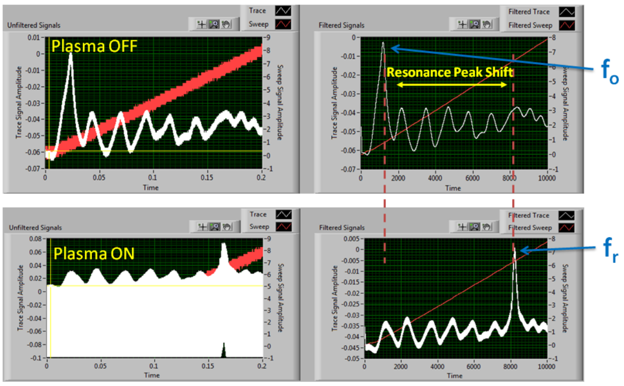

Fig. 5. Real-time acquisition of electron density via LabVIEW program

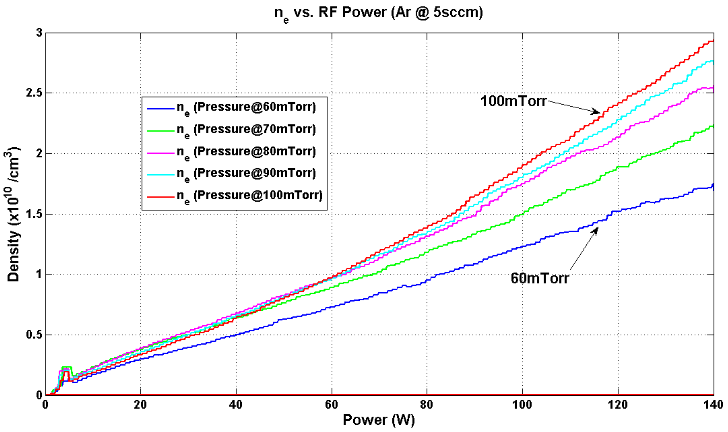

Fig. 6. Electron density as a function of the real-time rf power ramping for five different pressure 60 to 100 mTorr. Argon gas flow rate is 5 sccm.

3. SYSTEM ANALYSIS AND PI CONTROLLER DESIGN

3.1 Open Loop Response Analysis

Fig. 6 shows the static open loop response of electron density as a function of rf power at different chamber pressures as determined from hairpin probe measurements. An approximately linear relationship between rf power and electron density n_e is obvious from the plot, and the process gain K_P varies with chamber pressure.

The dynamic open loop response of electron density to a step change in rf power is shown in Fig. 7. The step response clearly shows that electron density in a plasma process is a type 0 system. The process may be modeled as a static gain K_P and a time delay θ, and hence the relationship between electron density $n_e(s)$ and rf power P(s) may be written in the form

$$n_e(s) = K_p e^{-s\theta} P(s), \tag{6}$$

where the static gain K_P is a function of the chamber pressure (Fig. 6).

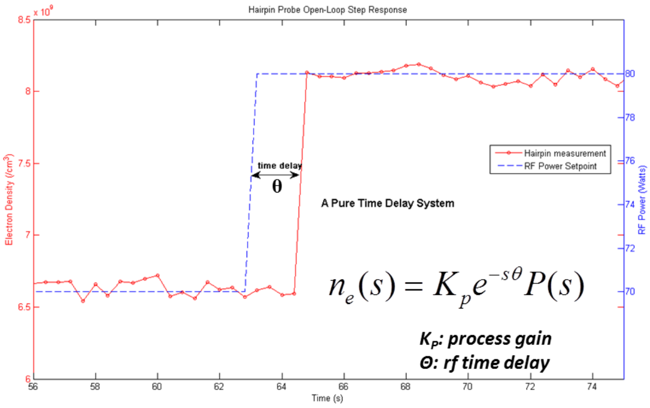

Fig. 7. Electron density open-loop step response. Chamber pressure is 100 mTorr. Argon gas flow rate is 5 sccm.

3.2 PI Tuning with Ziegler-Nichols Method

If the time delay θ is not too large, such a system may be controlled adequately by a PI controller. Given K_P and θ, suitable values of P and I which satisfy stability and performance requirements may be determined theoretically (see Silva *et al.* 2005).

However, in this case, the well-known Ziegler-Nichols tuning rules (see Ziegler *et al.* 1942) were used to tune the PI (proportional-integral) controller. Using Ziegler-Nichols technique, a controller may be designed without a process model. This approach worked sufficiently well that more advanced controller design methods were not considered at this stage. According to the Ziegler-Nichols method, initially set the I (integral) and D (derivative) gains to zero, increase the P (proportional) gain until the output reaches the ultimate gain K_u at which sustained oscillations occur (see Fig. 8). K_u and the oscillation period P_u are then used to set the PI controller parameters as follows:

$$\begin{aligned} K_P &= 0.45 K_u, \\ K_I &= \frac{P_u}{1.2}. \end{aligned} \tag{7}$$

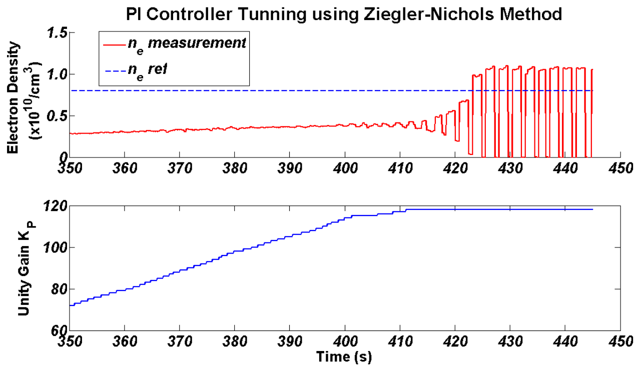

Fig. 8. Ziegler-Nichols tuning.

In this study, the plasma conditions for Z-N tuning procedure are: plasma density setpoint $8 \times 10^{10} cm^{-3}$, chamber pressure 100mTorr, and argon gas flow is 5sccm. The value of K_u and P_u were found to be 120 and 3s (Fig. 8), respectively. Hence, we obtained that K_P = 54 and K_I = 2.5 s for PI controller, and sampling time is 500ms.

3.3 Results

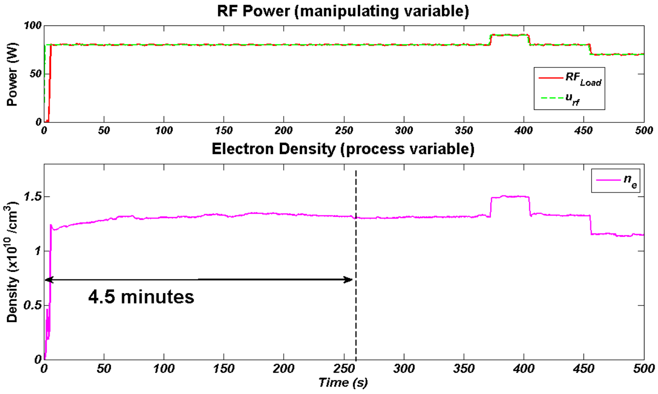

Fig. 9. Open loop control of electron density. Argon plasma, Argon gas flow at 5sccm.

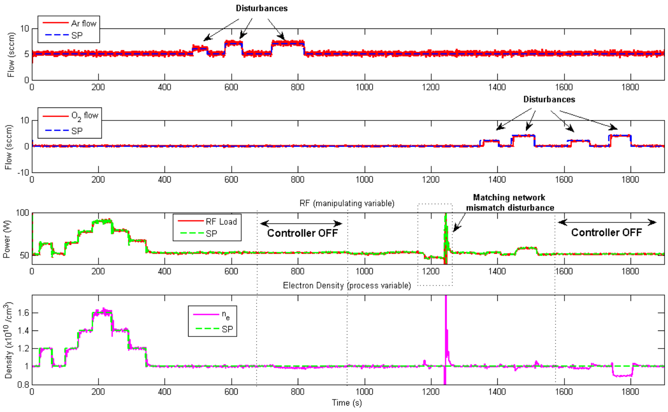

Fig. 10. Closed loop control of electron density with PI controller. Argon plasma, Argon gas flow at 5sccm.

The comparison of open loop control and closed loop control of electron density is shown in Fig. 9 and Fig. 10. Due to chamber's condition, a plasma discharge from a cold chamber in an 'open-loop' run, will take a few minutes to reach a steady-state. This 'warm-up' effect is much reduced by introducing a PI feedback control. The result also shows an effective set-point tracking and pressure disturbance rejection performance. By comparing the O_2 flow disturbance with and without PI controller (see Fig. 11), the disturbance rejection performance is clearly demonstrated. Fig. 12 further illustrates the excellent set-point tracking performance and good robustness.

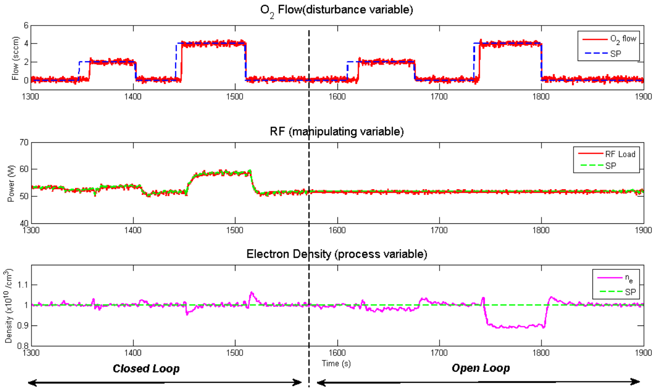

Fig. 11. Comparison of O_2 flow disturbance under closed loop and open loop controls. Argon plasma, Argon gas flow at 5sccm.

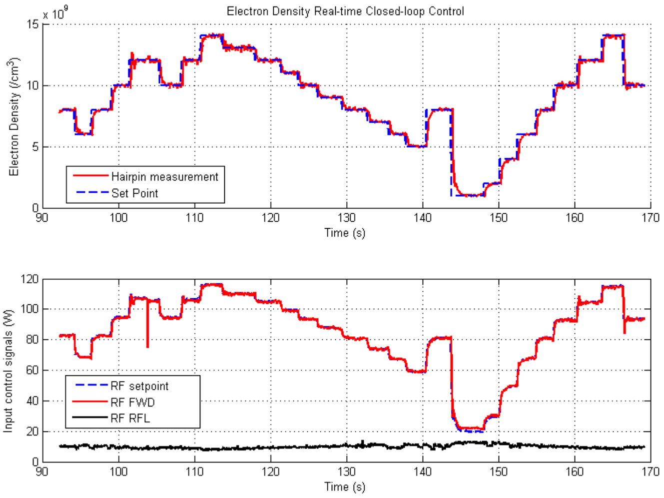

Fig. 12. Performance of PI controller in tracking set-point steps. Argon plasma, Argon gas flow at 5sccm.

4. CONCLUSION

Experimental results have been presented which demonstrate the real-time control of the electron density of a low pressure argon plasma. They demonstrate that a PI controller delivers good set-point tracking and disturbance rejection, when rf power is used as the actuator and a hairpin resonator probe is used as an electron density sensor. Future work will include multi-input multi-output control of a plasma process instead of the single-input single-output strategy reported above. Non-linearity and variable cross-couplings are expected to be very challenging from a controller design point of view.

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