

Real time feedback control of plasma density using a floating probe in semiconductor processing

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ABSTRACT

Real time feedback control of plasma density was developed and carried out in an inductively coupled plasma. This control method uses a floating probe as a sensor because it can measure plasma density in real time without modification of the plasma reactors and it does not perturb the plasma. The results show that through feedback control, plasma density can be maintained constant within a steady state error of less than 0.3% even if there is a sudden pressure disturbance. This feedback control method is expected to improve the repeatability and reliability of plasma reactors.

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1. Introduction

Real time feedback control methods have been used in many industries; however, processing plasma systems such as semiconductor manufacturing devices have still been mostly based on one-sided controls such as manual controls or open loop controls [1–11].

The feedback controls in processing plasmas have many advantages. They can help processing devices obtain good repetitive reliability, which decreases defective proportion and increases production yield. Many methods of feedback control can be used because plasma density, electron temperature, ion flux, gas pressure etc. can be key control parameter of feedback control system. Plasma density control is particularly powerful in etching and deposition processing because the etched and deposition rates are a function of the plasma density, and this density influences other processing parameters such as the number of radicals, uniformity, and processing time [5–7] [9–11]. Moreover, the plasma density variations can offer information about plasma instabilities caused by a pressure disturbance, unstable input power or problems with other actuators. These instabilities can be eliminated by using the plasma density feedback control.

However, it is difficult to apply the plasma density feedback control to processing plasmas since there are few effective diagnostic methods that can be used in processing plasmas. This is because measurement methods must not perturb the plasma and must be resistant to contaminations caused by processing gas or by-products [12–20]. Contaminations and plasma perturbations lead to inaccurate measurement, which results in incorrect feedback control. In particular, the perturbation must be minimized because it would cause serious problems in processing reliability by the altering processing conditions and performance.

A number of trials for plasma density feedback control have been performed for processing plasma devices. Chang et al. investigated the electron density feedback control in ICP with a heterodyne interferometer [9]. This method is noninvasive and can measure the electron density in real time. The electron density is obtained by measuring the phase shift of microwaves through the plasma. However, the heterodyne interferometer has some limitations when applied to commercial plasma processing reactors as it only measures the line averaged density, which therefore makes it insensitive to local density variations. Major remodeling and modifications of commercial manufacturing reactors are also required for control since the associated windows to path macro waves and two relatively large antennas to send and receive the microwave must be provided [9,12,13].

Klimecky et al. designed a real time feedback control using a broadband rf resonance cavity technique [10]. This method

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obtains the volume averaged plasma densities by monitoring changes in the cavity resonance peak frequencies of microwaves. However, the cavity resonance peak frequency can be affected not only by the plasma density but also by the chamber wall condition, chemical compositions. The processing chamber wall tends to become coated by dielectric materials with time leading to inaccurate density measurement and unreliable feedback control. For accurate density measurement, a complex model for plasma reactors that includes chamber geometry, plasma generation antenna, plasma sheath, and chamber wall state is required [10,11].

In this paper, a floating probe method [14] as the sensor of feedback controller was used. The basic idea of the floating probe method is to measure the harmonic currents resulting from the sheath nonlinearity and to obtain the electron temperature and plasma density from the harmonic currents. This method can measure the plasma density with little plasma perturbation because it works at a floating potential, and it only applies a small AC voltage to a probe. Since relatively high frequency is used to bias the probe, the method works well despite the contamination of the sensor in the processing plasmas [14]. For nonintrusive measurement, the probe was installed on the wall without intruding the plasma. An rf power generator was used as an actuator and proportional integral derivative (PID) control was employed.

2. Floating probe method

To derive the plasma density, we used a floating harmonic method (FHM) [14,21]. A schematic diagram of the floating probe is shown in Fig. 1. When the current flows through the probe circuit, only the ac current is measured by the sensing resistor, whereas the dc current is blocked by the capacitor. The output voltage across the sensing resistor was amplified using a differential amplifier and separated into harmonic components using a fast Fourier transform (FFT) method. In the diagnostic circuit, compensation for both RF noise and stray current was also conducted to improve the signal-to-noise ratio (S/N). The total current flowing into the probe circuit can be given by the sum of the electron and the ion current. Assuming Maxwellian EEDFs and the ion saturation current in the vicinity of the floating potential, when the sinusoidal bias voltage with $V_b = V_0 \cos \omega t$ is applied to the probe, the total probe current i_p is given by

$$i_p = i_{dc} + \sum_{k=1}^{\infty} |i_{k\omega}| \cos(k\omega t), \quad (1)$$

where i_{dc} is the dc component of the total probe current, and $i_{k\omega}$ represents the k th order harmonics caused by the nonlinearity

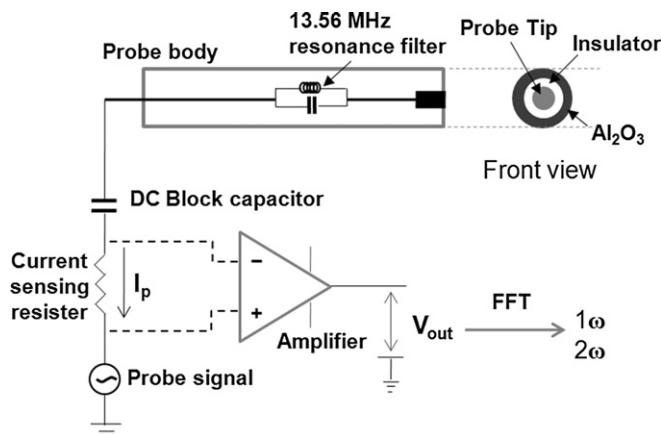


Fig. 1. A schematic diagram of the floating probe.

characteristics of the sheath. These harmonics terms can be rewritten as $i_{1\omega} + i_{2\omega} + \dots$, where the amplitude of the first harmonic $i_{1\omega}$ is relatively larger than that of other higher harmonics, and therefore it is commonly used to determine plasma density. As expected, i_{dc} becomes zero due to the existence of the dc blocking capacitor. Under these conditions, the plasma density n_i can be obtained from the amplitude of the first harmonic

$$n_i = \frac{|i_{1\omega}|}{2(0.61eu_B A_p)} \frac{I_0(V_0/T_e)}{I_1(V_0/T_e)}, \quad (2)$$

where e is the elementary electron charge, u_B is the Bohm velocity, A_p is the probe area and $I_n(v)$ is the n th order modified Bessel function. Similarly, the electron temperature T_e can be determined from the ratio of the first and second harmonics.

$$|i_{1\omega}|/|i_{2\omega}| = I_1(V_0/T_e)/I_2(V_0/T_e). \quad (3)$$

3. Experimental setup

Our experiment was carried out in an inductively coupled plasma. Fig. 2 describes a schematic of the experimental apparatus. The plasma reactor consists of a chamber, an RF power supply (13.56 MHz), a matching network and an antenna. The chamber has a 390 mm inner diameter and a 214 mm height. A quartz window with a thickness of 20 mm is placed on the chamber and an antenna is set on the window. The antenna consists of a one turn spiral coil of 290 mm in diameter. The matching network operates automatically to minimize the reflected rf power.

To sense the change in the plasma density, a floating probe with a flat disk was installed on the chamber wall surface. A sweep voltage of 50 kHz was applied to the probe tip made of soft-anodized aluminum in 10 mm diameter. The amplitude of probe bias voltage V_0 was set below 1.0 V, resulting in little distortion effect on the wall sheath formation. This probe monitors plasma density in real time by measuring the fundamental and the second harmonic currents flowing through the probe. The probe current was fed to a high speed analog to digital convertor and only the fundamental and second current were extracted through the FFT. Therefore the floating probe has a relatively high time resolution and a good signal to noise ratio. These features of the floating probe give advantages to adapt the plasma feedback control in the processing plasma reactor. This plasma density control system is organized into three parts: a sensor, a feedback controller and an actuator. The sensor is the floating probe, which measure the plasma density on the chamber wall in real time. The measured plasma density goes the controller, in which the density is

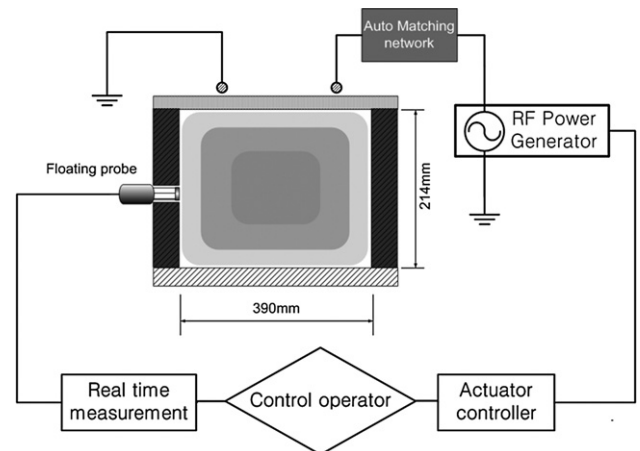


Fig. 2. A schematic diagram of the experimental setup.

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