Diagnostic technique for measuring plasma parameters near surfaces in radio frequency discharges

Shahid Rauf[a] and Mark J. Kushner[b]
Department of Electrical and Computer Engineering, University of Illinois, 1406 W. Green St., Urbana, Illinois 61801

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A plasma diagnostic technique for measuring the electron density, electron temperature, and ion current near a surface in radio frequency (rf) discharges is proposed. The sensor uses a small wire probe to determine the plasma potential and a small metal electrode to measure the current and voltage profiles. The values of current, sheath voltage, and time derivative of sheath voltage at three distinct points during the rf cycle are used in conjunction with an analytical sheath model to determine the plasma parameters. The technique is demonstrated by implementing the diagnostic in a computer model of an inductively coupled plasma reactor which has an rf biased substrate. Although any three disjoint sets of measurements can ideally be used, a sensitivity analysis is used to show that certain sets may be more suitable in experimental systems where noise is present.

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Feedback control has become an important issue in the design of radio frequency (rf) plasma processing equipment for microelectronics manufacturing. By implementing sensors in the plasma equipment and linking the sensors to actuators through feedback controllers, substantial improvements can be made in equipment reliability and performance. One ideally wants sensors that are nonobtrusive, simple to implement and which can measure many parameters. Electrical measurements (of voltages, currents, and power) satisfy the first two requirements. Due to the nonlinearity of the plasma medium,[1–4] these measurements have not traditionally been used to extract fundamental plasma parameters. It would, however, be helpful if they could also be used to determine plasma parameters, such as the electron density and temperature, which are more closely related to the generation of reactive species. In this regard, recent experiments by Sobolewski[5,6] and Miller and Riley[7] have demonstrated the potential of electrical measurements to reveal more in-depth information about the plasma dynamics. For example, Sobolewski[5] recently proposed an electrical sensor which uses voltage and current measurements to determine ion current to an electrode. He made use of the fact that at the time when the sheath voltage is large and negative, and the time derivative of the sheath voltage is zero, the sheath current primarily consists of the ion contribution.

In this letter, we extend Sobolewski's technique by combining electrical measurements with a sheath model in a sensor which also determines the electron density and electron temperature in the plasma adjacent to the sheath. This is accomplished by making $I-V$ measurements at additional times during the rf cycle and relating them through the sheath model. The proposed sensor is implemented in a computer model of an inductively coupled plasma (ICP) reactor, and the results are used to evaluate the practicality of the scheme.

[a]Electronic mail: rauf@uigela.ece.uiuc.edu
[b]Electronic mail: mjk@uiuc.edu

The proposed sensor consists of two parts. The first is a flush electrode where both the voltage V_E and current I are measured. The second is a small metal wire that ideally measures the plasma potential V_P in the presheath region above the metal electrode. In inductively coupled plasmas, the sheath is thin (less than a mm) and so the wire need not be more than a few mm long. Also since the plasma potential remains relatively constant in the bulk plasma region, the plasma potential measurement can be made remotely from the metal electrode if necessary. The small bulk plasma voltage drop allows one to approximate the sheath voltage as the difference between the wire and electrode voltages, $V = V_E - V_P$. In order to extract the plasma parameters from the sheath voltage drop and the current flowing through the sheath, we assume that the sheath dynamics are governed by Riley's sheath model.[1,7] The validity of this assumption has recently been demonstrated in both capacitively coupled[8] and inductively coupled plasmas.[7]

In Riley's model, the current through the sheath, I, is given by[1]

$$I = e n_0 \nu_i A - \frac{n_0 e}{4}\left(\frac{8 k_B T_e}{\pi m_e}\right)^{1/2} \exp\left(\frac{eV}{k_B T_e}\right) A + \epsilon_0 \frac{dV}{dt}\frac{dE}{dV} A, \tag{1}$$

where n_0, v_i, T_e, V, E, e, k_B, m_e, ϵ_0, and A are the electron density, ion velocity, electron temperature, sheath voltage drop, electric field, electron charge, Boltzmann constant, electron mass, vacuum permittivity, and surface area of the electrode, respectively. The terms on the right-hand side of Eq. (1) are the ion current, the electron current and the displacement current. In the limit that the effective voltage the ions see is the same as the actual voltage,[1]

$$E = \sqrt{\frac{2 n_0 k_B T_e}{\epsilon_0}}\left[\left(1 - \frac{2eV}{k_B T_e}\right)^{1/2} + \exp\left(\frac{eV}{k_B T_e}\right) - 2\right]^{1/2}. \tag{2}$$

dE/dV can then be computed using Eq. (2).

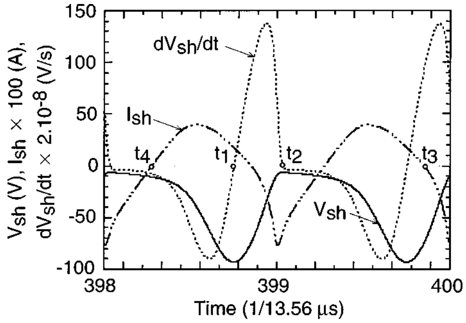

FIG. 1. Sheath voltage above the sensor (V_{sh}), sheath current (I_{sh}), and time derivative of sheath voltage (dV_{sh}/dt), obtained from the plasma equipment model for an ICP reactor in Ar at 500 W inductive power deposition, 20 mTorr gas pressure, and 100 V rf bias on the substrate. The sensor is at the location indicated in Fig. 2.

Equation (1) has three unknowns; n_0, T_e, and v_i. To determine these unknowns from the voltage and current profiles, one needs three distinct sets of values of voltages, currents, and time derivatives of voltages. Although any three disjoint sets of values should suffice, the times where different quantities cross zero seem to be the most appropriate. The sheath voltage, time derivative of sheath voltage, and sheath current are shown in Fig. 1 for an ICP reactor with a 100 V rf substrate bias for Ar at 20 mTorr. These $I-V$ characteristics were obtained using the plasma equipment model described below. Four relevant zero crossings are indicated in Fig. 1 as t_i, where $i=1,...,4$. The measurements at t_1, t_2 and either t_3 or t_4 will be used in the analysis. At t_1, the sheath voltage drop is maximum thereby retarding electron current and so the sheath current mainly consists of the ion current. Sobolewski used the $I-V$ characteristics at t_1 to determine the ion current.[5] At t_2, the sheath voltage drop is minimum and the electrons carry the majority of the current. Substituting these measurements into Eq. (1), we obtain the following three coupled nonlinear equations:

$$I_1 = en_0 v_i A - \frac{n_0 e}{4}\left(\frac{8k_B T_e}{\pi m_e}\right)^{1/2} \exp\left(\frac{eV_1}{k_B T_e}\right) A, \tag{3}$$

$$I_2 = en_0 v_i A - \frac{n_0 e}{4}\left(\frac{8k_B T_e}{\pi m_e}\right)^{1/2} \exp\left(\frac{eV_2}{k_B T_e}\right) A, \tag{4}$$

$$0 = en_0 v_i A - \frac{n_0 e}{4}\left(\frac{8k_B T_e}{\pi m_e}\right)^{1/2} \exp\left(\frac{eV_3}{k_B T_e}\right) A + \epsilon_0 \frac{dV_3}{dt}\frac{dE}{dV}(t_3) A, \tag{5}$$

where $V_i = V(t_i)$ and $I_i = I(t_i)$. [Values at t_4 may alternately be used in Eq. (5).] Equations (3)–(5) can be solved using Newton's method or a similar algorithm to determine n_0, v_i, and T_e.

We implemented the proposed sensor in a plasma equipment model of an ICP reactor. Briefly, the model is the hybrid plasma equipment model (HPEM)[9] with an imbedded circuit module.[8] The circuit module uses intermediate results from the plasma transport modules to construct a simple circuit representation of the plasma reactor which is connected to the external circuitry. The resulting circuit equations are solved implicitly in time until convergence. The steady-state voltages (dc, fundamental, and harmonics) at the electrodes and reactor surfaces are used in the plasma transport modules as boundary conditions for the solution of the Poisson's equation. This procedure is repeated until both plasma and circuit quantities converge.

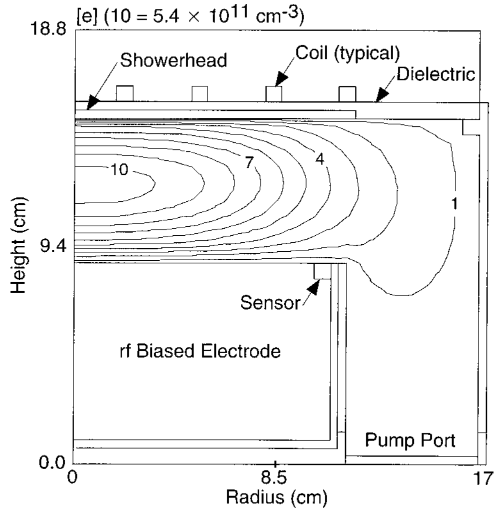

FIG. 2. Electron density in the ICP reactor with Ar at 20 mTorr, 500 W inductive power deposition, and 100 V rf bias on the substrate.

The reactor geometry is shown in Fig. 2 where the electron density is also shown for an ICP reactor operating in 20 mTorr argon pressure with 500 W inductive power deposition and with a 100 V rf bias on the substrate. The reactor consists of a four-turn antenna set on top of a dielectric window. Gas is injected through a showerhead at the bottom of the dielectric window and flows out through the pump port at the bottom of the reactor. The wafer sits on the rf biased substrate. The proposed sensor is placed at the outer edge of the biased electrode. To avoid perturbing the electric field at the edge of the electrode, the sensor was biased in the same manner as the substrate.

The computed voltage drop across the sheath on top of the sensor and current passing through it are shown in Fig. 1. The procedure outlined above was used to determine the plasma parameters from the sensor and they were found to closely match the values obtained in the HPEM simulation.

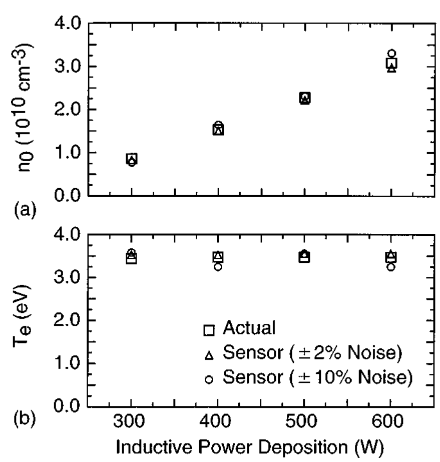

FIG. 3. Comparison of the actual (a) electron density and (b) electron temperature above the sensor and the values derived using the sensor as a function of power deposition for the ICP reactor shown in Fig. 2. Random noise of ±2% and ±10% were added to all voltage and current measurements.

TABLE I. Error produced by a ±5% variation in currents, voltages, and time derivative of voltages evaluated at times t_i.

Value Perturbed By ±5%	Variation in derived plasma parameters (%)		
	n_o	T_e	$V_{\rm ion}$
I_1	−12.35 to 13.15	−4.67 to 5.50	−7.22 to 8.41
I_2	−1.24 to 1.34	−2.22 to 2.08	−1.23 to 0.83
V_1	<±0.1%	<±0.1%	<±0.1%
V_2	−2.68 to 2.94	−5.13 to 5.05	−2.85 to 2.53
V_3	−9.99 to 10.30	−4.19 to 4.76	−9.32 to 11.09
dV_3/dt	−12.08 to 14.27	−5.50 to 5.85	−12.51 to 13.74
V_4	−19.0 to 25.7	−9.09 to 9.92	−20.47 to 23.48
dV_4/dt	−3.20 to 1.52	−0.65 to 1.28	−1.51 to 2.98

For example, the actual and sensor derived electron density and electron temperature are shown in Fig. 3 as inductive power is varied. The small differences between the plasma parameters obtained from the sensor and actual plasma parameters obtained from the HPEM are due to the addition of ±2% and ±10% random noise to the voltage and current measurements. The sensor appears robust against noise. Its sensitivity to noise will be quantified below. The technique has been tested with experimental current and voltage waveforms from both inductively and capacitively coupled discharges,[5,6] and the resulting plasma parameters are reasonably close to those obtained in independently performed simulations and experiments. A systematic comparison with experiments has, however, not yet been done because of the unavailability of the required simultaneous electrical and plasma measurements in the published literature.

$I-V$ characteristics are noisy in practice with many sources of uncertainties. These conditions require a robust sensor. A sensitivity analysis was therefore performed to determine the dependence of derived plasma parameters (n_0, v_i, and T_e) on variations in the sensor voltage and current measurements. The values of the individual voltage and current measurements were changed by ±5% and the maximum variations in n_0, v_i, and T_e were computed. The results are summarized in Table I for the conditions of Fig. 1. The plasma parameters are not particularly sensitive to variations in I_2, V_1, and V_2. For these quantities, a ±5% error in measurements leads to an error in the derived plasma parameters of generally less than 5%. The insensitivity to V_1 is due to the fact that electron current is small at t_1, and small changes in an already large value of V_1 do not significantly effect Eqs. (3)–(5). All quantities are sensitive to measurement errors in V_3 and dV_3/dt. An alternative to the use of values at t_3 is to use values at the other zero crossing of current at t_4. The results in the second half of Table I show that while the use of values at t_4 reduces the sensitivity to variations in dV/dt, the system has become more sensitive to errors in voltage. At t_3, ion current balances the displacement current, while at t_4 electron current plays a dominant role in balancing current. Since the electron current has an exponential dependence on sheath voltage, plasma parameters are sensitive to errors in V_4 when V_4 is small and comparable to the electron temperature. The $I-V$ measurements at both t_3 and t_4 can ideally produce the correct plasma parameters. The choice of which set is used in practice will depend on how accurately voltages and their time derivatives can be measured.

In summary, an electrical diagnostic has been proposed that can measure electron density, electron temperature, and ion current near a surface in rf discharges. The diagnostic uses sheath current and sheath voltage drop measurements and determines the plasma parameters by correlating them through Riley's sheath model. The method was demonstrated using a computer model of an ICP reactor. Although any three distinct voltage and current measurements work in principle, a sensitivity analysis showed that certain measurements fare better in the presence of experimental uncertainties. Since the proposed diagnostic does not perturb the plasma significantly, it is expected that it can prove useful for real time control applications.

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