IMPROVED METHOD FOR THE MEASUREMENT AND CONTROL OF THE ACTUAL POWER DISSIPATED IN RF GLOW DISCHARGES

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The method consists in calculating the voltage and current at the powered electrode from measurements outside the chamber, through an equivalent circuit having experimentally determined components. The circuit also includes resistive losses. Measurements of actual power for argon and silane discharges are presented and discussed.

Introduction

The problem of accurate control of the macroscopic parameters is commonly encountered in all plasma processes. This is particularly true for plasma CVD where the qualitative characteristics of the deposited films greatly depend on the exact plasma conditions. This includes, besides pressure, flow rate, power and temperature, other parameters that depend on the deposition history which in turn affects the way power is coupled to the discharge because of the change in transfer impedance.

In fact, power is the less controlled parameter in plasma deposition systems. It is usually measured by SWR bridges before the matching network, giving a value which include power losses in the matching and the parasitics networks. The last one consists of inductive, capacitive and resistive components associated with connecting cables, feedthrough's, and ground shields which intervene between the power coupling point and the rf electrode surface with respect to the grounded chamber. Thus the power really consumed by the discharge is not only much smaller, but also is not a constant fraction of the measured power. Moreover, the consecutive depositions of films change the chamber impedance and thus the power consumed in the process at exactly the same conditions. This means that two films grown in the same chamber but in different deposition sessions are not identical and since we don't know the exact conditions they cannot be repeated.

The problem is solved by adapting a more accurate measurement technique which involves the measurement of the current and voltage waveforms and the phase difference at the rf electrode. Since this is technically difficult, one can measure the respective waveforms outside the chamber, determine experimentally the components of the circuit between the measurement point and the electrode surface, and then convert them to the real waveforms at the electrode through simple equations.

This work is concerned with the improvement of the method accuracy and the presentation of results concerning argon and silane discharges.

Method description

The parallel plate plasma CVD chamber used for these measurements is 160 mm wide, having two 55 or 95.5 mm in diameter interchangeable electrodes. The interelectrode distance is continuously adjustable from 0 to 70 mm. The RF electrode is surrounded by a ground shield. Pressure and flow rate of gases are independently adjusted by a downstream throttle valve controller and mass flow controllers respectively [1]. The 13.56 MHz generator is coupled to the powered electrode through a wattmeter bridge, an L type matching network, and a shunt circuit. RF Voltage and current signals are recorded to a Lecroy 9400 digital storage oscilloscope using a 1:100 voltage probe and a 0.1 Ω transfer impedance current probe, mounted to the electrically isolated powered electrode lead outside the vacuum chamber. The digitized waveform signals are transferred to a personal computer for Fourier analysis. The formation of dust particles in the case of silane discharges is continuously checked by a laser scattering technique.

The dissipated power P is calculated from the voltage and current components at the powered electrode, $\mathbf{V}_{en}$, and $\mathbf{I}_{en}$ using the expression:

$$P = \frac{1}{2} \sum_{n=1}^{5} V_{en} I_{en} \cos \varphi_{en}$$

where φ_{en} is the phase of $\mathbf{V}_{en}$ relative to $\mathbf{I}_{en}$, and V_{en} and I_{en} are the magnitudes of $\mathbf{V}_{en}$ and $\mathbf{I}_{en}$, respectively. Only the first five harmonics appear in the Fourier analysis with considerable amplitude.

In order to calculate $\mathbf{V}_{en}$ and $\mathbf{I}_{en}$, one has to construct an electrical equivalent circuit for cell parasitics, to connect a shunt circuit which eliminates large displacement currents coming from these elements [2], and to calculate the propagation delays of the probes [3].

An inductive-capacitive (L-C) circuit, shown in Fig. 1, is used to account for the cell's parasitics. The values for L and C are determined by measuring the impedance of the cell at the fundamental frequency and the second harmonic.

Furthermore a shunt circuit consisting of a coil and an air variable capacitor (L_s-C_s circuit) is connected between the powered lead and the chamber ground, at a point between the current probe and the chamber. The shunt is tuned with the empty cell excited by a sinusoidal voltage at 13.56 MHz, and the C_s adjusted until the measured current is nulled. At that point the reactance of the cell's equivalent circuit is cancelled by the shunt's reactance according to the relation:

$$j\omega L_s + \frac{1}{j\omega C_s} = -\left(j\omega L + \frac{1}{j\omega C} \right)$$

When this condition is met, the value of C_s is independently measured and L_s is calculated from the above relation.

Propagation delays due to the probes and their cables from the measuring point to the oscilloscope are taken also into account, since a delay in the time domain diagram of a waveform, results to a phase shift in the frequency domain diagram of a Fourier transformation.

A problem with applying the method just described is that the cell and the shunt are not usually pure reactances. Some residual current is present even with the shunt properly tuned. The residual current is in phase with the voltage at the point of measurement with a deviation of ±3°, while the voltage to current ratio is almost constant. This has led us to add a resistor R_l, having the value of the above ratio, in the equivalent circuit at the position that is shown in Fig. 1, where all the other elements are those already mentioned. The additional capacitor C_l is used to maintain capacitive coupling to the cell in order not to short out the dc bias of the powered electrode. Its capacitance is considered to be infinite and is not involved in the calculations.

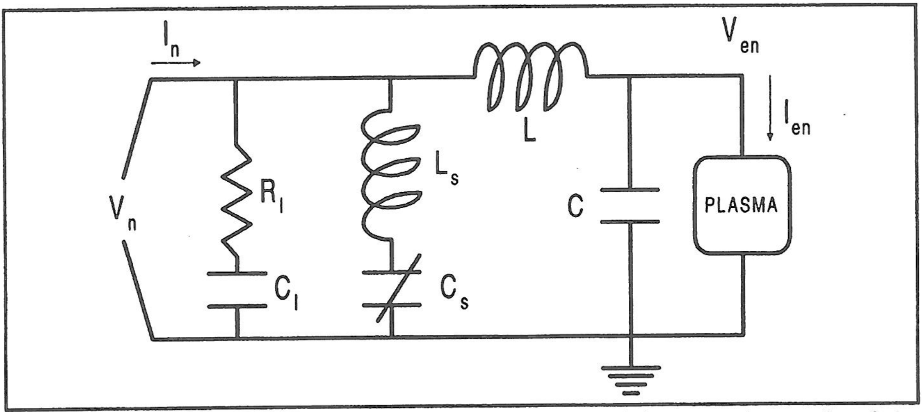

Figure 1. The electrical circuit for the determination of the cascade matrix of the network of parasitics. The L-C circuit representing the cell, the L_s-C_s shunt circuit and the R_l-C_l circuit for power loss.

The final relations that convert the measured values to the equivalent values at the electrode are given by the relations:

$$\mathrm{V_{en}} = \mathrm{V_n} - j\omega_n L\,\mathrm{I_{Ln}}$$

$$\mathrm{I_{en}} = (1-\omega_n^2 LC)\mathrm{I_{Ln}} - j\omega_n C\,\mathrm{V_n} \qquad \text{where:}$$

$$\mathrm{I_{Ln}} = \mathrm{I_n} - \frac{\mathrm{V_n}}{\mathrm{R_l}} - \frac{j\omega_n C_s \mathrm{V_n}}{(1-\omega_n^2 L_s C_s)}$$

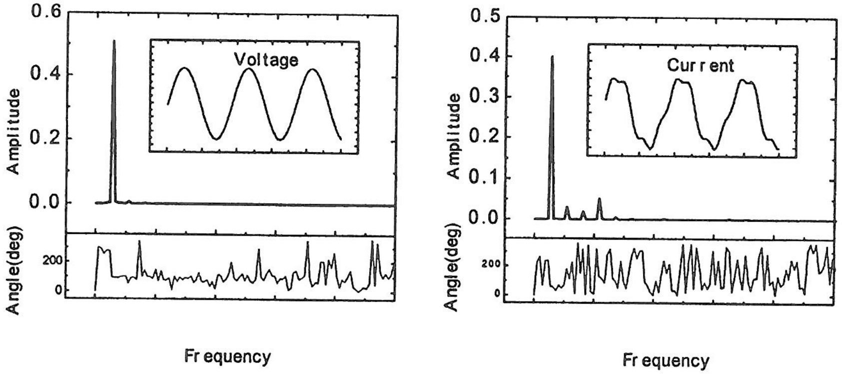

Figure 2. A typical frequency domain diagram of a discrete Fourier transform of voltage and current waveforms (insets). The waveforms have been recorded for a silane plasma of 50 mTorr.

Results and discussion

Fig. 2 presents the frequency domain diagram of measured voltage, V, and current, I, (insets) for a silane glow discharge at 50 mTorr pressure and 100 Volts rf peak-to-peak voltage, including amplitude and phase for each waveform. Using these values it is easy to calculate the actual power through the procedure described earlier.

In this figure one can observe the consequence of the non-linear behaviour of the plasma impedance. Namely, although the driving voltage is sinusoidal, having a very small contribution of higher harmonics in the amplitude diagram, in the respective current diagram there is significant contribution from four higher harmonics. This is an indication of the significance of various collision processes to the consumption of power in the discharge. A large number of this type of waveforms were recorded, and used for the calculation of power, for argon and silane at various peak to peak RF voltages and pressures. The results indicate in general that a small part of the power measured by the wattmeter is actually consumed by the discharge.

This can be seen in Fig. 3 and Fig. 4 which present the ratio P/P_t of the real dissipated power to that measured with a conventional powermeter, as a function of the fundamental component of the electrode voltage, for various silane and argon pressures. This ratio varies from 3% to 30% while it is not proportional to the rf driving voltage. Apart from this, this ratio strongly depends on the pressure. P_t changes with pressure are in general small. Therefore the observed increase is mainly due to the increase of P. Higher pressures produce more symmetric, better matched discharges, with an increased number of collisions, leading to higher power consumption.

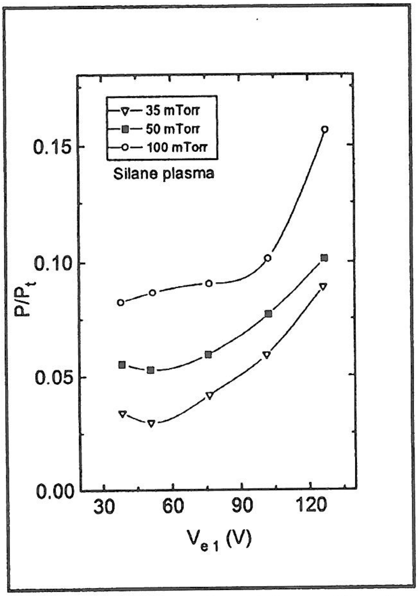

Figure 3. Ratio of real to wattmeter power as a function of electrode voltage for various pressures of silane.

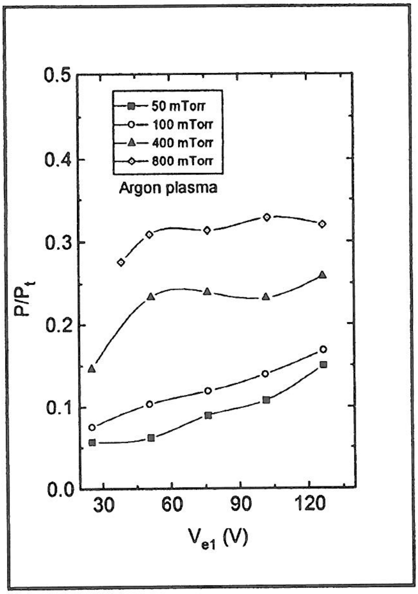

Figure 4. Ratio of real to wattmeter power as a function of electrode voltage for various pressures of Argon.

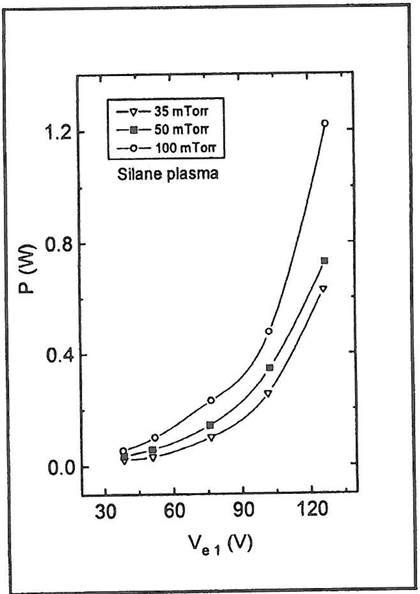

Figure 5. Power as a function of electrode voltage for various pressures of silane.

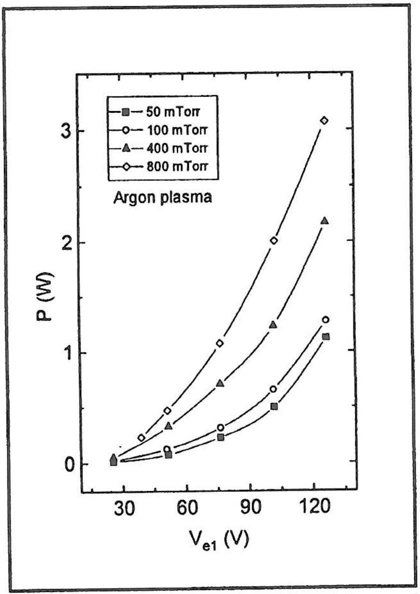

Figure 6. Power as a function of electrode voltage for various pressures of Argon.

The power measured for each pressure as a function of the voltage has a different behaviour indicating the different regimes of the discharge sustaining mechanism. This is observed by the change of the curve slopes at certain values of the voltage. These observations show how inaccurate and misleading is the conventional power measuring method which is not even representative of the power that is actually consumed in the glow discharge.

Fig. 5 and Fig. 6 present the variation of power as a function of the calculated electrode voltage for silane and argon discharges at various pressures. The value of the electrode voltage equals approximately one half of the RF peak to peak voltage in our system.

The trends of the curves in this case are significantly different mainly in the case of argon. The increasing number of collisions associated with higher voltages is also visible for both cases, with marking differences between the case of the atomic and the molecular gas discharge.

Conclusions

The proposed experimental method for the determination of the power that is actually consumed in both atomic and molecular discharges indicates large differences from the conventional powermeter. The method can be used effectively for parametric experiments based on the variation of power, for exact reproduction of the experimental conditions, as for example in deposition of thin films. In all these cases the use of the powermeter cannot be used successfully.

References

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