Electrical and Plasma Characteristics of RF Discharges for Plasma Processing

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Abstract

Until recently in the area of discharge processing the emphasis has been on developing improved or new processes with less attention to the characteristics of the plasma itself. The need to better characterize the processing plasma and to acquire a predictive capability through modeling based on measurements reproducible at different laboratories has now been recognized. A standardized discharge configuration and electrical measurement methods were developed. Using these methods, we measured discharge characteristics in argon, helium, and nitrogen. With a microwave interferometer, the line integrated electron densities were measured. Information on plasma loss mechanisms and ion species can be deduced from these measurements. Operated in pulsed mode, the decay time of the DC bias is important if negative ions and dust precursors are to be eliminated. To obtain reduced DC bias, increased plasma density and lower pressure operation, a magnetic field parallel to the electrodes was applied. The effect of the B-field depended on the attachment coefficient of the gas which determines the width of the electrode sheaths. To separate the plasma generation from the substrate treatment area and to operate at lower pressure and with controlled ion energy, an inductive discharge with an electron energy analyzer was used. At the lower pressure, the percentage of high energy electrons increased considerably. Investigating discharges with helical resonators, we measured electron densities comparable to or exceeding those in parallel plate discharges.

I. Introduction

In the rapidly growing application area of plasma processing, the development of new processes as well as the quality control of existing methods often uses an empirical approach. Predominantly the quality of the process is judged by analysis of the end product with little diagnosis of the process itself. Among the measurable operating parameters, gas pressure and flow rate of the constituent gases can be measured accurately, progress of the treatment process may be monitored by end point detectors, and the discharge power usually is measured by standard rf power meters. However, for the parallel plate reactor, the most common reactor type, it is well known (at least among the discharge research community) that this type of power measurement can be in error by a factor of two or even more in indicating the power into the rf plasma itself. Since the magnitude of this error depends on the operating parameters of the particular process, a parameter vital to the diagnostics and analysis of the plasma chemical process therefore cannot be relied upon. Research into the rf plasmas relevant to plasma processing has greatly increased in recent years. One of the basic problems with these efforts is the reproducibility of experimental results due to different experimental parameters and operating conditions and the difficulty to derive basic data required for theoretical models. In an effort to make measurements on plasma reactors more reliable and reproducible at different laboratory locations, a group of investigators at the Gaseous Electronics Conference (GEC) decided on a discharge configuration which simulates a commercial reactor and this standardized discharge cell was acquired by several laboratories (fig 1). The meas-

![Diagram of discharge cell and vacuum system](https://via.placeholder.com/150)

Fig. 1. Schematic diagram of the discharge cell and vacuum system initiated by the Gaseous Electronics Conference.

urement methods were standardized also. Measurements on the standard reactor in our laboratory will be reported. We also have investigated several methods proposed to allow processing at lower pressure (<0.1 Torr) than possible in a standard parallel plate reactor and avoid its high sheath voltage at higher power densities. With the continuing trend in the semiconductor industry to decrease feature sizes and the need for high anisotropy good control over the direction of ion velocity...
is required, demanding lower pressure operation. The first method increases ionization efficiencies by applying a magnetic field parallel to the electrodes. For high etch rates increased plasma density and separate control of plasma density and substrate bias are necessary. Separation of plasma source and processing volume makes this possible. The most common configuration is the ECR reactor, other choices are excitation by helicon waves, inductors and helical resonators. Electron losses to the walls have been reduced by magnetic cusp fields. We have made measurements on electron energy distributions in inductively excited discharges and electron density measurements downstream from a helical resonator.

II. Electrical measurements on the reference cell.

The reference cell design agreed upon by members of the Gaseous Electronics Conference simulates the characteristics of an actual plasma reactor in a relatively large vacuum containment vessel. This design results in a large asymmetry in the area of driven electron versus that of the grounded surfaces. Under the leadership of Sandia National Laboratories the problem of measuring the rf current and voltage at the discharge was considered by the researchers involved in the GEC reference cell studies. Representing the reference cell with an equivalent circuit model, all stray capacitances were lumped into one capacitance parallel to the plasma; the stray inductances were represented by a series inductance (fig 2).

\[
V_1 \parallel h_1 \quad V_0 \parallel h_0 \quad X_1 \parallel X_2 \parallel X_3
\]

where:
- \( V_1 \): Voltage at Terminals
- \( I_0 \): Current at Terminals
- \( V_0 \): Voltage At Discharge
- \( I_0 \): Current through Discharge
- \( L \): Inductance of Reactor
- \( C_0 \): Capacitance of Reactor
- \( L_0 \): Inductance of Shunt Circuit
- \( C_0 \): Capacitance of Shunt Circuit

then:
\[
X_1 = \left[ \frac{1}{V_0} - \frac{1}{X_0} \right]
\]

where:
\[
x = \frac{1}{X_0} \left( X_0 + X_1 \right) \quad V_0 = V \left( \frac{1}{X_0} - \frac{1}{X_1} \right)
\]

fig 2. Equivalent circuit for the GEC reference cell. A parallel LC circuit has been added to compensate for the parallel stray capacitance.

series LC resonance circuit tuned to resonate with the parallel capacitance was added. This eliminates the low impedance of the stray capacitance parallel to the small real part of the plasma impedance which one wants to measure for the plasma power. Unfortunately the losses introduced by the LC circuit cannot be neglected in the power computation. Also the capacitance of the electrode sheaths still causes a large phase delay of voltage versus current. The values of the two equivalent circuit components (no LC compensation) are obtained by driving the cell, no discharge, with a non-sinusoidal waveform. From voltage and current for fundamental and second harmonic the values for equivalent stray inductance and capacitance can be calculated. Current and voltage are measured with commercial or specially constructed probes. The phase difference between I and V probes is compensated by a delay adjustment which has to be very accurate. Voltage/current phase-angle \( \phi \), at least for electro-positive gases, is usually close to -90°. Inaccuracies in the phase measurement will cause large errors in power measurement, proportional to cos \( \phi \). Especially at higher powers and for asymmetric discharges, current and voltage have a high harmonic content. The power was therefore calculated by summing the current-voltage products of the first five harmonics, obtained using fast Fourier transform or Fourier analysis. Using the equivalent circuit analysis, the voltage, current, phase at, and power into the discharge can be calculated. Measurements of an argon discharge in five identical reference cells at different laboratories were found to agree within 10%. Thus the experimental measurements in the GEC reference cell can serve as a reliable basis for theoretical models of rf parallel plate discharges. These reference cells and measurement methods are now used by the various laboratories to perform other measurements, such as optical scans, ion energy determination, measurements on attaching gases etc.

III. Electron density measurements and transient characteristics.

We have used the GEC reference cell to measure electron densities in three different gases. A microwave interferometer was used to measure the line integrated density (LINE) (fig 3). The beam profile of the 35 GHz interferometer antennas, measured with an electric field probe, was found to be somewhat larger than the electrode gap; the resulting error was determined to be less than 10%. When averaging 20 readings of the inter-
ferometer output, the minimum LINE which could be measured was 10⁻³ cm². We also inserted a pyrex cylinder with a diameter only slightly larger than the electrode.

![Schematic diagram of the GEC reference cell and microwave interferometer antennas. The pyrex cylinder confining the discharge diameter is shown also.](image)

This was done to obtain a better defined plasma along the dimension of the microwave propagation but also served to investigate the influence of discharge confining walls. In argon (fig 4) the LINE, within the limits of accuracy, is independent of pressure down to 0.25 Torr, the difference for the measurement at 0.1 Torr could be caused by an increase of diffusion losses into regions not illuminated by the microwave interferometer.

![Argon line integrated electron densities for argon as a function of power into the discharge.](image)

When the discharge is confined (solid symbols), there are no changes of the LINE with pressure, however the LINE is also smaller, indicating increased losses due to the pyrex wall. This is significant, since the area of the wall seen by the discharge is only half the area of the electrodes. Comparing the LINE measurements in argon with measurements in helium and nitrogen we found that at 1 Torr helium has a slightly higher density, however at 0.1 Torr its density is much lower. In nitrogen curiously the LINE at 0.1 Torr is higher than at 1 Torr. Measurements in the confined configuration show significant decreases of the LINE in helium, especially at low pressure, but no large changes in nitrogen. The total charged particle loss rate in this type of discharge will consist of the sum of recombination and diffusion losses. Also note that in argon, for example, in very careful Langmuir probe measurements, a very low (0.31 eV) temperature of the bulk electrons was measured. An estimate of the relative loss rates for the three gases at 0.1 and 1 Torr based on recombination and mobility coefficients computed for low electron temperatures is given in table 1. Note that even at these low pressures recombination is still relevant in argon and nitrogen, a consequence of the inverse relationship of the recombination coefficient with electron temperature. Helium is diffusion dominated and its electron density therefore depends on gas pressure. The higher density in nitrogen at the lower pressure could be due to a change from the N⁺ ion at high pressure to N²⁺ at lower pressure (the recombination coefficient of N²⁺ is an order of magnitude larger than that of N⁺). Since the reference

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Relative Recombination and Diffusion Loss Rates</th>
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<tr>
<td>Argon:</td>
<td>Confined</td>
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<tr>
<td>1.0 Torr</td>
<td>Recombination 95%</td>
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<tr>
<td>0.1 Torr</td>
<td>Diffusion 60%</td>
</tr>
<tr>
<td>Helium:</td>
<td>Confined</td>
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<tr>
<td>1.0 Torr</td>
<td>Diffusion 100%</td>
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<tr>
<td>0.1 Torr</td>
<td>Diffusion 100%</td>
</tr>
<tr>
<td>Nitrogen:</td>
<td>Confined</td>
</tr>
<tr>
<td>1.0 Torr</td>
<td>Recombination 90%</td>
</tr>
<tr>
<td>0.1 Torr</td>
<td>Recombination 80%</td>
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</table>

The cell has a very large asymmetry between the areas of the driven electrode and the grounded surfaces, a large DC bias is to be expected. In the confined case and at 1 Torr, the DC bias is reduced 50%. In helium the bias in all cases is between 60% and 80% of the peak rf voltage; in nitrogen the DC bias ranges from 10% (1 Torr) to 70% (0.1 Torr) of the peak rf voltage.
In all these cases a reduction of the DC bias voltage implies an increase of the sheath capacitance of the driven electrode (thinner sheath) which agrees with the observed decrease of the sheath thickness with increasing pressure.

In etching applications negative ions are also present in the discharge. Due to their low mobility the negative ions are unable to overcome the electrode sheath potentials. Their loss mechanisms are primarily ion-ion recombination and detachment (volume processes). Since these negative ions are suspected to be the seed for the formation of clusters and ultimately dust particles, the negative ion density has to be decreased, for example by temporarily reducing or eliminating the electrode sheaths. We have operated the GEC reference cell with a pulsed rf generator and analyzed the voltage and current at the capacitively driven electrode. Comparing the decay constant of the DC bias at switch-off with the time constant computed from the product of the measured CW impedance for argon and the coupling capacitor we found that the measured decay constant is more than an order of magnitude slower. The DC bias decay is not a simple exponential function, since the plasma conductivity depends on recombination and diffusion coefficients and conductivity, all functions of the time-varying electric field. For all gases decay is faster at higher peak rf voltage, a consequence of higher discharge conductivity. From these results it is clear that the DC bias decay required to let negative ions recombine is a complicated function of gas type, pressure and operating power.

IV. Effects of a magnetic field parallel to an electrode.

It has been recognized for some time that a magnetic field parallel to the electrodes would improve the ionization in and adjacent to the sheath and allow operation at lower pressures. The DC bias voltage is relatively lower, allowing higher discharge powers, increased plasma density and therefore higher etch rates. A disadvantage of this method is the difficulty of achieving plasma uniformity. We have tested this technique in a simple parallel plate discharge tube with variable electrode distance and one electrode exposed to a multicusp magnetic field at variable distance. The effect of the magnetic field is already noticeable at pressures of 1 Torr in argon but becomes very large at 0.02 Torr. Using the model of Köhler, Coburn et al., which assumes collisionless sheaths and neglects the floating potential, the ratio of DC bias to rf voltage is

\[
\frac{V_{DC}}{V_{RF}} = \frac{C_t}{C_w}
\]

where \(C_t\) and \(C_w\) are the capacitances of the plasma to the driven sheath (target) and to the wall respectively. When a magnetic field is applied, the sheath width of the driven electrode shrinks and its capacitance increases. In Fig. 5 the ratio \(C_t/C_w\), as obtained from the DC to rf voltage ratio, is plotted against pressure with the magnetic field as a parameter. The measured average optical sheath width is plotted for comparison. For 1 to 0.1 Torr \(C_t/C_w\) at B = 0 follows the trend of the optical width. As the magnetic field increases \(C_t\) increases also and reaches the value of \(C_w\) at 600 Gauss and 0.02 Torr. CF, behaves similar to argon, at a magnetic field of 600 Gauss the bias reaches positive values. In SF\(_6\) at pressures above 0.2 Torr the power deposition into the discharge is still volume dominated and the magnetic field has little influence. In addition, since the sheaths are so much smaller than in the other gases, the DC bias also is very small. The insensitivity of SF\(_6\) to the magnetic field can also be due the fact that the observed sheath width is smaller or of the same order as the electron gyro radius at magnetic fields of less than 150 Gauss. The dependence of the peak to peak voltage on the electrode distance was measured for 0 and for 600 Gauss with the power held constant (assuming deposition into the sheaths

![Fig. 5 Ratio of C_t/C_w versus pressure for 0, 150 and 600 Gauss. Also shown is the measured time averaged optical sheath width in nm.](image)
only) or proportional to the electrode distance (assuming deposition into the volume). For both cases the extrapolated voltage drop representing the sheath voltages is a large or dominant part of the overall peak to peak voltage and its share increases with increasing magnetic field. This is an indication of the increase of the electron collision frequency in the sheaths caused by the magnetic field.

V. Separation of excitation and substrate space: Inductive and helical resonator excitation.

As previously discussed, the parallel plate reactor has limitations for advanced plasma processing and other, low pressure methods with separate excitation and ion acceleration have been developed. We have investigated some aspects of this type of discharge with inductive and helical resonator excitation. One parameter of interest is the electron energy distribution function. A discharge tube with inductive excitation and a simple retarding grid analyzer was used to measure the electron energy distribution function. The normalized distributions are shown in fig 6. At 0.1 Torr the distribution is approximately Maxwellian, at lower pressures the distributions show a rapid increase of high energy electrons. Electrons of such high energy could possibly cause damage to a substrate. Correspondingly, in a review of measurements of electron energy distributions in ECR discharges, Weng and Kushner also conclude that in most experiments there is evidence of a high energy tail at the lower pressures and they validate these experimental results with their theoretical model. Relatively large populations of ions with energies above 30 eV have been observed downstream of ECR discharges by observation of optical doppler shifts.

A modification of the inductive excitation is the use of a helical resonator used in the radio communications field many years ago to obtain high Q resonance circuits at frequencies in the 10 to 100 MHz range. This device was recently applied to plasma excitation and etching applications. Its advantage is that as a resonance circuit it does not require external tuning circuits or matching networks with their inherent losses when tuned by a mechanically variable tab feeding the rf energy to the helix. We have used a simple fixed-tab version tuning the rf frequency for minimum reflected power. The impedance matching was not optimized since with the plasma ignited the reflected power was at a minimum over a range of several hundred kHz. Line-integrated electron densities were measured in argon versus discharge power and at pressures from 0.02 Torr to 1 Torr. Assuming a uniform electron density distribution, the electron density at 80 W rf power was 1.4x10¹⁰ cm⁻³ and for SF₆, 1.2x10¹⁰ cm⁻³, in both cases at 100 W rf power and at 0.02 Torr, was measured. These electron density values compare favorably with those of other excitation methods.

Acknowledgements: It is a pleasure to acknowledge the contributions of Alan Garscadden to the GEC reference cell measurement interpretation, Merrill Andrews for his help in starting the microwave interferometer measurements, Fred Wells for his cooperation in the transient measurements and Robert Knight for his invaluable assistance in setting up the experimental equipment.

References:

2. P. J. Hargis, Jr. et al., Rev. Scientifc Instr., to be published.
(also known as MERIE, "Magnetically Enhanced Reactive Ion Etching")


