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Impedance determination of a RF plasma discharge by external measurements

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The University of Arizona, 1989
IMPEDEANCE DETERMINATION OF A RF PLASMA DISCHARGE
BY EXTERNAL MEASUREMENTS

by

Christof Gabriel Krautschik

A Thesis Submitted to the Faculty of the
DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING
In Partial Fulfillment of the Requirements
for the Degree of
MASTER OF SCIENCE
WITH A MAJOR IN ELECTRICAL ENGINEERING
In The Graduate College
THE UNIVERSITY OF ARIZONA

1989
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ABSTRACT

The equivalent impedance of a RF plasma was experimentally determined by monitoring the voltage and current waveform for different input powers in real time. Average ion energies and fluxes were determined by a computer model which takes ion collisions in the sheath regions into account. In addition two models were proposed which explain how RF energy is converted to DC potential energy in the sheath. Etch rates of Si in a CF$_4$ discharge were also evaluated and related to the measurements.
CHAPTER 1

INTRODUCTION

The use of radio-frequency (RF) plasma discharge in the fabrication of semiconductor devices has recently renewed the interest in the understanding of basic plasma phenomena. The continuous shrinking of devices dimensions in VLSI (very large scale integration) has made plasma etching the preferred method of pattern transfer.

In order to maximize the usefulness of the plasma process a better understanding of the chemical and electrical properties of the plasma are necessary. The analysis of RF discharges is particularly complex due to the large variety of gases, pressures, reactor geometries, RF frequencies, and different materials to be processed. A better understanding of the electrical properties of gas discharges such as the DC bias, power absorption, ion energies and transport could only enhance the usefulness of the etch process.

This thesis attempts to relate an experimentally determined RF equivalent impedance to several internal parameters of the plasma. Four electrical parameters were monitored during the etch process. These quantities consisted of the RF voltage, current, phase angle, and the DC bias voltage. In addition, a computer model was used to determine other important parameters such as ion flux and average ion energies. The analysis takes collisions of ions in the sheath region into consideration.

One of the earliest attempts to model RF discharges by circuit elements was done by Koenig and Maisel\textsuperscript{1}. They were the first to recognize the capacitive effect and rectifying effect of the sheath region. Keller and Pennebaker\textsuperscript{2} took this model and
actually calculated the electron and ion currents for low density discharges. From this result they showed how the DC bias is related to the RF voltage and the electron temperature. Unfortunately, the results can only be used at very low pressures (sputtering systems) but the authors recognized the importance of power dissipation by positive ions in the sheath. They even showed how to calculate the sheath resistor which is in parallel with the capacitor. Lieberman\textsuperscript{3} has proposed a self-consistant oscillating sheath model which assumes no collisions in the sheath. The model even predicts the nonlinear RF voltages across the sheath, but does not address power absorption by the ions.

Several authors have determined the plasma potential by measuring both the RF and DC voltages. When this is done the sheath regions are assumed to consist only of capacitors and the voltage drop across the plasma resistor is assumed to be negligible\textsuperscript{4,5,6}.

Chapter 2 of this thesis reviews fundamental concepts of plasma physics which are particularly important for RF discharges. The important concepts of Debye length and plasma frequency are introduced.

The third chapter shows that the RF equivalent circuit of the plasma region consists of a resistor, inductor, and capacitor in parallel, of which the resistor constitutes the dominant element. The asymmetric discharge is replaced by a spherical shell model for the purpose of deriving analytical expressions for the three circuit elements.

In Chapter 4 it is shown that the sheath impedance consists of a capacitor and a resistor in parallel. The sheath capacitance results from the absence of electrons in the sheath and the sheath resistor accounts for the time-average power dissipated by the cations. Two models are proposed which account for the conversion of RF power
to DC power in the sheath.

The experimental apparatus and procedures are described in Chapter 5. It is shown that the chamber introduces a capacitive impedance in parallel with the equivalent impedance of the discharge.

Chapter 6 shows how the external measurements are related to each circuit element of the RF equivalent circuit. The capacitive sheath approximation is made for the purpose of calculating the sheath voltages.

The dynamics of ions in a collisional sheath are discussed in Chapter 7. It is shown that ion flux, ion energies, and ion power absorption can be determined from two coupled differential equations which are solved numerically. Results and analysis of the experimental data are presented and discussed in detail in chapter 8.

The last chapter summarizes the conclusions of this thesis and suggests further work to be undertaken.
Plasmas have been studied and utilized extensively long before plasma etching became of economic importance. The basic properties of plasma phenomena are best understood by using Maxwell's equations and the kinetic theory of gases. The development of a macroscopic electrical circuit follows directly from this formalism.

A plasma can be defined as a collection of mobile charged and neutral particles which exhibit collective behavior and satisfy quasi-neutrality. These charged particles consist of electrons, anions, and cations. Collective behavior refers to the long range electromagnetic forces the plasma experiences due to the motion of individual charge carriers. The motion of an individual charge will affect the motion of other charged particles. By quasi-neutrality is meant that the difference in the number densities of the electrons and ions is much less than the number density of each charge carrier.

A useful quantity to describe a plasma is the Debye length:

\[
\lambda_D = \sqrt{\frac{k_B T_e}{\epsilon_0 e^2 n_e}}
\]  

where \( k_B \) is the Boltzman constant, \( T_e \) the electron temperature, \( e \) the charge of the electron, \( n_e \) the electron number density and \( \epsilon_0 \) the dielectric constant of free space. The Debye length is a measure of the shielding distance of a positive ion. In order for a plasma to exist, the dimensions of the plasma chamber must be much larger than the Debye length.
The plasma frequency is another important parameter. It is given by

\[ \omega_- = \sqrt{\frac{e^2 n_-}{\varepsilon_0 m_-}} \]  

(2.2)

for electrons,

\[ \omega_+ = \sqrt{\frac{e^2 n_+}{\varepsilon_0 m_+}} \]  

(2.3)

for cations, and

\[ \omega_a = \sqrt{\frac{e^2 n_a}{\varepsilon_0 m_a}} \]  

(2.4)

for anions. \( n_+ \), \( m_+ \) and \( n_a \), \( m_a \) are the number density and atomic mass for cations and anions, respectively. \( m_- \) is the electron atomic mass.

The plasma frequency is the natural frequency at which the plasma resonates. Consider an electromagnetic wave of frequency \( \omega \) impinging on a plasma. As long as \( \omega \) is less than \( \omega_- \), \( \omega_+ \), and \( \omega_a \) both electrons and ions will position themselves in such a way that the incident electric field cannot penetrate the plasma for more than a few Debye lengths. Even at intermediate frequencies, when \( \omega_- > \omega > \omega_+ \), \( \omega_a \), the incident field will be screened out by the motion of electrons. The ions will be too massive to counteract the field. Many plasma etch chambers operate at 13.56 MHz. This corresponds to a frequency intermediate to the ion and electron plasma frequency. As a result ions will not be able to respond to the excitation frequency. Consider a CF\(_4\) gas with an electron number density of \( 10^9 \) cm\(^{-3} \), cation (CF\(_3^+\))
density of $10^{10}$ cm$^{-3}$, and an anion ($\text{CF}_3^-$) density of $9.9 \times 10^9$ cm$^{-3}$. We find that the cation plasma frequency ($\nu_+ = \omega_+ / 2\pi$) is 2.2 MHz, $\nu_- = 275$ MHz, $\nu_a = 2.5$ MHz, and the excitation frequency is 13.56 MHz. From these values we expect the dynamic behavior of the plasma to come entirely from the electronic motions. This does not mean that the electric field is zero inside the plasma. Only a small field is necessary to produce large conduction currents, since the plasma region is in general highly conductive.

Most plasma etchers consist of an asymmetric parallel plate capacitor. Fig.(2.1) illustrates the geometry of a commercial etcher. The wall electrode, which is grounded and has the shape of an inverted U, represents an equipotential surface. In addition, the target electrode is insulated from ground by a circular ceramic ring. The electric field generated by the two electrodes is anisotropic and impossible to solve analytically.

The plasma is confined between the grounded wall plate and the target electrode. When the target electrode is initially excited by the generator, a very large electric field exists between the plates. A very small fraction of the gas molecules are ionized at room temperature. These free electrons will acquire kinetic energy from the field and collide with neutrals. Some of the collisions result in the ionization of neutrals. In this way more and more free electrons are generated. This avalanche process cannot continue indefinitely. The electrons will diffuse and be driven by the large electric field to the positively charged electrode. The net result is an electron charge accumulation on both electrodes and a very thin cation layer adjacent to the plates. This space charge region is called the sheath. It screens the plasma region from the large applied electric field. This screening process is equivalent to a DC voltage. The cations will be accelerated toward the electrode and recombine with the electrons. In
Figure 2.1 Skemetic of the etch chamber shows asymmetric electrode geometry, cooling system, and RF electrode.
steady state the electrons are replenished once during each cycle. These phenomena lead to the collapse of the sheath for a time much shorter than the period of the applied voltage. The positive ion sheath population is replenished by the diffusion of cations from the plasma region.
CHAPTER 3

MODELING THE PLASMA REGION

The plasma region occupies most of the volume between the two electrodes. The electric field is quite small in this region due to the shielding effect of the two sheaths. In addition, the conductivity of the plasma is quite large: only small voltages are necessary to produce large currents. The three types of charge carriers in the plasma region are electrons, positive ions, and negative ions. Anions may form by attachment of electrons to neutrals. Nonetheless, charge neutrality must be obeyed:

\[ n_+ = n_- + n_a \]  

(3.1)

Anions and electrons are in general confined to the plasma whereas cations occupy both the sheath and plasma regions.

The RF electric field inside the plasma is the direct result of imperfect shielding by the sheaths. We assume that the excitation frequency component of the electric field is divergenceless within the plasma. Due to the asymmetric geometry of the chamber (Fig. 2.1), it is evident that the electric field is a function of position. Such an awkward geometry is easiest to handle by replacing the chamber electrodes by a spherical shell capacitor (Fig. 3.1). We assume the plasma is confined between the target areas \( A_t \) and the wall areas \( A_w \) with radial distances \( r_t \) and \( r_w \), respectively. The two areas encompass the same solid angle \( \Omega \), bounded by the angle \( \theta \) and the two electrodes are displaced a distance \( (D + d_t + d_w) \) apart. Then using spherical coordinates, it can be shown that the solid angle subtended by the two areas is given by
Figure 3.1 Asymmetric chamber geometry is modeled by a spherical shell capacitor.
\[ \Omega = 4\pi \sin^2(\theta/2) = \frac{(\sqrt{A_w} - \sqrt{A_t})^2}{(D + d_t + d_w)^2}. \]  

(3.2)

In addition, the radial distances \( r_t \) and \( r_w \) are of the form:

\[ r_t = \frac{(D + d_t + d_w)\sqrt{A_t}}{\sqrt{A_w} - \sqrt{A_t}} \]

(3.3)

\[ r_w = \frac{(D + d_t + d_w)\sqrt{A_w}}{\sqrt{A_w} - \sqrt{A_t}} \]

(3.4)

If we apply Poisson's equation to the plasma region and assume that the RF electric field is divergenceless, then

\[ \nabla \cdot E_p\{r, t\} = e(n_+\{r, t\} - n_-\{r, t\} - n_a\{r, t\}) = 0 \]

(3.5)

where \( E_p\{r, t\} \) is the electric field of the plasma region. Then computing the divergence in spherical coordinates and integrating from \( r_t + d_t \) to \( r_w - d_w \) yields

\[ E_p\{r, t\} = E_p r^2 \frac{r_t^2}{r^2} e^{i\omega t} \hat{r} \quad \text{for } r_t + d_t \leq r \leq r_w - d_w \]

(3.6)

where \( E_p \) is the maximum field amplitude at the target electrode and \( \omega \) the angular RF frequency. The current density is then given by Ohm's law:

\[ J_p\{r\} = \sigma_c E_p\{r\} \]

(3.7)

where the time dependence has been dropped and \( \sigma_c \) is the complex conductivity.
which includes both conduction and displacement components. In addition, the total current $I_p$ across any cross-sectional area is a constant:

$$I_p \{r\} = \sigma_c A(r)E_p \{r\} = \text{constant} \quad (3.8)$$

where $A(r) = 4\pi r^2 \sin^2(\theta/2)$ and $\sin(\theta/2) = 1/(2\sqrt{\pi D})[\sqrt{A_w} - \sqrt{A_t}]$. Using the relation

$$E_p = -\frac{dV}{dr} \hat{r} \quad (3.9)$$

where $V(r)$ is the voltage potential, and substituting into Eq.(3.4) and setting up the integrals yields

$$I_p \frac{4\pi \sigma_c \sin^2(\theta/2)}{4\pi \sigma_c \sin^2(\theta/2)} \int_{r_t+d_t}^{r_w-d_w} \frac{dr}{r^2} = -\int_{\phi_t-V_t}^{\phi_w-V_w} dV \quad (3.10)$$

where $d_w$ and $d_t$ are the wall and target sheath thickness respectively. $\phi_w$ and $\phi_t$ are the wall and target potentials and $V_w$ and $V_t$ the wall and target sheath voltages.

Hence,

$$I_p \frac{4\pi \sigma_c \sin^2(\theta/2)}{4\pi \sigma_c \sin^2(\theta/2)} \left\{ \frac{1}{r_t - d_t} - \frac{1}{r_w - d_w} \right\} = \phi_t - \phi_w - V_t - V_w = V_p \quad (3.11)$$

but $\phi_t - \phi_w - V_t - V_w$ is simply the voltage across the plasma $V_p$. Then making the approximations

$$r_w - d_w \approx r_w \quad (3.12)$$
\[ r_t + d_t \approx r_t . \] 

(3.13)

substituting for \( \sin^2(\theta/2) \) and rearranging produces the final result

\[ \frac{V_p}{I_p} = Z_p = \frac{D}{\sigma_c A_t} = \frac{D}{\sigma_c A_{eff}} . \] 

(3.14)

\( Z_p \) is the impedance of the plasma and the effective area is given by

\[ A_{eff} = A_t \left[ \frac{A_w}{A_t} \right] . \] 

(3.15)

Next, we have to relate \( \sigma_c \) to the actual charge carriers and the driving force. Amperes current law states that the total current density is the sum of displacement and conduction current. Then

\[ J[r,t] = i \omega e_0 E_p[r,t] + e_n v_+ [r,t] - e_n v_+ [r,t] - e_n v_- [r,t] \] 

(3.16)

where \( v_+, v_a, v_- \) are the velocity for cations, anions, and electrons respectively. The equation of motion for a charged particle in an electric field is given by

\[ m \frac{dv}{dt} = qE_p - mv \] 

(3.17)

This equation is representative of all three charge carriers as long as we use the proper values for the mass \( m \), the collision frequency \( \nu \), the velocity \( v \), and the charge \( q \). For a uniform conductivity, it follows from Eq.(3.8) that the velocity is of
the form

\[ v(r,t) = \frac{v_0 t^2}{r^2} e^{i\omega t} \hat{r} \]  

(3.18)

where \( v_0 \) is the complex velocity amplitude. This result can also be derived from the continuity equation, assuming no charge accumulation and a uniform number density of carriers.

The total time derivative is the sum of a partial and convective derivative:

\[ \frac{dv}{dt} = \frac{\partial v}{\partial t} + v \cdot \nabla v \]  

(3.19)

Then substituting for \( v \) into Eq.(3.18) yields

\[ \frac{dv}{dt} = \left\{ i\omega v - \frac{2v^2}{r} \right\} \hat{r} . \]  

(3.20)

Due to the high RF frequency, it can be shown that \( \omega >> 2v/r \). Therefore, the convective derivative can be neglected. Then substituting Eq.(3.20) into (3.17) yields

\[ v_0 = \frac{qE_0}{m} \frac{1}{\nu + i\omega} . \]  

(3.21)

From this equation it is clear that the inertial mass of a charge carrier determines the magnitude of the velocity in an electric field. The electron mass is about four orders of magnitude smaller than the mass of positive or negative ions. Even if electron attachment reduces the electron number density by two orders of magnitude, the electrons will still be the major conduction carriers. Then ignoring the conduction
due to ions we obtain

\[ J_p(r,t) = \left[ \frac{e^2n_\infty}{m_\infty \nu_\infty \left( 1 + \frac{i \omega}{\nu_\infty} \right)} + i \omega \varepsilon_0 \right] E_p(r,t) \]  

(3.22)

The term \( e^2n_\infty / m_\infty \nu_\infty \) is the DC electron conductivity \( \sigma_0 \). Comparing Eq. (3.7) with Eq. (3.22) produces the result

\[ \sigma_c = \frac{\sigma_0}{1 + \frac{i \omega}{\nu_\infty}} + i \omega \varepsilon_0 \]  

(3.23)

The plasma impedance \( Z_p \) can then be put in the following form:

\[ \frac{1}{Z_p} = Y_p = \left\{ \frac{\sigma_0}{1 + \frac{\omega^2}{\nu_\infty^2}} + i \omega \varepsilon_0 - \frac{i \omega}{\nu_\infty} \left[ \frac{\sigma_0}{1 + \frac{\omega^2}{\nu_\infty^2}} \right] \right\} A_{eff_\infty} D \]  

(3.24)

We can then define the plasma resistance, capacitance, and inductance, respectively by

\[ R_p = \frac{1 + \frac{\omega^2}{\nu_\infty^2}}{\sigma_0} \frac{D}{A_{eff_\infty}} \]  

(3.25)

\[ C_p = \frac{\varepsilon_0 A_{eff_\infty}}{D} \]  

(3.26)
These three circuit elements then represent the electrical model of the plasma region which are depicted in Fig. 3.2. The plasma resistance is associated with the heating of neutrals molecules in elastic and inelastic collisions. The plasma capacitance is the result of the displacement current present. For all good conductors the displacement current is negligible compared to the conduction current. The third element represents the inertial effect between the applied field and the velocity of the electron. If the electron undergoes many collisions during each RF cycle then the electron will move in phase with the electric field. Then for \( \omega/\nu_- \ll 1 \) the inductor can be discarded. The inductor only becomes important when the electron collides every few RF cycles or \( \omega/\nu_- \gg 1 \). Then the electron velocity lags 90° with respect to the electric field.

We will now show that the resistor is the dominant element under normal etch conditions. Typical parameters for a plasma are the following: pressure = 100 mtorr, \( n_- = 10^{10} \text{ cm}^{-3} \), \( A_t = 224.3 \text{ cm}^2 \), \( A_w = 349 \text{ cm}^2 \), \( D = 3.4 \text{ cm} \), \( \nu_- = 2 \text{ GHz} \). Using these values the impedances for the resistor, capacitor, and inductor are

\[
R_p = 8.6 \ \Omega
\]

\[
Z\{C_p\} = -11660 \ \Omega
\]

\[
Z\{L_p\} = -i52 \ \Omega.
\]

It is clear that the capacitor and inductor are negligible compared to the resistor.
Figure 3.2  Diagram depicts RF equivalent circuit for the plasma and two sheath regions. The surge of electrons is accounted for by the nonlinear elements $D_t$ and $D_w$. 
We, therefore, model the plasma region by a single resistor. The average power absorbed by the plasma is then given by

\[ P_p = \frac{1}{2}I^2R_p \]  \hspace{2cm} (3.28)

where \( I \) is the amplitude (zero to peak) of the AC plasma current.

Typical discharge voltages and currents are about 600 volts (zero to peak) and 5 amperes, as is shown later. The voltage drop across the plasma region is then about 43 volts which is much less than the sheath voltage. The power absorbed by the plasma amounts to about 100 watts or 17% of the total input power. Therefore, most of the power goes to the sheath region where it is absorbed by positive ions.
CHAPTER 4

IMPEDEANCE MODEL OF SHEATH REGION

The sheath region consists of a thin space charge layer which surrounds the plasma. The sheath results from the high mobility of electrons which initially diffuse and attach to the surrounding electrode surfaces. Adjacent to the negatively charged surface, a thin layer of cations forms. The electric field lines start on the positively charged carriers and end on the negatively charged electrodes (Fig. 4.1). This region then shields the highly conductive plasma region from the applied RF field. The positive ions will be attracted to the negatively charged external boundary. This results in a constant flow of cations to both electrodes. The cation sheath population must be constantly renewed, otherwise the sheath would begin to collapse. A constant flux of cations from the plasma to the sheath must then balance the recombination of ions with electrons at the electrodes.

The applied RF field directly modulates the positive and negative charge populations. Electrons are the only charge carriers which can follow the field. Both cations and anions are simply too massive and only see the time-average electric field. Nevertheless, the cation population in the sheath can be modulated at RF frequencies. This effect can occur for example by an oscillating sheath boundary, which has been observed by several authors. The oscillation comes from the movement of electrons which cover and uncover part of the cation layer.

How the sheath oscillates and the electron flux replenishes the lost negative charge on the electrode is illustrated in Fig. 4.2. The two sheaths and the plasma region are shown over an entire RF cycle.
Figure 4.1 Sheath region consists of cations which are accelerated by a strong electric field toward the wafer.
Figure 4.2  Simple oscillating sheath model shows sheath thickness and electron surge for a symmetric discharge over one RF cycle.
We assume the discharge is symmetric and the voltage is of the form $V \cos(2\pi t/T_0)$ where $T_0$ is the RF period and $V$ is the RF amplitude. At time $t = T_0/4$ and $3T_0/4$ the total voltage across the discharge is zero. Therefore, only the DC charge populations are present and the DC voltage across both sheaths are equal and opposite. Then at $t = 0$ the sheath boundary at the target electrode collapses and electrons diffuse to the target electrode. At the same time the wall sheath widens to expose more positive ion and to double the wall sheath voltage. At $t = T_0/2$ the role of the target and wall sheaths are reversed and electrons surge to the wall. This descriptive model is rather simplistic but very clearly illustrates how an oscillating AC charge can lead to a capacitive effect for each sheath region. Therefore, each sheath can be represented by a capacitor which accumulates and recombines charge once during each cycle. Many authors have modeled the sheath in this way$^{1,2,4,5,6,12}$.

Most of the power absorbed by the plasma is dissipated by ions in the sheath, as is revealed by the theoretical analysis. The cations diffuse from the plasma to the plasma-sheath boundary and are then accelerated by the DC sheath voltage toward the electrode. The ions acquire kinetic energies equal to the plasma potential if no collisions occur$^{2-12}$. This energy is then lost as heat by collisions with the wafer or wall. Secondary electron emission can put part of the energy back into the plasma but we shall ignore this effect$^9$. If the ion undergoes collisions inside the sheath the final energy will be reduced. No matter whether collisions occur or not the power dissipated by the ions at the target electrode the is given by

$$P_{\text{abs}} = e \gamma_+^i A_t V_{\text{DC}}^i,$$  

(4.1)

where $\gamma_+^i$ is the target ion flux and $V_{\text{DC}}^i$ the time average target sheath voltage.
Each ion which arrives at the target electrode decreases the energy stored in the DC electric field of the sheath by an amount $eV_{DC}$. In order to maintain the DC voltage the energy lost by the ions must be restored. This energy can only be supplied by the generator at the RF frequency. It must, therefore, be initially converted to DC potential energy to be of any use to the ions. The conversion process must then show up as a resistor in an AC circuit. How then can the electrons absorb energy at the RF frequency to maintain the power balance of the discharge? Two models which initially seem quite different can at least explain phenomenologically how this conversion process could possibly take place.

The first model we shall call the "oscillating sheath boundary model" and the second the "electron injection model". Both models deal with the voltage and current across the sheath and show that power absorption in the sheath occurs.

First, we consider an oscillating sheath boundary which is driven by the RF field $V\cos(\omega t)$. The sheath has an average thickness $d_0$ and an AC amplitude $\Delta d\sqrt{1+\epsilon^2}$ (Fig. 4.3). The change in sheath thickness can be imagined to result from the movement of electrons which cover and uncover the ion population of the sheath. When electrons cover a volume which was previously occupied by ions, this volume becomes devoid of charge. The entire sheath is assumed to consist of a uniform ion population, but only those ions affected by the electrons are shown in the figure.

The time dependence of the sheath is then of the form

$$d(t) = d_0 + \Delta d\sqrt{1+\epsilon^2}\cos(\omega t - \tan(\epsilon)),$$

or
Figure 4.3 Oscillating sheath boundary exposes and covers cations at the plasma-sheath boundary.
\[ d\{t\} = d_0 + \Delta d[\cos(\omega t) + \epsilon \sin(\omega t)] \]

where \( \tan^{-1}(\epsilon) \) is the phase angle by which the sheath boundary lags behind the voltage. We assume the AC amplitude of the sheath is small compared to the DC sheath thickness, so all the oscillating charge has approximately the same capacitance. The AC charge accumulation per unit area is then of the form

\[ Q(t) = Q_0 + \frac{\Delta Q}{\sqrt{1 + \epsilon^2}}[\cos(\omega t) + \epsilon \sin(\omega t)]. \quad (4.3) \]

where \( Q_0 = \epsilon n_0 d_0 \) and \( \Delta Q = \epsilon n \Delta d \sqrt{1 + \epsilon^2} \). The work done per unit area per unit time by the AC charge is then given by

\[ P_{\text{abs}} = V(t)\dot{Q}(t) = V(t) \frac{dQ(t)}{dt}. \quad (4.4) \]

\[ P_{\text{abs}} = -\frac{\omega \Delta Q V}{\sqrt{1 + \epsilon^2}} \sin(\omega t) \cos(\omega t) + \frac{\epsilon \omega \Delta Q V}{\sqrt{1 + \epsilon^2}} \cos^3(\omega t). \quad (4.5) \]

If we let \( \Delta Q = CV \) then the result becomes

\[ P_{\text{abs}} = -\frac{\omega CV^2}{\sqrt{1 + \epsilon^2}} \sin(\omega t) \cos(\omega t) + \frac{\epsilon \omega CV^2}{\sqrt{1 + \epsilon^2}} \cos^3(\omega t). \quad (4.6) \]

The first term oscillates at \( 2\omega \) and averages to zero over one cycle. It simply represents the AC charge which alternates between potential and kinetic energy. It is a capacitive effect. The second term is always positive if \( \epsilon > 0 \), and implies that energy is taken from the RF field. It acts like a resistor which is given by
The average power absorbed from the AC field is then given by

$$P_{\text{abs}} = \frac{C\sqrt{1 + \epsilon^2}}{A_t \epsilon \omega}. \quad (4.7)$$

This power loss from the RF field must equal the power gain by the sheath which must also be equal to the power loss from the ions. Then equating (4.8) and (4.1) yields the sheath resistance

$$R = \frac{V_{DC}^t}{2e\gamma^t_i} A_t. \quad (4.9)$$

where we assumed $V_{DC}^t \approx V$. It is evident that the resistance goes to infinity in the limit that the ion flux goes to zero. This result, therefore, agrees with our interpretation that the resistor accounts for the energy dissipated by the ions.

We have thus shown that the sheath can be modeled by a resistor and capacitor in parallel (Fig.3.2). Many authors leave out the resistor from their model\textsuperscript{1,9,10,12}. They did not recognize that the resistance comes from the movement of electrons not ions. Neglecting the sheath resistor for the purpose of determining the plasma potential can be done without introducing much error. Computing the power absorbed by the discharge would lead to a gross error.

The sheath model has so far neglected the periodic collapse of the sheath when electrons diffuse to the electrode. This occurs once during each cycle when the sheath collapses and electrons can surmount the small voltage barrier. The number
of electrons and ions reaching the electrode must be equal, since they recombine as electron-ion pairs. The actual current trace is not pure sinusoidal but contains higher frequency components. The nonlinear effect from the electron surge can be represented by a reverse biased diode across the sheath (Fig. 3.2). Even though the effect of the diodes can be observed we neglect them in our circuit model, since the higher frequency components amount to less that 5% of the fundamental.

Another way of looking at the conversion of RF power to DC power is provided by the electron injection model. If we consider the flux of electrons toward the wall electrode in time, it should look similar to Fig. 4.4. The average electron is prevented from reaching the wall electrode during most of the cycle since it cannot surmount the large potential barrier. Only when the sheath voltage collapses can the electrons replenish the negative charge which was lost from ion-electron recombination.

If we expand the electron flux in terms of a Fourier series, it will be of the form

\[ \gamma_e(t) = \gamma_0 - \gamma_1 \cos(\omega t + \phi_1) - \gamma_2 \cos(2\omega t + \phi_2) - \ldots \], \hspace{1cm} (4.10) \]

where \( \gamma_0 \) is the average electron flux and must equal the ion flux for charge neutrality to be maintained. \( \gamma_1 \) and \( \gamma_2 \) are the first and second harmonic amplitudes, respectively, \( \phi_1 \) and \( \phi_2 \) the corresponding phase angles. We assume the electron enters the plasma sheath boundary with a velocity \( v_0 \). The values for \( \gamma_1, \phi_1, \gamma_2, \phi_2 \) and higher terms will depend on the details of the exact current waveform which is unknown. Nevertheless, we can gain some insight into power conservation of the plasma by computing the power transported to the wall by the electron current. If
Figure 4.4 The real-time wall sheath voltage $V_w(t)$ is depicted by the positive ordinate and the electron current $I_e^w(t)$ by the negative ordinate. Electrons surge across the wall and target sheath once during each RF cycle to replenish the electrons which are lost to recombination. This occurs when the voltage across the sheath is at a minimum.
we assume the voltage across the wall sheath is of the form

\[ V_w(t) = V_{DC}^{w} + V_{w}\cos(\omega t). \tag{4.11} \]

where \( V_{DC}^{w} \) is the DC voltage and \( V_{w} \) the RF voltage across the wall sheath region.

Then the power transported to the target electrode due to the electrons is

\[ \mathcal{P}_w(t) = \gamma_{-}(t) A_w \left[ \frac{1}{2} m_v v_0^2 - eV_w(t) \right]. \tag{4.12} \]

Substituting for \( V_w(t) \) and \( \gamma_{-} \) yields the result

\[
\begin{align*}
\mathcal{P}_w(t) &= \gamma_{0} A_w \left[ \frac{1}{2} m_v v_0^2 - eV_{DC}^{w} - eV_{DC}^{w}\cos(\omega t) \right] \\
&\quad - \gamma_{1} A_w \left[ \frac{1}{2} m_v v_0^2 - eV_{DC}^{w} \right] \cos(\omega t + \phi_{1}) \\
&\quad + \gamma_{1} A_w eV_{w} \cos(\omega t) \cos(\omega t + \phi_{1})
\end{align*}
\tag{4.13}
\]

where the harmonic of second order or higher have been dropped. If we now convert fluxes to currents by letting

\[ eA_w \gamma_{0} = I_0 \tag{4.14} \]

\[ eA_w \gamma_{1} = I_1 \tag{4.15} \]

and average over one period, we obtain
\[ \langle \mathcal{E}_w \rangle = I_0 \left[ \frac{1}{2} m_0 V_0^2 - V_{DC}^w \right] + \frac{1}{2} I_1 V_w \cos\{\phi_1\} . \] (4.16)

This result is exact, since the higher frequency terms of \( \gamma \) will average to zero. Hence, the average power absorbed by the sheath consists of three terms. The first term represents the initial kinetic energy with which the electrons enter the sheath. It generally amounts to only a few watts and is much smaller than the remaining terms. The second term is negative and represents the power gained by the sheath from the constant flux of electrons.

The last expression is the power absorbed from the RF field if \( \cos\{\phi_1\} \) is positive. From Fig. 4.4 we see that the power absorbed by the electron current is very small because the voltage is almost zero when electrons cross the sheath. Therefore, we can set the time-average power dissipated by the electrons inside the wall sheath to zero. In addition if \( V_{DC}^w \approx V_w \), \( \phi_1 \approx 0 \), as will be shown in the next chapter. Then neglecting the first term in Eq. (4.16) yields the final result

\[ \langle \mathcal{E}_w \rangle = 0 = -I_0 V_{DC}^w + I_1 V_w . \] (4.17)

This very simple result may at first seem trivial, but it states that all the RF power taken from the RF sheath field is converted to electric energy stored in the time-average electric field in the sheath. This energy of course goes to the cations which are important in bombarding the surface of the wafer.

The RF energy flow is illustrated by the schematic diagram in Fig. 4.5. It shows that RF energy can be directly converted to stored electric field energy (path 1). This would correspond to more positive charge being exposed by an expanding sheath. The second way of channeling RF energy to the ions is provided through paths 2 and 3.
Figure 4.5 RF energy flow diagram illustrates the varies paths energy can be stored and dissipated.
Initially, RF energy is converted to kinetic energy carried by electrons. If very high energy electrons cross the sheath and attach to the electrode the initial kinetic energy is converted to electrostatic potential energy. This energy results in a increase in the electric sheath field which accelerates the cations to even larger energies. The power provided by the high energy electrons is very small since the probability of an electron to acquire a kinetic energy of several hundred electron volts is negligable.

We have thus shown by the two models that the interpretations of the sheath resistor is really the conversion of RF to DC energy. In addition, the sheath capacitor accounts for the AC charge oscillations which are in phase with the RF sheath voltage.
CHAPTER 5

MEASUREMENTS OF EXPERIMENTAL DATA

The etch system consisted of a Tegal 702 etch chamber. The system was comprised of the following components: a single wafer parallel plate etch chamber, a 13.56 MHz generator, a matching network, a temperature control unit, a rotary mechanical pump, and a set of five mass flow controllers.

During the etch process four electrical properties were monitored: the total RF voltage $V$, the RF current $I$, the DC bias voltage $V_{DC}$, and the phase angle $\theta$ by which the current leads the voltage. In addition, the plasma pressure was measured by a pressure gauge. The actual experimental set-up is illustrated in Fig. 5.1.

The RF voltages were simply too large to be displayed on an oscilloscope. As a result the voltage had to be stepped down using a capacitive voltage divider. A standard 10:1 voltage probe has an input impedance of a 10 pf capacitor in parallel with a 10 MΩ resistor. The parallel resistor can be neglected at RF frequencies. The signal displayed on an oscilloscope is then 1/10 of the actual voltage. In order to step down the signal by a factor of 100, a 10/9 pf capacitor must be connected in series with the probe. The displayed signal is then 1/100 of the actual voltage. A ceramic 1 pf capacitor was used for all voltage measurements. The step down factor for this circuit had to be experimentally determined.

The DC bias voltage was easily measured by connecting a DC voltmeter to a low-pass filter which was attached to the target electrode. The low-pass filter was directly built into the matching network.

Monitoring the AC current $I$ was done with two different current probes. At
Figure 5.1 Experimental set-up for measuring $V$, $I$, and $V_{DC}$. $\dot{\theta}$ is then obtained from the oscilloscope trace.
current levels below 3.5 Amperes (zero to peak) a Pearson model 2877 current probe was used. This device can be used in the frequency range from 300 Hz to 200 MHz (3dB point) and at current levels of up to 3.5 Amperes. At larger currents a Pearson model 410 had to be employed. It has a current rating of 50 Amperes and a high frequency cutoff (3dB point) at 20 MHz. Using the model 410 at 13.5 MHz, care must be taken to correct for the attenuation and phase shift of the signal.

The RF current and voltage measurements were made by connecting the current and voltage probes as closely as possible to the target electrode. The resulting traces are then displayed on an oscilloscope. From the phase shift between the current and voltage waveform, the equivalent impedance as seen between target electrode and ground can be inferred. It must be remembered that this equivalent impedance is the impedance of the plasma model in parallel with the impedance of the chamber itself (Fig. 5.2). The chamber itself acts as a large capacitor since it represents ideally two parallel plates. Actually the target electrode sees two ground plates. One is the grounded wall chamber and the other the ground plate of the wafer cooling system for the target electrode (Fig. 2.1). A simple calculation will show that the capacitance as seen between wall and target electrode is negligible compared to the ground-plate/target electrode capacitance. Nonetheless, these two capacitances are in parallel and must be measured by extinguishing the plasma. By flooding the chamber with N₂ the voltage and current are measured. This capacitance was found to be 78pf.

The actual voltage and current traces are not true sinusoidal, since the plasma generates higher harmonics which distort the waveform. The distortion is clearly visible on an oscilloscope (Fig. 8.1). In order to eliminate the higher frequency components and recover the fundamental frequency component, a 20 MHz low-pass filter on the scope was used. The attenuation of the 13.56 MHz signal due to the 20
Figure 5.2  The 78pf capacitor is in parallel with the RF equivalent circuit. As a result all measurements must be corrected for the capacitance.
MHz cut-off had to be compensated for. Experimentally it was found that by multiplying the recovered fundamental component by the factor 1.21 produced the correct result.

From the voltage and current traces on the oscilloscope the equivalent circuit of the discharge in parallel with the chamber can be easily computed:

\[
R_{eq} = \frac{V}{I_{cos\theta}} \tag{5.1}
\]

\[
C_{eq}' = \frac{I_{sin\theta}}{\omega V} \tag{5.2}
\]

The equivalent capacitance of the discharge is then given by

\[
C_{eq} = C_{eq}' - 78 \text{pf} \tag{5.3}
\]

\(R_{eq}\) and \(C_{eq}\) then have to be related to the model of the plasma discharge (Fig. 5.2). In the next chapter it will be shown how \(R_{eq}\) and \(C_{eq}\) are related to the target and wall sheath impedances.

All measurements were performed under the following discharge conditions: pressure = 120 mtorr, chuck temperature = 20° C, gas flow = 50 sccm (90% CF₄ and 10% O₂). The power of the generator was changed from 100 to 800 watts. The absorbed power which was measured across the discharge was generally lower than the power indicated on the generator dial. This discrepancy probably stems from losses in the matching network.

The etch rates were determined by evaluating the trench etch of Si wafers coated with a SiO₂ mask. The trench depth was measured by an alpha stepper. All
wafers were etched for 10 minutes.
CHAPTER 6

RELATING IMPEDANCE MODEL TO MEASUREMENTS

The complete AC circuit model consists of five elements and is shown in Fig. 6.1. The target and wall sheath regions can both be modeled by a resistor and capacitor in parallel. The plasma itself is represented by a single resistor.

These five elements then have to be related to the Thevenin equivalent circuit which consists of $R_{eq}$ and $C_{eq}$ in parallel. At first sight it appears to be an impossible task to relate four measured quantities to five unknowns. If we make use of the fact that the plasma resistance is small and the sheath is mostly capacitive we can easily calculate all elements except $R_p$. In addition $V_{DC}^W$ and $V_{DC}^t$ can be determined.

From the voltage measurements we know the the voltage across the discharge is of the form

$$P'(t) = V\cos(\omega t) - V_{DC}. \quad (6.1)$$

It follows from Figs. 6.2 and 6.3 that the voltages across the target, plasma, and wall regions are respectively given by

$$V_t^t\{t\} = V_t\cos(\omega t + \phi_t) - V_{DC}^t \quad (6.2)$$

$$V_p^t\{t\} = V_p\cos(\omega t + \phi_p) \quad (6.3)$$
Figure 6.1  Simplified RF equivalent circuit of plasma and sheath regions.
Figure 6.2  RF voltage signal across the plasma, wall, and target sheath regions where it was assumed that $\phi_t$, $\phi_p$, and $\phi_w = 0$. 
Figure 6.3  Time-average or DC voltage across the plasma, wall, and target sheath.
where $\phi$ represents the phase shift with respect to the total RF voltage. If we neglect $V_p$, since $V_p \ll V_t, V_w$, and assume $\phi_t = \phi_w = 0$, then we can equate the AC and DC components

$$V = V_t + V_w$$  \hspace{1cm} (6.5)$$

and

$$V_{DC} = V_{DC}' - V_{DC}''$$  \hspace{1cm} (6.6)$$

Then letting $V_t \approx V_{DC}$ and $V_w \approx V_{DC}'$, adding Eqs.(6.5) and (6.6) yields

$$V_t = V_{DC}' = \frac{V + V_{DC}}{2}$$  \hspace{1cm} (6.7)$$

and subtracting Eq.(6.6) from (6.5) yields

$$V_w = V_{DC}'' = \frac{V - V_{DC}}{2}.$$  \hspace{1cm} (6.8)$$

Neglecting the phase shifts has two implications. The resistor and capacitive voltage divider attenuate the signal equally. This implies

$$\frac{V_w}{V} = \frac{R_w}{R_t + R'} = \frac{C_t}{C_w + C_t}$$  \hspace{1cm} (6.9)$$
and $\phi_p = \phi_t = \phi_w = 0$. The phase shifts can also be neglected if the capacitors are the dominant elements of both sheaths. For a CF$_4$ plasma it was found that the ratio of sheath resistance to sheath capacitance impedance varies between four to five. Köhler quotes a factor of 6 for Ar.$^4$

One way of seeing that the voltage drop across the plasma must be relatively small and the sheath regions look very capacitive can be deduced from Fig. 6.4. External measurements have shown that the current leads the voltage by about 73°. If we then draw the equivalent impedance in the complex plane, we see that the maximum voltage which could possibly occur across the plasma is given by the line segment AB. Note that the impedance is numerically equal to the voltage if the current is one Ampere in magnitude. AD which represents $R_p$, cannot exceed the line segment AB. If $R_p = 0$, then $V_t + V_w$ is given by the line AC, assuming $V_t, V_w$ are colinear. On the other hand, if $R_p \neq 0$, then $V_t + V_w$ is represented by the line segment DC. Since, $|DC| \approx |AC|$ for small values of $R_p$, we can calculate $V_t$ and $V_w$ using Eqs.(6.7) and (6.8). This method has been used by many authors and is called the capacitive sheath approximation. Christensen$^5$ reports good agreement between actual plasma potential measurements and using Eqs.(6.7) and (6.8)$^{1,9,11,12}$. $R_p$ cannot be directly determined from the RF equivalent impedance, but can only be estimated from power conservation calculations. Using the power absorbed by the plasma region as calculated by the computer model, the error introduced by the capacitive sheath approximation is less than 9%.

If we neglect the plasma resistance and assume equal voltage attenuation between the resistor and capacitor (DE and EC are collinear) we can easily relate the equivalent circuit to the four circuit elements in question:
Figure 6.4  Impedance diagram of RF equivalent circuit.
We had to make a substantial amount of approximations to obtain the final result Eqs.(6.9) to (6.12). Having found the two sheath capacitors we can find the corresponding sheath thickness if we assume that the AC charge is concentrated at a very thin surface layer. In the oscillating sheath boundary model this imples \( d_0 > \Delta d \sqrt{I + \epsilon^2} \). Then we find that

\[
R_t = \frac{V_{DC}}{V} R_{eq} \tag{6.10}
\]

\[
C_t = \frac{V}{V_{DC}} C_{eq} \tag{6.11}
\]

\[
R_w = \frac{V_{DC}}{V} R_{eq} \tag{6.12}
\]

\[
C_w = \frac{V}{V_{DC}} C_{eq} \tag{6.13}
\]

We have thus shown how to calculate the four elements of the sheath region. The plasma resistance cannot be directly determined but can be estimated from power conservation.
CHAPTER 7

DYNAMICS OF IONS IN SHEATH

The cation population constitutes one of the most important factors in the actual etch process. The cations are responsible for breaking bonds of Si and removing inert substances from the wafer surface. Knowing more about the ion flux and ion energies could only enhance our understanding of wafer etching.

In Chapter 5 we have shown that the sheath resistance stands for the power ultimately going to the ions. In this chapter we will show how the ion flux, ion energy, and power absorption can be determined from the circuit model of the discharge. We shall assume that CF$_3^+$ is the only ion present in the sheath. Thompson$^{13}$ has shown through mass spectrometer measurements that CF$_3^+$ is the dominant ion for CF$_4$ discharges.

The sheath cations are confined to the volume $A_t d_t$ and the time-average number density of ions will be a function of position. The density variation will depend on several different parameters such as the collision frequency $\nu_+$ and the initial velocity $v_+\{0\}$ with which the ions enter the sheath. An average ion enters the sheath with an initial velocity $v_+\{0\}$, collides several times with neutrals before smashing into the target electrode. We must, therefore, solve the equation of motion for a single positive ion which should be representative of the ensemble average. Newton's law for positive charge carriers$^{15}$ is given by

$$\frac{m_+}{d_t} \frac{dv_+}{dt} = eE(x) - k_B \frac{T_+}{n_+(x)} \frac{\partial n_+}{\partial x} - m_+ \nu_+ v_+ .$$  \hspace{1cm} (7.1)
The first term represents the force on the ion due to the time-average electric field, the second term is the force which results from diffusion, and the last force contribution is due to collisions. In the sheath region we expect the diffusion to be negligible compared to the other two terms. We shall therefore drop the second term.

Since we are only interested in the steady state solution we can write

\[ \frac{dv_+}{dt} = \frac{\partial v_+}{\partial t} + \frac{\partial v_+}{\partial x} \frac{dx}{dt} = v_+ \frac{\partial v_+}{\partial x}. \] (7.2)

Then rewriting Eq.(7.1), neglecting diffusion, and using Eq.(7.2) yields

\[ v_+ \frac{dv_+}{dx} = \frac{e}{m_+} E(x) - m_+ \nu_+ v_+. \] (7.3)

The collision frequency \( \nu_+ \) is in general dependent on the energy of the ion:

\[ \nu_+ = n_0 \nu_+ Q_+(v_+). \] (7.4)

where \( n_0 \) is the density of neutrals and \( Q_+ \) the collision cross-section for cations which also depends somewhat on the ion energy. For \( \text{Ar}^+ \), \( Q_+ = 5 \times 10^{-19} \, \text{m}^2 \) at \( kT_+ = 100 \, \text{eV} \), while at \( kT_+ = 16 \, \text{eV} \) the cross-section changes to \( 7 \times 10^{-19} \, \text{m}^2 \). From these values it is evident that \( Q_+ \) can be set to a constant value without introducing a large error. \( Q_+ \) represents the sum of the elastic collision and charge exchange cross-section, because both types of collisions will produce a frictional effect on an ion.

The following method of estimating \( Q_+(kT_+) \) can be used if a table of \( Q_+ \) versus \( kT_+ \) is at hand. Given the sheath thickness \( d_t \), the sheath voltage \( V_{DC}^t \), the neutral
number density \(n_0\), then the initial guess for \(Q_+(kT_+\})\) is \(Q_+\{eV_{DC}/2\}\). The factor of \(1/2\) is due to averaging. The mean free path between collisions is given by

\[
\lambda = \frac{1}{n_0 Q_+ \{v_+\}}.
\] (7.5)

An ion's kinetic energy is destroyed after each collision. As a result we can approximately calculate the average ion energy from the expression

\[
\langle k_B T_+ \rangle \approx \frac{eV_{DC}}{2d_t} \quad \text{for } \lambda \leq d_t
\]

\[
\langle k_B T_+ \rangle \approx \frac{eV_{DC}}{2} \quad \text{for } \lambda > d_t.
\] (7.6)

Then substituting for \(\lambda\) yields

\[
\langle k_B T_+ \rangle = \frac{eV_{DC}}{d_t n_0 Q_+ \{k_B T_+\}} \quad \text{for } \lambda \leq d_t
\] (7.7)

If \(\langle kT_+\rangle\) is significantly different from \(eV_{DC}/2\) then the new value for \(Q_+\{kT_+\}\) is \(Q_+\{\langle kT_+\}\}\). This procedure is then iterated until the two energy values converge. Unfortunately, cross-sectional data for only a very few types of ions is available. Even when such data is available it is usually limited to small energy values.

Newton's law can then be rewritten in terms of the cross-section and the electric field potential \(\phi\)

\[
\frac{dV_+}{dx} = -\frac{e}{m_+ v_+} \frac{d\phi}{dx} - n_0 Q_+ v_+^2.
\] (7.8)
The potential is the result of the DC charge population and can be calculated using Poisson's equation:

\[ \frac{d^2 \phi}{dx^2} = -\frac{n_+[x]}{\epsilon_0} - \frac{e\gamma_+}{\epsilon_0 v_+[x]}, \quad (7.9) \]

where we assumed a constant ion flux throughout the space charge region. This implies no ionization of neutrals occurs in the sheath. Consequently, \( \gamma_+ \) is equal to \( n_+[0]v_+[0] \). Both \( n_+[0] \) and \( v_+[0] \) are also unknown but \( v_+[0] \) has to be larger than a minimum value which is given by the Bohm sheath velocity\(^1\). The Bohm velocity is given by

\[ v_B = \sqrt{\frac{k_B T_-}{m_+}} \]

where \( k_B T_-/e \) is on the order of a few electron volts\(^1\). For an electron plasma energy of 4eV, the Bohm velocity is then \( 2.36 \times 10^3 \) m/s.

In order to solve the two coupled Eqs. (7.8) and (7.9) we have to find three boundary conditions. We choose our coordinate system in the following way: \( x = 0 \) is the plasma-sheath boundary, \( x = d_t \) is the position of the target electrode (Fig. 7.1). The boundary conditions are then given by

I) \( \phi[x = 0] = 0 \) \quad (7.11)

II) \( v_t[x = 0] = v_t[0] \) \quad (7.12)
Figure 7.1  Coordinate system for solving the coupled Eqs. (7.6) and (7.7).
The first boundary condition simply defines the ground potential. The second condition assumes the ion enters the sheath with a velocity $v_+\{0\}$. The third boundary condition defines the electric field at the plasma-sheath interface. It assumes the ions are driven by a small electric field at $x = 0$ and are limited by their mobility. This result can also be obtained by setting $dv_+/dx$ in Eq.(7.3) to zero and solving for $E(x)$.

In Eq.(7.9) $\gamma_+$ is unknown and a fourth condition is necessary to find a unique solution for Eqs.(7.8) and (7.9). The fourth boundary condition makes use of Eq.(6.7) and simply states that the total time-average voltage across the target sheath is $V_{DC}^t$:

$$\text{IV) } \phi(x = d_t) = -V_{DC}^t \quad \text{where } V_{DC}^t > 0 \quad (7.14)$$

The two coupled differential equations (7.8) and (7.9) can then be numerically integrated across the sheath region until condition IV) is satisfied. If $\gamma_+$ is too small, the initial guess for the voltage across the sheath will be too small and vice versa. This procedure is then repeated until boundary condition IV) is met. A software package called "DAREP" was used to solve Eqs.(7.6) and (7.7). The program required the input of the two differential equations and the first three boundary conditions.

The cross-section $Q_+$ was set to $5 \times 10^{-19}$ m$^2$ which corresponds to $Q_+$ for Ar$^+$, not CF$_3^+$. This value is often quoted by other computer simulations$^{9,12}$. No crosssectional data is available for CF$_3^+$ ions.

It appears that the above procedure is quite limited by the uncertainty in the Bohm sheath velocity. In reality the final results are only weakly dependent on $v_+\{0\}$ as is shown in the next chapter.
Solving the coupled equations yields two important parameters: the ion flux $\gamma_+$ and the average ensemble ion energy $1/2m_+v_+d_i$. The power by the ions can then be calculated by employing Eq.(4.1).
CHAPTER 8

DISCUSSION OF RESULTS

The voltage and current measurements lie at the heart of this work, since all results follow from them. Great care was, therefore, exercised to calibrate each piece of equipment.

A typical voltage and current trace as displayed on the oscilloscope is shown in Fig. 8.1. It displays the unfiltered waveforms with some harmonic distortion. The current trace shows more distortion than the voltage. This result can probably be attributed to the surge of electrons toward the target electrode which occurs once during each cycle. It can be seen that the current leads the voltage by about 80°. This indicates a predominantly capacitive impedance of the discharge.

When the 20 MHz low-pass filter is activated, the two traces will become attenuated but essentially pure sinusoids. Only now, can the phase angle $\theta$, between $I$ and $V$, be accurately determined. The actual amplitudes must be corrected for attenuation. Experimentally it was found that the filter decreased the signal by the factor 1.21. The absorbed power is easily calculated from the two traces.

The RF voltage (zero-to-peak) and the DC bias are plotted as a function of absorbed power in Fig. 8.2. The DC bias is an indication of the asymmetry of the voltage division between the two sheath regions. For symmetric systems $V_{DC}$ equals zero. The target RF amplitude $V_t$ was calculated using Eq.(6.7). The ratio of $V_t/V$ stays relatively constant at 72%. Therefore, larger voltages are available to the ions at the target sheath than the wall.

The chamber current $I$ and discharge current $I$ are depicted in Fig. 8.3. It is
Figure 8.1  Real-time voltage and current trace as displayed on a 250 MHz oscilloscope.
Figure 8.2  RF and DC voltage as measured by an oscilloscope and voltmeter. In addition $V_t$ represents the RF voltage across the target sheath. Eq.(6.7) was used to compute $V_t$. 
Figure 8.3 The total current flowing into the chamber is depicted by $I$. About half the current flows directly to ground through the 78pf ground-plate. The actual current flowing through the discharge is represented by $I$. 
evident that only about one-half of the chamber current flows through the discharge itself. The other half is diverted through the target electrode water capacitor to ground. It is important to note that only the discharge current can lead to power absorption.

Fig. 8.4 shows that the phase angle stays quite constant with increasing powers. \( \theta \) corresponds to the actual phase angle measured. It is positive and indicates that the current leads the voltage. \( \theta \) is the corrected phase angle if we exclude the 78 pf contribution from the chamber. It too stays quite constant and indicates that \( R_{eq} \) and \( Z(C_{eq}) \) change in equal proportions with power.

The sheath thicknesses were calculated using Eqs.(6.14) and (6.15). As can be seen from Fig. 8.5, the sheath thicknesses \( d_t \) and \( d_w \) both decrease as the input power or voltage are increased. The large error bars are the direct result from the uncertainty in estimating the areas for \( A_t \) and \( A_w \). As is evident from Fig. 2.1, identifying these areas is not an easy task due to the complexity of the geometry of the chamber.

Fig. 8.6 shows the ion flux at the target and wall electrodes versus the input power. As the input power increases from 100 to almost 600 watts the ion flux increases by a factor of six. The flux toward the target electrode is greater than the flux toward the wall. This result must occur for an asymmetric discharge, since the time average surface charge densities \( (C/m^2) \) stored inside the two sheaths are not equal. If we assume the recombination time for the stored charge at both sheaths are equal, then more charge per unit area recombines at the target electrode. The only way to refresh this charge discrepancy is by a larger flux of ions to the target electrode.

The solution of the coupled equations depends to some extent on the initial
Figure 8.4  $\theta$ represents the measured phase angle between $I$ and $V$. Correcting for the 78pf capacitance yields $\theta$. 
Figure 8.5 Sheath thickness decrease for both target and wall sheaths as power increases.
Figure 8.6 Depicts variation of $\gamma_4^i$ with input power.
condition \( v_+\{0\} \). Fig. 8.7 shows the variation of \( \gamma_+^i \) versus the initial velocity \( v_+\{0\} \). It can be seen that \( \gamma_+^i \) varies only by about 10% for reasonable values of the initial velocity.

In the computer program we cannot actually determine the ion number density at the plasma-sheath boundary, since the velocity \( v_+\{0\} \) is not accurately known. After we have determined the value for \( \gamma_+ \), which is given by

\[
\gamma_+ = \gamma_+\{x = 0\} = n_+\{0\}v_+\{0\} ,
\]

(8.1)

\( n_+\{0\} \) will be dependent on \( v_+\{0\} \). We can plot the relative increase in ion number density (\( N_i^* \)) if we assume \( v_+\{0\} \) does not increase with input power. In Fig. 8.8 the relative ion density has been normalized to the density at 100 watts (\( N_i^0 \)).

The ion flux toward the wafer should give some indication of the etch rates. The following table shows the fluxes and etch rates of Si for three different input powers.

<table>
<thead>
<tr>
<th>RF INPUT POWER watts</th>
<th>ETCH RATE ( \delta ) Å/min</th>
<th>ION FLUX ( 1/m^2s )</th>
<th>TARGET ION POWER watts</th>
</tr>
</thead>
<tbody>
<tr>
<td>370</td>
<td>1750</td>
<td>( 1.2 \times 10^{20} )</td>
<td>150</td>
</tr>
<tr>
<td>480</td>
<td>1900</td>
<td>( 1.8 \times 10^{20} )</td>
<td>250</td>
</tr>
<tr>
<td>630</td>
<td>2100</td>
<td>( 2.1 \times 10^{20} )</td>
<td>340</td>
</tr>
</tbody>
</table>

It is evident that the etch rates are not a linear function of either the ion flux or ion power. Nonetheless, we would expect increasing etch rates with larger ion fluxes. The ions are largely responsible for breaking Si covalent bonds and ridding
Figure 8.7  Graph indicates sensitivity of $\gamma^\dagger_+$ to the change in initial velocity $v_+(0)$. $v_B$ corresponds to an electron plasma temperature of 4eV (2.36x10^3 m/s).
Figure 8.8 Relative increase in ion densities as a function of RF power. $N'_i$ corresponds to the ion density at the plasma sheath boundary for 100 Watts.
the surface of inert molecules such as SiF. Without the availability of free radicals the etch process cannot proceed. Therefore, \( \gamma_+ \) only accounts for part of the etch rate.

The ion energy is plotted as a function of input power in Fig. 8.9. The target ions are almost three times as energetic than the wall ions. If we compare Figs. 8.2 and 8.9, we notice that the ions do not possess the plasma potential, but the energy has been reduced by collisions inside the sheath. The number of collisions an average ion experiences has a detrimental effect on the resulting average ion energy. At decreasing pressures we expect the ions to approach the plasma potential since the probability for a collision to occur is directly proportional to the number density of neutrals.

The total input power must be divided between the plasma and the two sheath regions. A plot of how the power of each region is related to the total input power is provided by Fig. 8.10. The dashed line represents the total input power and the second curve from the bottom shows the power absorbed by the ions in both sheaths. If we subtract the second curve from the dashed line, we obtain an area which is equal to the power absorbed by the plasma. This area indicates that the power absorbed by the plasma stays relatively constant, though the input power increases from 100 to almost 600 watts. When we increase the input power, we expect the electron and ion number densities to increase. At the same time the current also increases. The power absorbed by the plasma region is given by

\[
P_{\text{abs}} = \frac{1}{2} R_p I_p^2 = A \frac{I_p^2}{n_-}
\]

(8.2)
Figure 8.9  Ion energies are reduced by collisions in the sheath.
Figure 8.10 Depicts total power budget of discharge.
where \( A \) is a constant. In Eq.(8.2) we have used the fact that \( R_p \) is inversely proportional to \( \sigma_c \) and \( \sigma_c \) is directly proportional to \( n_\infty \). If \( P_{\text{abs}} \) remains approximately constant as \( I \) increases by a factor of three, then \( n_\infty \) must increase by a factor of 9. Fig. 8.3 shows that \( I \) increases by a factor of 3 as the input power goes from 100 to almost 600 watts. The number density actually increases by a factor of 7 as seen from Fig. 8.8. Therefore, the results of Fig. 8.10 appear to be in reasonable agreement with the external measurements.
CHAPTER 9

CONCLUSIONS

External electrical measurements on plasma reactors can provide useful information for evaluating the plasma environment. Measurements of the RF and DC bias voltages represent the single most useful information, since the degree of anisotropy of etch is largely determined by ion energies. The target sheath voltage gives a relatively good estimate of ion energies. This measurement only yields the average ion energy but provides no information about the energy distribution of ions.

Ion flux can be estimated by solving two coupled differential equations if the sheath thicknesses and sheath voltages are known. This method is limited by the lack of knowledge for many gases. Nonetheless, reasonable results appear to be possible.

Further work is necessary to include Langmuir probe measurements in order to determine more accurately the electron number density and the plasma potential. These results then should be compared with the voltage measurements done by invoking the capacitive sheath approximation.
APPENDIX A: COMPUTER PROGRAM

The following computer program was used to solve the coupled differential Eqs. (7.6) and (7.7).

*01

* PHI_=PDOT
  V,=-1.391304*VS/VO/VO/VO*PDOT-1.61*ZO*V
  PDOT=-180.791*ZO*ZO*RPLUS/VS/V
END

* VS=SHEATH POTENTIAL IN VOLTS
* VO=INITIAL VELOCITY IN X1000 m/s
* ZO=SHEATH THICKNESS IN mm
* RPLUS=ION DENSITY IN XE16 ions/m3
  TMAX=1.0
  NPOINT=11
  VO=2.36
  VS=205
  ZO=1.1
  A=VO*VO*ZO/VS
  RPLUS=4.8

* INITIAL CONDITIONS
  PHI=0.0,V=1.0,PDOT=-1.15719*A
END

LIST PHI,PDOT,V

END

COMPUTER OUTPUT:

LIST PHI,PDOT,V

<table>
<thead>
<tr>
<th>TIME</th>
<th>PHI</th>
<th>PDOT</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00000E+00</td>
<td>0.00000E+00</td>
<td>-3.45834E-02</td>
<td>1.00000E+00</td>
</tr>
<tr>
<td>1.00000E-01</td>
<td>-2.58612E-02</td>
<td>-4.42311E-01</td>
<td>1.74272E+00</td>
</tr>
<tr>
<td>2.00000E-01</td>
<td>-9.26468E-02</td>
<td>-6.76851E-01</td>
<td>2.66229E+00</td>
</tr>
<tr>
<td>3.00000E-01</td>
<td>-1.59127E-01</td>
<td>-8.45732E-01</td>
<td>3.40773E+00</td>
</tr>
<tr>
<td>4.00000E-01</td>
<td>-2.50789E-01</td>
<td>-9.83746E-01</td>
<td>4.01116E+00</td>
</tr>
<tr>
<td>5.00000E-01</td>
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<td>-1.10390E+00</td>
<td>4.50928E+00</td>
</tr>
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<td>-1.21239E+00</td>
<td>4.92866E+00</td>
</tr>
<tr>
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<td>-5.97492E-01</td>
<td>-1.31261E+00</td>
<td>5.28822E+00</td>
</tr>
<tr>
<td>8.00000E-01</td>
<td>-7.35501E-01</td>
<td>-1.40665E+00</td>
<td>5.60162E+00</td>
</tr>
<tr>
<td>9.00000E-01</td>
<td>-8.78662E-01</td>
<td>-1.49886E+00</td>
<td>5.87889E+00</td>
</tr>
<tr>
<td>1.00000E+00</td>
<td>-1.03254E+00</td>
<td>-1.58116E+00</td>
<td>6.12748E+00</td>
</tr>
</tbody>
</table>
APPENDIX B: NORMALIZED DIFFERENTIAL EQUATIONS

This section derives three normalized first order differential equations which were used by the software package "DAREP" to calculate ion flux. The equations which govern flux of ions across the sheath are given by

\[
\frac{dv_+}{dx} = -\frac{e}{m_+v_+} \frac{d\phi}{dx} - n_0Q_+v_+ \tag{B 1}
\]

\[
\frac{d^2\phi}{dx^2} = -\frac{e\gamma_+}{\varepsilon_0v_+} = -\frac{en_+0v_+0}{\varepsilon_0v_+} \tag{B 2}
\]

subject to the four boundary conditions:

1) \(\phi(x=0) = 0\) \tag{B 3}
2) \(\phi(x=d) = V_s\) \tag{B 4}
3) \(\phi'(x=0) = -m_+n_0Q_+v_+^2\) \tag{B 5}
4) \(v_+(x=0) = v_+(0)\) \tag{B 6}

where

\[m_+[CF_4] = 1.15\times10^{-25} \text{ Kg}\]

\[n_0 = 3.22\times10^{-21} \text{ molecules/m}^3 \text{ (at 100 mtorr)}\]

\[Q_+ = 5.0\times10^{-19} \text{ m}^2\]

\[e = 1.6\times10^{-19} \text{ C}\]

\[v_+(0) = 2.36\times10^3 \text{ m/s (assume k_B T_+ = 4eV)}\].
We make the following change of variable:

\[ v_+ = v_+(0) \xi \]  \hspace{1cm} (B 7)

\[ \phi = V_s \chi \]  \hspace{1cm} (B 8)

\[ x = z_0 \lambda \]  \hspace{1cm} (B 9)

Then,

\[ \frac{d v_+}{d \lambda} = \frac{v_+(0)}{z_0} \frac{d \xi}{d \lambda} \]  \hspace{1cm} (B 10)

\[ \frac{d \phi}{d \lambda} = \frac{V_s}{z_0} \frac{d \chi}{d \lambda} \]  \hspace{1cm} (B 11)

\[ \frac{d^2 \phi}{d \lambda^2} = \frac{V_s}{z_0^2} \]  \hspace{1cm} (B 12)

Notice that \( \xi, \chi, \) and \( \lambda \) are dimensionless variables. This leads to

\[ \frac{d \xi(\lambda)}{d \lambda} = -\frac{e V_s}{m_+ v_+^2(0) \xi(\lambda)} \frac{d \chi(\lambda)}{d \lambda} - n_0 Q_+ z_0 \xi(\lambda) \]  \hspace{1cm} (B 13)

\[ \frac{d^2 \chi(\lambda)}{d \lambda^2} = -\frac{en_+(0) z_0^2}{\epsilon_0 V_s \xi(\lambda)} \]  \hspace{1cm} (B 14)

Similarly, the four boundary conditions transform to:
I) \( \chi(\lambda=0) = 0 \) \hspace{1cm} (B 15)

II) \( \chi(\lambda=1) = -1 \) \hspace{1cm} (B 16)

III) \( \frac{d\chi(\lambda=0)}{d\lambda} = - \frac{en_0Q_+z_0v_+^2[0]}{eV_s} \) \hspace{1cm} (B 17)

IV) \( \xi(\lambda=0) = 1 \) \hspace{1cm} (B 18)

Notice, now the normalized sheath thickness \( \lambda \) is defined on the interval from 0 to 1. Similarly, \( \chi \) varies between 0 to -1. Using the numerical values values for \( m_+, n_0, Q_+, e, \) and \( v_+[0] \) and letting

\[
v_+[0] = v_+[0]x10^3 \text{ m/s}
\]

\[
z_0 = z_0x10^{-3} \text{ m}
\]

\[
n_+[0] = n_+[0]x10^{16} \text{ ions/m}^3
\]

yields the equations:

\[
\dot{\xi} = - \frac{1.391304V_s}{v_+^2[0]} \chi - 1.61z_0\xi
\]

(B 19)

\[
\chi = - \frac{180.791n_+[0]z_0^2}{V_s}\xi
\]

(B 20)

and boundary conditions:

I) \( \chi[0] = 0 \) \hspace{1cm} (B 21)

II) \( \chi[1] = -1 \) \hspace{1cm} (B 22)

III) \( \dot{\xi}[0] = - \frac{1.15719z_0v_+^2[0]}{V_s} \) \hspace{1cm} (B 23)

IV) \( \xi[0] = 1 \)
where we have to remember that

\[ z_0 \text{ is in mm} \]
\[ v_+\{0\} \text{ is in km/s} \]
\[ V_s \text{ is in volts} \]
\[ n_+\{0\} \text{ is in } 10^{16} \text{ ions/m}^3 \]

The software package "DAREP" can only solve first order differential equations. Therefore, we have to convert to three first order equations. Then letting

\[ \chi = \Phi \quad (B\ 25) \]
\[ \dot{\chi} = \dot{\Phi} \quad (B\ 26) \]
\[ \xi = V \quad (B\ 27) \]

and

\[ v_+\{0\} = \Omega \quad (B\ 28) \]
\[ z_0 = \Omega_0 \quad (B\ 29) \]
\[ n_+\{0\} = R_+ \quad (B\ 30) \]
\[ V_s = V_s \quad (B\ 31) \]
Then

\[
PHI = PDOT \quad (B \ 32)
\]

\[
\dot{V} = -1.391304 \frac{VS}{VO^2V} PDOT - 1.61(ZO)V \quad (B \ 33)
\]

\[
PDOT^2 = -180.791 \frac{RPLUS(ZO)^2}{VS(V)} \quad (B \ 34)
\]

and the boundary conditions become:

I) PHI = 0 \quad (B \ 35)

II) PHI[1] = -1 \quad (B \ 36)

III) PDOT[0] = -1.15719 \frac{ZO(VO)^2}{VS} \quad (B \ 37)

IV) V[0] = 1 \quad (B \ 38)

Notice, that boundary condition II) cannot be used by "DAREP" because it is defined at the end of the interval of integration. Therefore, we have to guess initially at RPLUS until condition II) is satisfied.
REFERENCES


