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ELECTRICAL CHARACTERIZATION & PLASMA IMPEDANCE MEASUREMENTS OF A RF PLASMA ETCH SYSTEM

by

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ABSTRACT

A modified Tegal MCR-1 plasma etch system has been electrically characterized, and the plasma impedance has been measured at 13.56MHz. Important aspects of radio-frequency (RF) impedance measurements are addressed as they pertain to the measurement of the plasma impedance. These include: transmission line effects, magnitude and phase errors of the measurement probes, and the intrinsic impedance of the empty plasma chamber. Plasma harmonics are discussed, and a technique for measuring the plasma impedance at harmonic frequencies is presented.

Transients in the plasma impedance are observed during the first 5 minutes after the plasma is initiated, and represent a decrease in the plasma impedance. Residual gas analysis (RGA) confirms the presence of H\textsubscript{2}O in the plasma. The H\textsubscript{2}O ion current measured by RGA shows a downward transient similar to the impedance transients, suggesting a possible relationship between H\textsubscript{2}O and the impedance transients. A possible explanation for these impedance transients is presented.
CHAPTER 1

Introduction

Plasma impedance has been studied by many researchers [1-9]. These have been investigations of plasma impedance as a function of RF power [1, 2], frequency [2], gas pressure [1, 2, 3], different gases and gas mixtures [1, 3, 4], and particle contaminants [4, 5, 6, 7]. Although few reports on plasma impedance as a function of discharge time have appeared in the literature, one of these shows the plasma impedance becoming more resistive with discharge time for a silane based plasma [6]. It has been suggested that depletion of the plasma electron density by particles in dusty plasmas will cause the plasma to become more resistive with time [6, 7, 8].

In order to accurately measure the plasma impedance of an RF discharge, corrections must be made for: transmission line effects, magnitude and phase errors of the measurement probes, and the intrinsic impedance of the empty plasma chamber. At the RF frequencies typically used in most systems (13.56 MHz and harmonics thereof) transmission line effects and cables of different length and permittivity will cause magnitude and phase errors in the measured impedance. High frequency commercial probes used to measure the RF voltage and current have been shown to produce magnitude and phase errors too [9, 10]. The calibration of these probes to
known reactive loads, and the use of correction factors obtained through calibration have been shown to be an effective method of correcting these errors. It is also important to know the equivalent circuit of the empty plasma chamber. Each plasma system will have its own unique intrinsic impedance which will influence the plasma impedance, and impedance measurements in general. Many researchers have invested a lot of effort in order to calculate the intrinsic impedance of the Gaseous Electronics Conference (GEC) plasma reactor for just such reasons [11].

In this work, electrical characterization and plasma impedance measurements are performed on a modified Tegal MCR-1 plasma etch system. Transmission line effects, magnitude and phase errors of the measurement probes, and the empty chamber intrinsic impedance are all taken into account when making plasma impedance measurements. The LC equivalent circuit for the intrinsic impedance allows accurate measurement of the plasma impedance, which is not the case for GEC systems [11] in which the intrinsic impedance dominates the plasma impedance. The plasma impedance is measured only for the fundamental frequency (13.56 MHz); no attempt is made to measure the harmonic plasma impedance due to the added complexity of this measurement. However, a technique for measuring the harmonic plasma impedance is discussed.

Transients in the plasma impedance occur during the first 5 minutes after the plasma has been initiated. These transients are a decrease in plasma resistance and reactance. During the first 5 minutes, the resistance and reactance typically decrease
by 10-20% of their initial values for system parameters used in this work. After 5 minutes, the resistance and reactance appear to reach a plateau, and remain relatively unchanged for up to 15 minutes, the length of time investigated in this work, and perhaps even longer. Water vapor in the plasma is thought to be the most likely source of the impedance transients. From the results obtained in the process of tracking down the source of these impedance transients, it is apparent that this phenomena is not an artifact of the plasma system, but rather an effect that may be present in many plasma systems under similar conditions. If this is indeed true, the work presented here should be of considerable interest to the semiconductor manufacturing industry, since the impedance transients represent changes in fundamental plasma parameters occurring over a time period comparable to etch times used in industrial processes.

This thesis is organized as follows. Chapter 2 describes the major pieces of equipment used in this work, including: the plasma etch system, the laser light scattering equipment used for viewing particles, optical emission spectroscopy (OES), and residual gas analysis (RGA) systems. In chapter 3 electrical measurements are described. The voltage and current probes used for measuring the RF voltage and current are described, along with the data acquisition system, and the technique used to calculate plasma impedance from voltage and current measurements. Transmission line effects are described in detail, and a calibration procedure is described which corrects
for magnitude and phase errors. Chapter 4 is a detailed derivation of the intrinsic impedance of the empty plasma chamber based on measurements made using an impedance analyzer. The empty chamber is modeled by an LC equivalent circuit, and the effect this intrinsic impedance has on the measurement of the plasma impedance is discussed. Harmonics in the plasma are discussed and a technique for measuring the harmonic plasma impedance is presented.

Chapter 5 is a presentation of all experimental results. These include: plasma impedance measurements, OES measurements, and RGA measurements. In chapter 6 these experimental results are discussed. A possible explanation for the impedance transients, in terms of water vapor, is presented. Suggestions for future work are also given. Chapter 7 is the conclusion. The accomplishments and major results of this work are summarized in this chapter.
CHAPTER 2

Equipment

2.1 Plasma Etch System

All experiments were performed in a modified Tegal MCR-1, single wafer, plasma etch system. A schematic of the system is shown in Fig. 2.1. Power is supplied to an aluminum (Al) electrode, 20 cm in diameter, at the base of the chamber. This
powered electrode, shown in Fig. 2.2, is driven by a RF power supply (ENI HF-1) at 13.56 MHz. The RF power is transmitted to the electrode through a matching network via a RG-8/U coaxial cable, which is permanently attached to the powered electrode, as shown in Fig. 2.2. The powered electrode is water cooled by a temperature controlled water supply. For these experiments, a raised cathode is placed upon the powered electrode. This raised cathode is a hollow cylinder of stainless steel, 11 cm in diameter, 5.3 cm high, and 1 cm thick. It is machined to fit over a groove on the powered electrode. This groove prevents the raised cathode from moving in a transverse direction. A ceramic Macor ring insulates the powered electrode from

![Figure 2.2: A cross-sectional view of the etch chamber interior.](image-url)
the grounded electrode and the chamber sidewall, which is also grounded. The cylin-
drical sidewall (Sidewall 1) is stainless steel with four, 7.5 cm diameter viewports
as shown in Fig. 2.3. Sidewall 1 is 11.8 cm high, has an inner diameter of 25.6 cm
and an outer diameter of 30.5 cm. Two of the viewports have quartz windows

![Diagram of etch chamber interior]

Figure 2.3: A top view of the etch chamber interior.

for viewing the plasma and observing particles with a laser and camera. The other
two ports are sealed with blank conflat flanges. Sitting on top of the sidewall is the
aluminum grounded electrode, 31.1 cm in diameter. The electrode gap, the distance between the raised cathode and the grounded electrode, as shown in Fig. 2.2, is 9.7 cm. Connected to the top of the grounded electrode is a stainless steel, exhaust stack, as shown in Fig. 2.1. A motorized gate valve, bolted on top of the exhaust stack, controls the gas pressure in the chamber. The chamber is pumped by a turbomolecular pump (Leybold Turbvac 1000) which sits on top of the gate valve. The turbomolecular pump is backed by a mechanical pump (Alcatel 2060C).

A second sidewall (Sidewall 2) and raised cathode were used for some experiments. Both of these are made of Al. Sidewall 2 is cylindrical, 7 cm in height, with an inner diameter of 25.6 cm and an outer diameter of 30.6 cm. Sidewall 2 has two 3.8 cm diameter viewports with sapphire windows. The two viewports are located 180° from each other. The cylindrical raised cathode is solid Al, 3.5 cm high, and 11.1 cm in diameter. It is also machined to fit over the same groove on the powered electrode as the stainless steel raised cathode. The electrode gap for Sidewall 2 with the Al raised cathode is 6.7 cm.

Chamber pressure is monitored by a capacitance manometer (MKS 221k) for pressures between 1-1000 mTorr. An ion gauge (Varian NRC 840) is used for monitoring pressures below 1 mTorr. Gas flows in through a single length of 6.25 mm diameter Al tubing at the base of the side wall, as seen in Fig. 2.1, and enters the chamber through six uniformly spaced holes in the Macor ring. Gas flow is controlled by mass flow controllers (URS-100).
2.2 Laser Light Scattering

The two quartz windows on the chamber viewports of Sidewall 1 allow the observation of particles in the plasma. One window is used for the transmission of light from a 35 mW Helium-Neon (He-Ne) laser (Spectra-Physics 127) at a wavelength of 632.28 nm. The other window is used to view the scattered light with a CCD camera (Javelin JE3462HR). This technique, by which particles in a plasma are observed using laser light scattering, has been used and developed by others [12, 13].

The He-Ne laser beam is directed, using a mirror, through an elliptical lens and into the chamber as shown in Fig. 2.4. The elliptical lens is used to expand the laser beam vertically, allowing a larger volume of light to interact with the particles. Light from the laser then scatters off particles in the plasma. The chamber has a number of different configurations for viewing the scattered light, depending on which ports the two quartz windows are attached to. In this work, scattered light was viewed at an angle of 45 degrees with respect to the incoming laser beam. At this angle the scattered light signal was maximized, and internal reflections of the laser off the chamber walls were minimized.

The CCD camera, consisting of an image intensifier (Xybion IRO-201-R), optical bandpass filter, and zoom lens, is used to view the light scattered from the particles. An image intensifier is used for viewing scattered light from very small particles at the initiation of the discharge. Scattered light from these small particles is very dim and requires amplification. Since a plasma discharge is rich in optical emissions, an
Figure 2.4: The setup of laser scattering apparatus.
optical bandpass filter is used to filter out light from the discharge and pass only the scattered laser light at 632.28 nm. A zoom lens is used to magnify the image of the particles in the plasma. Particle clouds, formed from particles which have diameters on the order of tenths of microns or smaller, cannot be seen without the aid of the zoom lens. Images of the particles are viewed on a television monitor (Javelin CVM-13B). These images can be recorded onto super-VHS tape using a video cassette recorder (JVC BR-S378U).

2.3 Plasma Diagnostic Equipment

Gas phase constituents of the plasma discharge are monitored using optical emission spectroscopy (OES) and residual gas analysis (RGA) systems. Both of these systems are shown schematically in Fig. 2.1.

The OES system (EG&G 1470) is a triple grating spectrograph system. The grating used for this work can operate over a spectral range of 200-1000 nm, but can only scan over a window of 100 nm. In this work a center wavelength of 350 nm was chosen, and the spectra were taken over a range of wavelengths from 300 nm to 400 nm in order to monitor emissions from hydroxyl (OH) and nitrogen (N$_2$) in this wavelength range. Light is collected from the plasma discharge by a fiber-optic bundle placed in front of one of the quartz windows. The light is then separated spatially by the grating and detected by a linear photo-diode array. This particular OES system is computer controlled, and a software package (Process Vision©) is
used for collecting, analyzing, and displaying the optical spectra. For this work, the relative optical intensity was monitored as a function of time.

The RGA system (MKS) is an RF quadrupole mass filter. Gas is sampled by the RGA from the exhaust of the plasma chamber. An ionizer is then used to ionize the exhaust gas. The mass filter separates mass based on the mass-to-charge ratio \( \frac{M}{Q} \) of the ions generated in the ionizer. Here \( M \) is the ion's mass in atomic mass units (AMU), and \( Q \) is the ion's charge in units of the elementary charge \( (1.602 \times 10^{-19} \text{ C}) \).

When ionized, each gas molecule will dissociate in its own particular manner. This is referred to as the molecule's cracking pattern. Although cracking patterns are generally well known for many gases and vapors [14], each RGA will have its own unique cracking variations based on the ionization potential used and the method of mass filtering. With a plasma present, cracking patterns become distorted; it becomes difficult to determine how a particular molecule will crack, since species in the plasma are continually dissociating and recombining to form new species. Despite these problems, the RGA was a very useful tool in this work for determining, qualitatively, the various gases present in the plasma chamber, along with their relative concentrations.

Mass spectra are collected, analyzed, and displayed using a computer and the RGA's own software package (PPT version 4.42). A number of data display modes are available, including a display of ion current versus time for up to 16 different \( \frac{M}{Q} \) ratios simultaneously. In this work ion current versus time was monitored.
CHAPTER 3

Electrical Measurements

3.1 Voltage & Current Measurements

In order to monitor the impedance of the plasma discharge, the voltage and current of the discharge must be measured. A coil-type current probe (Pearson 2878) is used to measure the current. This current probe operates on the principle of magnetic induction. A current carrying wire is placed through the toroidal coil. The probe's output is a voltage which is proportional to the current flowing in the wire, according to Faraday's Law. The 2878 has an output ratio of 0.1 volts per amp. The output terminal of the current probe is a SMA connector, with an SMA-to-BNC adapter attached. The rated bandwidth for this probe is 70 MHz. The manufacturer specifies an amplitude error of less than 1%, and a phase shift error of less than 6° for frequencies between 7-70 MHz.

Voltage is measured by a 100:1 high voltage probe (Phillips PM9100), having a bandwidth of 200 MHz. The manufacturer specifies a DC attenuation error of
±2.5% for this model. This probe has a hook-like input terminal with an alligator-clip grounding terminal, as found with most oscilloscopes. The voltage probe cable is 1.5 m long.

![Diagram of probe station](image)

**Figure 3.1:** A cross-sectional view of the probe station.

The current probe is housed in an aluminum box, 13.1 x 7.5 x 5.3 cm, in order to provide shielding from any stray RF radiation, as well as to provide shielding to instruments outside the box. There is a female UHF connector at either end of the box, so it can be placed in-line with the RF power flow. A wire soldered between the two UHF connectors allows transmission of the RF current. The torroidal current probe surrounds this wire, as specified in the manufacturer's instructions. A short (<10 cm) tap wire off one of the UHF center conductors is connected to a female BNC, mounted in the top of the box, for the voltage measurement. There is a short (<1 cm) wire soldered into the BNC center conductor to which the hook-like voltage probe is attached. This aluminum box which houses the current probe and connectors
for the voltage probe is henceforth referred to as the probe station. A detailed cross-
section of the probe station is shown in Fig. 3.1. A digital oscilloscope (HP54601A) is
used to measure the voltage and current waveforms. Each of the four channels of the
digital oscilloscope has an input impedance of 1 MΩ in shunt with 13 pF. The voltage
probe is connected directly to the oscilloscope. The current probe is terminated, via
a 1.8 m length of RG-58/U coaxial cable, in a 50 Ω load, as recommended by the
manufacturer. The 50 Ω load, with male and female BNC connectors at either end,
is connected to a separate channel on the oscilloscope.

3.2 Data Acquisition

Real-time voltage, $V(t)$, and current, $I(t)$, waveforms are measured by the respec-
tive probes, and displayed on two separate channels of the digital oscilloscope. Both
channels of the oscilloscope are triggered simultaneously off the voltage waveform.
This oscilloscope is used to digitize the waveforms into 2000 discrete points. Each
waveform is digitized over approximately 68 cycles of the 13.56 MHz frequency. Dig-
itizing the waveforms over many cycles, as opposed to just one cycle, reduces the
effects of aliasing at the edges of the waveform.

The waveforms $V(t)$ and $I(t)$ are actually the product of the RF signal and a
unity amplitude square pulse whose width, in the time domain, is equal to the width
of the oscilloscope screen as determined by the time base setting of the oscilloscope.
For example, when taking data used in this work, the time base of the oscilloscope
is $500 \text{ ns/division}$. There are 10 divisions across the oscilloscope screen; therefore, the width of the square pulse would be: $(500 \text{ ns/division})(10 \text{ divisions})=5 \mu s$. The edges of the square pulse are a source of high frequencies which cause aliasing in the frequency domain. Digitizing more than one cycle of the waveform results in an averaging effect which helps to reduce the distortion caused by aliasing of these high frequency components. It should also be mentioned that the digitizing process limits the resolution of the waveforms to 0.2 MHz in the frequency domain. Because of this, the impedance calculation cannot be made at exactly 13.56 MHz, and is calculated at 13.6 MHz instead. This is not believed to cause any significant error in the impedance calculations since frequency measurements of the RF power supply, made using the digital oscilloscope, indicate that the RF output frequency is only accurate to 0.1 MHz.

The digitized waveform data is transmitted to a computer by means of a General Purpose Interface Bus (GPIB) which connects the oscilloscope to the computer. A computer program, written in C programming language, was used to store the data from the oscilloscope on the computer's hard disk drive. The source code for this program can be found in Appendix A. The current and voltage waveforms are saved as separate ASCII data files. A schematic diagram of the entire experimental setup is shown in Fig. 3.2.
Figure 3.2: A schematic of the experimental setup.
3.3 Impedance Calculation

Digitized voltage and current waveforms are analyzed using Matlab©, a commercially available mathematics software package. Because the waveforms contain harmonics of 13.56 MHz, they must be analyzed using a discrete Fourier transform (DFT) routine. The DFT routine used came included in the Matlab© software package. The real-time voltage \( V(t) \) and current \( I(t) \) can be expressed as [15]:

\[
V(t) = \sum_{n=-\infty}^{\infty} V_n e^{j(\omega_n t)} \\
I(t) = \sum_{n=-\infty}^{\infty} I_n e^{j(\omega_n t)}
\]  

(3.1)

Here, \( j = \sqrt{-1} \), and \( V_n \) and \( I_n \) are the complex Fourier amplitudes, or phasors, given by:

\[
V_n = |V_n| e^{j\alpha_n} \\
I_n = |I_n| e^{j\beta_n}
\]

(3.2)

Also, \( \omega_n \) is the angular frequency such that if \( \omega_0 \) is the fundamental frequency, \( \omega_0 \equiv 2\pi(13.56 \text{ MHz}) = 8.52 \times 10^7 \text{ s}^{-1} \), then \( \omega_n = n\omega_0 \) is the nth harmonic, where \( n \) has integer values. The phase angles associated with the nth harmonic voltage and current are \( \alpha_n \) and \( \beta_n \) respectively, and \( |V_n| \) and \( |I_n| \) are real amplitudes. A DFT is performed to find values for \( V_0 \) and \( I_0 \) at the fundamental frequency. The impedance, \( Z_0 \), can be calculated as

\[
Z_0 \equiv \frac{V_0}{I_0} = \frac{|V_0| e^{j\alpha_0}}{|I_0| e^{j\beta_0}} \equiv |Z_0| e^{j\theta_0}
\]

(3.3)
where \( |Z_0| = \frac{|V_0|}{|I_0|} \) and \( \theta_0 = \alpha_0 - \beta_0 \) are the magnitude and phase of the impedance phasor \( Z_0 \) at the fundamental frequency. The Matlab code written to calculate \( Z_0 \) can be found in Appendix B. Henceforth, the subscript 0 will be dropped since all measured quantities in this work are for the fundamental frequency only. Unless stated otherwise, \( Z \equiv Z_0, V \equiv V_0, I \equiv I_0, \) and \( \omega_0 \equiv \omega \).

Although the calculation of \( Z \) may appear simple, arriving at the correct value of the plasma impedance, \( Z_p \), is complicated by measurement errors. The remainder of this chapter will discuss the sources of measurement error, and calibrations for correcting them.

### 3.4 Transmission Line Effects

Since the voltage and current measurements are made a distance \( l \) from the powered electrode, the impedance calculated using the measured phasors \( V \) and \( I \) is not the actual impedance of the plasma. This is due to the impedance transforming properties of the transmission line connecting the probe station to the powered electrode. For a transmission line with an attached load impedance \( Z \), the measured value of \( Z(x) \), which varies along the length of the transmission line [16], is given by:

\[
Z(x) = Z_0 \left( \frac{Z \cos(kx) + j Z_0 \sin(kx)}{Z_0 \cos(kx) + j Z \sin(kx)} \right)
\]

where \( Z_0 \) is the characteristic impedance of the transmission line in ohms. The wavevector \( k \) is given by:

\[
k = \frac{\omega \sqrt{\varepsilon}}{c}
\]
where $\epsilon$ is the relative permittivity of the cable's dielectric, and $c$ is the speed of light in vacuum. The quantity $Z(x)$ is the position dependent impedance which is a function of position $x$ from the load $Z$. In making measurements of $V$ and $I$ at a distance $x = l$ from the powered electrode, one is measuring $Z(x = l)$, which is not the same as the load impedance $Z$. In order to find the plasma impedance one must first find $Z$. For simplicity let $Z_b \equiv Z(x = l)$. Solving Eq. 3.4 for $Z$ one finds:

$$Z = Z_0 \left( \frac{Z_0 \cos(kl) - jZ_0 \sin(kl)}{Z_0 \cos(kl) - jZ_b \sin(kl)} \right)$$

(3.6)

The transmission line connected to the powered electrode is RG-8/U for which $Z_0=52 \, \Omega$, and $\epsilon=2.26$ [17]. The length of this particular cable is $l=1.27 \, m$. The expression in Eq. 3.6 is used for converting the impedance measured by the probes, $Z_b$, to the actual load impedance, $Z$.

3.5 Probe Calibration

Due to the different lengths and permittivities of the cables which connect the voltage and current probes to the oscilloscope, there will be errors in the phase and magnitude of the measured waveforms. Additional errors will arise due to the intrinsic probe errors mentioned at the beginning of this chapter. Other authors have encountered similar problems when measuring RF voltages and currents [9, 10, 11].

The voltage probe has a set screw which is used to adjust the amplitude response. This adjustment was used to calibrate the voltage probe to a 13.56 MHz sine wave of known amplitude. The sine wave was generated by a function generator (HP3314A).
The current probe has no adjustable parts, so its amplitude response could not be calibrated. Neither probe has phase adjustments.

To compensate for phase and magnitude errors, the probes are calibrated to a known reactive load, as suggested in [9]. The probes are calibrated only at 13.56 MHz, since this work is not concerned with electrical measurements at harmonic frequencies. The empty plasma chamber, which is a reactive load, was used to perform the calibration. It should be emphasized that all electrical connections to the powered electrode must be made via the RG-8/U cable, which is permanently attached to the powered electrode as shown in Fig. 2.2. Because of this all impedance measurements, of either the empty chamber or the plasma, must be made at the input of this RG-8/U cable. The impedance measured at the input of the RG-8/U cable can then be referred to the plasma chamber input using Eq. 3.6. The impedance of the empty plasma chamber is measured by the probes and by an impedance analyzer (HP4191A). The impedance $Z_b$ measured by the probes can be expressed in terms of a magnitude $|Z_b|$ and a phase $\gamma$. Correction factors for these two quantities are determined by the ratio of the impedance measured by the impedance analyzer, $Z_{HP}$, to the impedance measured by the probes, $Z_b$.

$$\frac{Z_{HP}}{Z_b} = \frac{|Z_{HP}|e^{j\phi}}{|Z_b|e^{j\gamma}} = me^{j\Delta} \tag{3.7}$$

The quantities $m = \frac{|Z_{HP}|}{|Z_b|}$ and $\Delta = \phi - \gamma$ are the correction factors for the magnitude and phase angle respectively. Once appropriate values of $m$ and $\Delta$ have been
determined the corrected value of $Z_b$ can be calculated as:

$$Z'_b = Z_b m e^{j\Delta}$$  \hspace{1cm} (3.8)

where the quantity $Z'_b$ replaces the uncorrected impedance $Z_b$ in Eq. 3.6. It is important to note that the load used for calibration, the transmission line, and the probes are all circuits which are linear and passive, and therefore the correction factors can be applied to any system load at 13.56 MHz.

In order to determine the appropriate values of $m$ and $\Delta$, five independent measurements of the empty plasma chamber impedance were made using the probes and the impedance analyzer. By independent it is meant that consecutive measurements were not necessarily performed on the same day, and that the probe and impedance analyzer measurements were not performed simultaneously. Measurements using the impedance analyzer were made by soldering short wires (<5 cm) onto the center conductor and ground conductor of the male UHF connector on the RG-8/U coaxial cable. Since the impedance analyzer has a binding post type input connector, this was the only way to make an electrical connection between the impedance analyzer and the powered electrode.

The procedure for making measurements on the empty chamber with the probes is exactly the same as measuring the plasma impedance with the probes, except the function generator replaces the RF generator as the signal source. The probe station is connected in line between the function generator and the input to the RG-8/U cable. The chamber is excited by a 10 volt peak-to-peak sine wave at 13.56 MHz
from the function generator. Voltage and current measurements, and impedance calculations are made as mentioned previously.

The results of the measurements made by the impedance analyzer and the probe station are shown in Table 3.1. The impedance analyzer and the probe measurements have not been corrected for transmission line effects. The average of each of the

<table>
<thead>
<tr>
<th>Measurement</th>
<th>$Z_{HF}(\Omega)$</th>
<th>$Z_0(\Omega)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$34.10\angle-86.27^\circ$</td>
<td>$30.73\angle-74.84^\circ$</td>
</tr>
<tr>
<td>2</td>
<td>$33.95\angle-86.77^\circ$</td>
<td>$30.76\angle-74.85^\circ$</td>
</tr>
<tr>
<td>3</td>
<td>$34.37\angle-86.65^\circ$</td>
<td>$30.76\angle-74.81^\circ$</td>
</tr>
<tr>
<td>4</td>
<td>$33.44\angle-87.07^\circ$</td>
<td>$30.49\angle-74.73^\circ$</td>
</tr>
<tr>
<td>5</td>
<td>$33.24\angle-86.86^\circ$</td>
<td>$30.51\angle-74.65^\circ$</td>
</tr>
<tr>
<td>Average</td>
<td>$33.82\angle-86.72^\circ$</td>
<td>$30.65\angle-74.77^\circ$</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>$0.46\angle0.29^\circ$</td>
<td>$0.13\angle0.08^\circ$</td>
</tr>
</tbody>
</table>

five measurements was used to calculate $m$ and $\Delta$. The values of $m$ and $\Delta$ used when calculating the plasma impedance are:

$$m = 1.10$$

$$\Delta = -11.95^\circ \quad (3.9)$$

The standard deviation given in Table 3.1 indicates the precision of the impedance measurements. Although the probes exhibit significant magnitude and phase errors in comparison to the impedance analyzer, repeated measurements of the empty plasma chamber indicate that these probes are very precise. In the case of the impedance analyzer, the standard deviation is most likely attributable to the wires that must be
soldered to the male UHF connector. These wires had to be removed whenever the plasma system was run, and then re-soldered to the connector to make additional impedance measurements. It is believed that slight variations in the quality of the solder connection, and in the length and configuration of the wires are the reasons for the standard deviation being as large as it is ($\approx 2\%$).
CHAPTER 4

Equivalent Circuit of Empty Plasma Chamber

The previous chapter discussed transmission line effects and phase and magnitude errors associated with the probes. Up to this point, the correct value of the measured impedance, \( Z \), can be expressed as:

\[
Z = Z_0 \left( \frac{Z'_b \cos(kl) - jZ_0 \sin(kl)}{Z_0 \cos(kl) - jZ'_b \sin(kl)} \right)
\]  

(4.1)

where the corrected probe impedance \( Z'_b \) has replaced \( Z_b \). In addition to these effects, the intrinsic impedance of the empty plasma chamber, \( Z_i \), has an effect on the plasma impedance \( Z_p \). For the Tegal MCR-1, \( Z_i \) is in shunt with \( Z_p \), similar to what has been found by other researchers in their plasma systems \[9, 10, 11\]. The measured impedance \( Z \) is the parallel combination of \( Z_p \) and \( Z_i \). Once \( Z_i \) and \( Z \) are known, the calculation of \( Z_p \) is trivial.

4.1 Intrinsic Impedance

The impedance analyzer was used to measure \( Z_i \), the intrinsic impedance of the Tegal MCR-1 at a distance \( l \) from the powered electrode. As mentioned previously, the distance \( l=1.27 \text{ m} \) is the length of the RG-8/U cable permanently attached to
the powered electrode. These impedance measurements were made on the empty chamber at atmospheric pressure without the raised cathode. Measurements were originally made with Sidewall 1 and grounded electrode in place. Later, these were removed and measurements were made on the powered electrode alone, without a sidewall or grounded electrode. It was found that the powered electrode was the main contributor to $Z_i$. The presence of the sidewall and grounded electrode caused no change in the resistance of $Z_i$, and only a 5.7% change in the reactance of $Z_i$ at 13.56 MHz.

Impedance measurements were made over a range of frequencies, from 1 MHz to 40 MHz. The impedance analyzer was connected to the powered electrode via the RG-8/U coaxial cable. Equation 3.6 was used to convert the impedance $Z_i$ measured at the input of the RG-8/U cable to $Z_i$, the impedance that would be measured directly at the powered electrode. The results of these measurements are given in Tables 4.1 and 4.2.

When making impedance measurements on the powered electrode, a resonance was observed for $Z_i$ at approximately 21 MHz. In order to verify that this was indeed a resonance in the powered electrode and not in the RG-8/U cable, an impedance measurement of an identical length of RG-8/U cable, with no attached load, was made. The cable exhibited no resonance at, or around, 21 MHz, confirming that the resonance occurs in the powered electrode itself. At resonance, the impedance $Z_i$ reaches a minimum, indicating that the powered electrode behaves like an RLC
Table 4.1: Impedance analyzer measurements of the powered electrode without sidewall & grounded electrode.

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>$Z_l(\Omega)$</th>
<th>$Z_i(\Omega)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.000</td>
<td>20.0-j710.0</td>
<td>97.2-j1566.1</td>
</tr>
<tr>
<td>5.077</td>
<td>4.50-j136.9</td>
<td>22.3-j321.4</td>
</tr>
<tr>
<td>9.960</td>
<td>2.10-j58.70</td>
<td>8.95-j153.2</td>
</tr>
<tr>
<td>13.56</td>
<td>1.70-j33.40</td>
<td>6.15-j105.4</td>
</tr>
<tr>
<td>15.00</td>
<td>1.76-j25.60</td>
<td>5.86-j91.99</td>
</tr>
<tr>
<td>19.38</td>
<td>1.95-j7.50</td>
<td>5.17-j67.83</td>
</tr>
<tr>
<td>21.21</td>
<td>1.86</td>
<td>4.24-j58.79</td>
</tr>
<tr>
<td>25.00</td>
<td>2.48+j13.75</td>
<td>4.24-j47.36</td>
</tr>
<tr>
<td>27.12</td>
<td>2.37+j22.80</td>
<td>3.23-j41.14</td>
</tr>
<tr>
<td>30.00</td>
<td>3.00+j36.30</td>
<td>2.90-j34.67</td>
</tr>
<tr>
<td>35.00</td>
<td>6.60+j70.60</td>
<td>2.88-j25.75</td>
</tr>
<tr>
<td>40.00</td>
<td>30.2+j165.7</td>
<td>2.93-j17.43</td>
</tr>
</tbody>
</table>

Table 4.2: Impedance analyzer measurements of the powered electrode with sidewall & grounded electrode.

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>$Z_l(\Omega)$</th>
<th>$Z_i(\Omega)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.000</td>
<td>30.0-j680.0</td>
<td>131-j1424</td>
</tr>
<tr>
<td>5.077</td>
<td>4.40-j133.0</td>
<td>20.4-j302.7</td>
</tr>
<tr>
<td>9.960</td>
<td>2.00-j56.50</td>
<td>7.98-j144.1</td>
</tr>
<tr>
<td>13.56</td>
<td>1.70-j31.50</td>
<td>6.15-j105.4</td>
</tr>
<tr>
<td>15.00</td>
<td>1.70-j23.80</td>
<td>5.46-j86.22</td>
</tr>
<tr>
<td>19.38</td>
<td>1.98-j5.77</td>
<td>4.87-j63.40</td>
</tr>
<tr>
<td>20.76</td>
<td>1.86</td>
<td>4.07-j56.71</td>
</tr>
<tr>
<td>25.00</td>
<td>2.48+j16.00</td>
<td>3.87-j43.71</td>
</tr>
<tr>
<td>27.12</td>
<td>2.43+j25.40</td>
<td>2.99-j37.78</td>
</tr>
<tr>
<td>30.00</td>
<td>3.30+j39.80</td>
<td>2.84-j31.46</td>
</tr>
<tr>
<td>35.00</td>
<td>7.50+j78.00</td>
<td>2.73-j22.78</td>
</tr>
<tr>
<td>40.00</td>
<td>43.0+j202.0</td>
<td>2.76-j14.39</td>
</tr>
</tbody>
</table>
series circuit, with a resonant frequency:

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$  \hfill (4.2)

Notice that the resonance at 21 MHz is no longer present after $Z_i$ is converted to $Z_i$ using Eq. 3.6. The resonance did not disappear, it has been shifted to a higher frequency by the impedance transforming properties of the transmission line. Evidently the true resonant frequency of the powered electrode is not 21 MHz. Once the $L$ and $C$ of the RLC circuit are known, the true resonant frequency of the powered electrode can be calculated using Eq. 4.2.

A schematic representation of the equivalent circuit elements for the empty plasma chamber are shown in Fig. 4.1. These elements are redrawn in Fig. 4.2 to give a full equivalent circuit for the empty chamber. The equivalent circuit is

![Figure 4.1: A schematic representation of empty chamber equivalent circuit.](image-url)
primarily determined by the physical properties of the powered electrode, shown in cross-section in Fig. 4.1. This electrode consists of two parallel, aluminum plates; the upper plate, connected to the center conductor of the RG-8/U cable, and the lower plate, connected to the outer conductor of the RG-8/U cable. These plates are separated by insulating spacers. The element $C_1$ is the capacitance between these plates, representing the stored energy in the RF electric field. RF current flows in a loop from the RG-8/U center conductor through the upper plate as conduction current; then through $C_1$ as displacement current; and finally through the bottom plate as conduction current to the outer conductor of the cable. The stored energy in the magnetic field associated with this RF current can be represented by an equivalent inductor $L_1$. The resistance $R_1$ is the resistance along the RF conduction current path, and is expected to be small. The resistance $R_2$, which is in shunt with $C_1$, is associated with the leakage current through the insulating spacers. Using a digital multimeter (Fluke 77), the measured DC resistance of $R_2$ is $\approx 800 \, \text{k}\Omega$. It is assumed that $R_2$ is significantly larger than the shunt reactance of $C_1$, and thus $R_2$ can be neglected in the circuit analysis. Finally, $C_2$ is the stray capacitance between the upper plate and
other surrounding grounded surfaces inside the empty chamber. With the plasma present, $C_2$ is replaced by the plasma impedance $Z_p$.

Measurements of $Z_i$ at multiple frequencies allow for the calculation of elements $L_1$, $C_1$, and $C_2$ using circuit theory. Values calculated for these elements are: $L_1 \approx 83$ nH, $C_1 \approx 106$ pF, and $C_2 \approx 6$ pF. Using the values of $L_1$ and $C_1$, the true resonant frequency of the empty chamber, given by Eq. 4.2, is 53.6 MHz. The series resistance $R_1 \approx 6$ Ω was measured at 13.56 MHz by the impedance analyzer (see Table 4.1). Since $C_2$ is small compared with $C_1$, and $R_1$ is a small resistance, elements $C_1$ and $L_1$ dominate the equivalent circuit.

Now that all the values of the circuit elements are known, circuit theory can be used to reduce the circuit in Fig. 4.2 to an equivalent circuit, which turns out to be capacitive in nature at 13.56 MHz. The equivalent circuit for $Z_i$ at 13.56 MHz is shown in Fig. 4.3. At this frequency $Z_i = 6 - j97$ Ω. This impedance is the same order of magnitude as $Z_p$, so $Z_i$ will not limit the accuracy with which $Z_p$ can be measured, a problem which has been encountered by others [11].

![Figure 4.3: Tegal MCR-1 equivalent circuit at 13.56 MHz.](image-url)
4.2 Plasma Impedance

When a plasma is present in the chamber, a shunt impedance is added to the circuit in Fig. 4.3. This shunt impedance is the plasma impedance, which can be modeled as a resistor and capacitor in series [18]. The capacitor represents the capacitance of the plasma sheaths, while the resistor represents ohmic heating of electrons in the plasma bulk, and stochastic heating of electrons in the plasma sheaths [19]. The complete equivalent circuit with the plasma present is shown in Fig. 4.4. Given $Z_i$ from measurements of the empty plasma chamber and $Z$ from Eq. 4.1, $Z_p$ can be determined quite easily from circuit theory.

$$Z_p = \frac{Z_i Z}{Z_i - Z}$$  \hspace{1cm} (4.3)

Figure 4.4: Equivalent circuit with plasma present.
4.3 Harmonics

In an RF plasma, harmonics of the driving frequency arise from nonlinearities in the plasma sheath [19] and asymmetries in the geometry of the plasma chamber [20]. The harmonics occur at integer multiples of the 13.56 MHz RF power; 27.12 MHz and 40.68 MHz are the second and third harmonics respectively. Although this work is not concerned with making electrical measurements of the plasma impedance at harmonic frequencies, this is a topic of interest among other researchers [9, 10, 11]. For this reason, plasma impedance and harmonics will be discussed.

Consider the equivalent circuit of a plasma system for the fundamental frequency, $\omega$, as shown in Fig. 4.5. The RF generator $V_g$ is external to the plasma and has an output impedance of $Z_{go}$, where the subscript 0 indicates the impedance at the fundamental frequency. The matching network is located between the RF generator and the plasma chamber, and is represented by a two-port network labeled $Z_{m0}$. The impedance measurement for the fundamental is made at the point after

\[\text{Figure 4.5: Equivalent circuit for the fundamental frequency.}\]
the matching network, as shown in Fig. 3.2, and indicated by $V_0$ and $I_0$ in Fig. 4.5. The quantities $Z_{p_0}$ and $Z_{i_0}$ are the plasma impedance and intrinsic impedance respectively, as discussed previously.

Measurement of the plasma impedance of a harmonic is not a simple matter. The voltage source for the nth harmonic, $V_{p_n}$, is located inside the plasma. The equivalent circuit for the nth harmonic is shown in Fig. 4.6. This equivalent circuit is analogous to the circuit in Fig. 4.5, except that the voltage source $V_{p_n}$ is within the plasma,

![Figure 4.6: Equivalent circuit for the nth harmonic.](image)

and the external power source at 13.56 MHz now appears as a passive impedance $Z_{g_n}$. A measurement of $\frac{V_n}{I_n}$ at a harmonic frequency $\omega_n$ only yields the impedance of the external circuitry at the nth harmonic, which is $Z_{m_n}$ in shunt with $Z_{g_n}$. Obviously, this is not the nth harmonic plasma impedance, $Z_{p_n}$, and is of little interest.

Harmonic plasma impedances cannot be measured in the same way as the fundamental plasma impedance. A different technique must be used. Consider the circuit of Fig. 4.6 with an LC tank circuit inserted after the matching network, but before
the voltage and current measurements made by the probes. This arrangement is shown in Fig. 4.7. The tank circuit will resonate at the frequency given by Eq. 4.2, and present a high impedance to currents at this frequency. The variable capacitor allows the resonant frequency of the tank circuit to be tuned.

The harmonic plasma impedance $Z_{p_n}$ can be measured by making two sets of measurements of the nth harmonic voltage and current: $V_{n_1}$, $I_{n_1}$ and $V_{n_2}$, $I_{n_2}$. For the first measurement, the tank circuit is tuned to resonate at the nth harmonic frequency. Assuming the impedance of the tank circuit at resonance is large enough to be considered an open circuit, the circuit in Fig. 4.7 will reduce to the circuit shown in Fig. 4.8. When the tank circuit is tuned to resonate at the nth harmonic frequency, $I_{n_1} = 0$. The harmonic plasma current $I_{p_n}$ will flow in a loop through $Z_{p_n}$ and $Z_{i_n}$. This is a simple voltage divider circuit for which:

$$V_{n_1} = \frac{Z_{i_n}}{Z_{i_n} + Z_{p_n}} V_{p_n} \quad (4.4)$$

![Figure 4.7: Equivalent circuit for the nth harmonic, with LC tank circuit.](image-url)
It is assumed that $Z_i$ is known, having been measured using the technique described previously in this chapter. For the second measurement, the tank circuit is detuned slightly so that some nth harmonic current will flow, thus $I_{n2} \neq 0$. Now the circuit behaves like a current divider, with $I_{i}$ flowing through $Z_i$ and $I_{n2}$ flowing toward the external circuitry, as shown in Fig. 4.9. The plasma current, $I_{pn}$, is:

$$I_{pn} = I_{i} + I_{n2} = \frac{V_{n2}}{Z_i} + I_{n2}$$

(4.5)

The voltage $V_{n2}$ can be expressed as:

$$V_{n2} = V_{pn} - I_{pn}Z_{pn}$$

(4.6)
Substituting Eq. 4.5 into Eq. 4.6 results in:

\[ V_{n2} = V_{pn} - \left( \frac{V_{n2}}{Z_{in}} + I_{n2} \right) Z_{pn} \]  \hspace{1cm} (4.7)

Equations 4.4 and 4.7 represent a pair of equations with two unknown quantities: \( V_{pn} \) and \( Z_{pn} \). Combining these two equations to eliminate \( V_{pn} \) results in:

\[ Z_{pn} = \frac{Z_{in}(V_{n2} - V_{n1})}{V_{n1} - V_{n2} - I_{n2}Z_{in}} \]  \hspace{1cm} (4.8)

where \( Z_{pn} \) is the nth harmonic plasma impedance. The expression in Eq. 4.8 can be used to calculate the plasma impedance of any harmonic from the measured quantities: \( Z_{in}, V_{n1}, V_{n2}, \) and \( I_{n2} \). Once \( Z_{pn} \) has been calculated, the value of the harmonic voltage source \( V_{pn} \) can be calculated using Eq. 4.7.
CHAPTER 5

Experimental Results

5.1 Clean versus Dusty Plasmas

Particles are generated in the modified Tegal MCR-1 by sputtering graphite from a graphite disk, 100 mm in diameter and 5 mm thick, placed on top of the raised cathode as shown in Fig. 5.1. A 50 mm silicon (Si) wafer is placed concentrically on top of the graphite. This geometry on the raised cathode is known to form ring and dome-shaped particle traps at the plasma sheath interface [21]. Particles have been seen in this configuration using laser light scattering.

It was originally thought that trapped particles were the cause of the impedance transients, since the particles appear in the traps on approximately the same time scale as the transients. However, comparison of a dusty plasma to a plasma with no particles shows that this is probably not the case. Two experiments were run, one with the graphite disk and Si wafer (the dusty plasma), and the other with the chamber thoroughly cleaned (the clean system) with no graphite disk or Si wafer. The following system parameters were used during both experiments: 100 Watts (W) RF power, argon (Ar) gas flow of 10 sccm, gas pressure of 15 mTorr, and chamber base
pressure of $2 \times 10^{-6}$ Torr. Sidewall 1 was used in all experiments, unless otherwise noted. Data was taken over a period of 20 minutes. Plots of the plasma resistance and reactance versus time for the dusty plasma and clean system are shown in Figs. 5.2 and 5.3 respectively. The peak-to-peak RF voltage and current for the 13.6 MHz waveforms are shown in Fig. 5.4 for the dusty plasma experiment. The RF current remains relatively constant throughout the experiment, and RF voltage exhibits a transient. It is believed that the voltage and current characteristics shown in Fig. 5.4 are typical for all the experiments in the work.

Using laser light scattering, particles from the dusty plasma were seen entering the traps on the same time scale as the impedance transients. The traps continued to fill with particles, and after 20 minutes a large particle cloud could be observed.
Figure 5.2: Time evolution of plasma impedance for a dusty Ar plasma.
Figure 5.3: Time evolution of plasma impedance for a clean Ar plasma.
Figure 5.4: Peak-to-peak voltage & current in a dusty Ar plasma.
No particles were ever seen in the clean system, even after the plasma had run for 20 minutes.

It is concluded that particles in the plasma are probably not responsible for the observed impedance transients. Also, it is very unlikely that electrical effects are responsible for the transients, since the decay time observed in Figs. 5.2 and 5.3 is on the order of minutes. Electrical transients in plasma systems are typically on the order of micro- or milli-seconds. In addition, no transients were ever observed when measuring the impedance of the empty plasma chamber, so the transient phenomena must be associated with the plasma itself.

5.2 Plasma Chemistry Effects

Impedance transients, similar to those for Ar, are also observed when the plasma chemistry is changed, as shown in Fig. 5.5. A plasma formed from a mixture of Ar and the etching gas sulfur hexafluoride (SF\(_6\)) was run for 20 minutes using Sidewall 2. The gases were mixed in a ratio of 50% Ar and 50% SF\(_6\) by flow. System parameters for this run were: 200 W RF power, 5 sccm Ar, 5 sccm SF\(_6\), gas pressure of 15 mTorr, and base pressure of 5\(\times\)10\(^{-6}\) Torr.

For this experiment, a 200 mm diameter Si wafer was placed on the raised aluminum cathode. Sitting on the wafer were six 50 mm diameter Al disks in a hexagonal array around a 75 mm diameter Si disk placed concentrically on top of the 200 mm
Figure 5.5: Impedance transients in a 50% Ar 50% SF₆ plasma.
wafer. The original purpose for using this elaborate array was to increase the trapping of particles generated by the SF\textsubscript{6}. Regardless of this, it would appear from comparing the results shown in Figs. 5.2, 5.3, and 5.5 that the impedance transients are not very dependent upon the plasma chemistry, or the geometry of wafers and disks placed on the raised cathode.

5.3 Temperature Effects

There is a possibility that the impedance transients are being caused by changes in the temperature of the raised cathode. Although the powered electrode remains at a fixed temperature, determined by the cooling water, the raised cathode, which is not water cooled, will begin to heat up when the plasma is on.

Three experiments were run, using Sidewall 2, to determine if the temperature of the raised cathode would effect the impedance transients. The raised cathode was removed and a 200 mm Si wafer was placed directly on the powered electrode. Sitting on the wafer were six 50 mm diameter Al disks in a hexagonal array around a 75 mm diameter Si disk placed concentrically on top of the 200 mm wafer. Data was taken for cooling water temperatures of: 2°C, 18°C, and 36°C. The system parameters used in these three experiments were: 200 W RF power, 5 sccm Ar, 5 sccm SF\textsubscript{6}, gas pressure of 15 mTorr, and a base pressure of $5 \times 10^{-6}$ Torr. Results of these experiments, in Figs. 5.6, 5.7, and 5.8, show that impedance transients are present.
Figure 5.6: Plasma impedance for powered electrode temperature: 2°C.
Figure 5.7: Plasma impedance for powered electrode temperature: 18°C.
Figure 5.8: Plasma impedance for powered electrode temperature: 36°C.
for all cooling water temperatures. One may therefore conclude that the transients are not associated with changes in temperature.

5.4 Repeatability

![Graph showing plasma impedance behavior for a sequential, periodic excitation.](image)

Figure 5.9: Plasma impedance behavior for a sequential, periodic excitation.

The repeatability of the impedance transient phenomena was tested by making consecutive plasma runs separated by short plasma-off times. The 100 mm graphite disk and 50 mm Si wafer were placed upon the raised cathode, and the plasma
was run for 3.5 minutes and turned off for 30 seconds. This process was repeated for five consecutive iterations. The system parameters used during this experiment were: 100 W RF power, 10 sccm Ar, gas pressure 15 mTorr, and base pressure $2 \times 10^{-6}$ Torr. The results of this experiment, shown in Fig. 5.9, clearly indicate the repeatability of the impedance transient phenomena.

5.5 OES Data

OES was used to observe the time evolution of hydroxyl (OH), nitrogen ($N_2$), and oxygen ($O_2$) impurities in the plasma. Water ($H_2O$), $N_2$, and $O_2$ are introduced into the chamber when the system is vented to atmosphere, and taken apart for cleaning. It is also believed that small air leaks in the chamber are a source of these impurities while the system is under vacuum. The OH is generated by electron assisted dissociation of $H_2O$ in the plasma: $e^- + H_2O \rightarrow OH + H^- \ [22]$. Observation of OH emission lines in the spectral range of 305-310 nm, shown in Fig. 5.10, indicate an initial transient (starting at $t=0$) on approximately the same time scale as the impedance transients. In this spectral range OH has four strong emission lines at: 306.36 nm, 306.72 nm, 307.8 nm, and 308.9 nm. All information on spectral emission lines presented here is taken from Ref. 23. All OES data in this section was taken simultaneously with the impedance data shown in Fig. 5.9.

It is uncertain why the OH emission starts to increase after approximately 2 minutes. This may be attributable to increased emission from Al, which emits at 308.2 nm
Figure 5.10: Optical emission from OH in the 305-310 nm range for a sequential, periodic excitation.
and 309.2 nm, being sputtered from the grounded and powered electrodes. Also, sulfur oxide (SO), which emits strongly at 306.4 nm, may be contributing to these emissions, since the plasma system is regularly used to run SF₆ plasmas. Judging from Fig. 5.10, there is no apparent correlation between the OH spectra and the impedance transients shown in Fig. 5.9.

The N₂ emissions, monitored in the spectral ranges 353-355 nm and 357-358 nm, are shown in Fig. 5.11. These are a combination of emissions from N₂, at 353.67 nm

Figure 5.11: Optical emission from N₂ (353-355 nm) and N₂⁺ (357-358 nm) for a sequential, periodic excitation.
and 357.69 nm, and $N_2^+$, at 353.26 nm, 353.83 nm, and 354.89 nm. The emissions from $N_2$ and $N_2^+$ tend to remain fairly constant while the plasma is on, and appear to have no correlation with impedance transients. However, these emissions do indicate a constant background of $N_2$ present in the plasma chamber.

Finally, a single $O_2^+$ emission line at 383.05 nm is shown in Fig. 5.12. The initial transient in the $O_2^+$ is probably due to outgassing from the chamber walls after the plasma discharge is initiated. Other than this initial transient, emission from $O_2^+$ remains fairly constant while the plasma is on, an indication of a constant
O₂ background in the chamber. This result does not seem to indicate any relation between O₂⁺ emission and impedance transients.

5.6 RGA Data

The RGA system was used to monitor the exhaust gases from an Ar plasma. In experiments using the RGA, the raised cathode was used but no graphite disk or Si wafer was present. The plasma was on for 3.5 minutes and off for 30 seconds. This process was repeated for five consecutive iterations, then the plasma was turned off, and remained off, after approximately 20 minutes. The system parameters were: 100 W RF power, 10 sccm Ar, 15 mTorr gas pressure, and 3×10⁻⁶ Torr base pressure.

Unfortunately, the RGA’s data acquisition software uses the same computer that is used to collect data from impedance measurements. Thus, when the RGA was used no impedance measurements of the plasma could be made. However, the repeatability of the impedance transients strongly suggests that they are always present.

Of particular interest is the time evolution of H₂O, mass number 18. As can be seen in Fig. 5.13, water vapor is suppressed when the plasma is on. The upward peaks seen in Fig. 5.13 correspond to the 30 second time periods when the plasma is off. During this off-time it is believed that H₂O is entering the system through leaks in the chamber. It is uncertain why the H₂O ion current is suppressed while the plasma is on. It is significant that the repeatable transients in the H₂O ion current
Figure 5.13: Time evolution of H$_2$O (M=18), OH (M=17), and O (M=16) ion currents for a sequential, periodic excitation.
appear to be on the same timescale as the repeatable impedance transients in Fig. 5.9. Thus water vapor may be the source of the impedance transients.

Also shown in Fig. 5.13 are M=16, 17. These represent atomic oxygen (O) and the OH molecule respectively. Both of these species result from the dissociation of H\textsubscript{2}O, either in the plasma or in the ionizer of the RGA. The OH and O both tend to follow the same pattern as the H\textsubscript{2}O when the plasma is turned on and off repeatedly, although this pattern is less pronounced than that of H\textsubscript{2}O. These trends in the OH and O ion currents further indicate a relationship between the presence of water in the plasma and the impedance transients.
CHAPTER 6

Discussion

6.1 Electrical Characterization & Impedance Measurements

In chapters 3 and 4 an expression was derived to calculate the plasma impedance \( Z_p \), which is restated again here:

\[
Z_p = \frac{Z_i Z}{Z_i - Z}
\]

where \( Z_i = 6 - j97 \ \Omega \) is the intrinsic impedance measured for the empty chamber at 13.56 MHz. Also shown before, the expression for \( Z \) is:

\[
Z = Z_o \left( \frac{Z_i \cos(kl) - jZ_o \sin(kl)}{Z_o \cos(kl) - jZ_i' \sin(kl)} \right)
\]

The impedance \( Z_i' = \frac{V_i}{I} me^{j\Delta} \) is calculated from the RF voltage and current measured by the probes, and corrected for magnitude and phase errors using the correction factors \( m = 1.10 \) and \( \Delta = -11.95^\circ \). To summarize, the process for correctly measuring the plasma impedance at the fundamental frequency requires the following 5 steps.

1. Using voltage and current probes, measure the RF voltage \( V \) and current \( I \) at the fundamental frequency and calculate \( Z_b = \frac{V}{I} \).
(2) Determine magnitude and phase correction factors, \( m \) and \( \Delta \), by calibrating the voltage and current probes to a known reactive load. Then apply these correction factors to \( Z_b \) to determine the corrected impedance \( Z'_b = Z_b me^{j\Delta} \).

(3) Using Eq. 6.2, correct \( Z'_b \) for transmission line effects. This results in the corrected impedance \( Z \).

(4) Measure the intrinsic impedance \( Z_i \) of the empty plasma chamber at the fundamental frequency. Correct \( Z_i \) for transmission line effects using Eq. 6.2 by substituting \( Z_i \) for \( Z'_b \). This results in the corrected intrinsic impedance \( Z_i \).

(5) Calculate the plasma impedance \( Z_p \), with the known quantities \( Z \) and \( Z_i \), using Eq. 6.1.

It cannot be emphasized enough how important these 5 steps are for accurately determining the plasma impedance. With the exception of work done on GEC systems [11], to this author’s knowledge no one else has investigated the problems involved in measuring the plasma impedance of a RF plasma etch system with this level of detail.

6.2 Electron Attachment

It is evident from the data presented in the previous chapter that impedance transients appear under a variety of conditions. They are insensitive to the temperature of the powered electrode, the plasma chemistry, and, most interestingly, the presence of particles. They are not likely to be the result of electrical transients either. Unlike
many researchers who have attributed changes in the plasma impedance with the presence of particles [4, 6, 7, 8], there appears to be no evidence that particles are the cause of the impedance transients in Ar plasmas with a graphite particle source. In order to understand why impedance transients occur, one must investigate the behavior of the electron density \( n_e \) in the plasma.

Electrons in a plasma will interact with neutrals and ions in many ways. One such interaction is electron attachment. Electron attachment is a process which depletes \( n_e \), since the electrons are no longer free to conduct current. Attachment is most likely to occur in the presence of electro-negative gases, like \( \text{H}_2\text{O} \) [22], \( \text{SF}_6 \) [24], and \( \text{O}_2 \) [25].

A process similar to electron attachment will occur when particles are present in the plasma. Particles in the plasma will acquire a negative charge and deplete \( n_e \) [26]. Electron accumulation on particles has been the suggested cause of impedance changes in Ar plasmas [4, 6, 7, 8]. However from observations made using laser light scattering, relatively few particles were seen on the time scale of the impedance transients in this work. Thus it is highly unlikely that electron accumulation on particles is responsible for the impedance transients because of the relatively short time scales involved, and also on the basis that impedance transients are still present in clean plasmas.

However, electron dissociative collisions with \( \text{H}_2\text{O} \) can provide an explanation for the impedance transients. Electron attachment to atomic hydrogen will result from
the following reaction:

\[ e^- + H_2O \rightarrow OH + H^- \]  \hspace{1cm} (6.3)

This reaction is maximized for electron energies of 6.5 eV [22], which is a typical average energy for electrons in the RF discharges examined in this work. When this electron dissociative reaction occurs \( n_e \) is depleted as \( H^- \) is formed. Because the plasma cannot have a net charge, equal amounts of positive and negative charged species must exist in the plasma. Thus the following relation must hold:

\[ n_i^+ = n_e + n_i^- \]  \hspace{1cm} (6.4)

where \( n_i^+ \) is the density of positive ions, such as \( Ar^+ \), and \( n_i^- \) is the density of negative ions, such as \( H^- \). Previous research using the modified Tegal MCR-1 has shown that \( n_i^+ \) remains constant over time for Ar plasmas [26]. OES data taken for Ar and \( Ar^+ \) emission lines also suggests that \( n_i^+ \) remains constant in the plasma. The explanation for the impedance transients is based on the constancy of \( n_i^+ \), and the assumption that the density of \( H^- \) follows the same transient behavior as the \( H_2O \) RGA ion current shown in Fig. 5.13. Based on this assumption and according to Eq. 6.3, when the \( H_2O \) content of the plasma decreases, so too must the \( H^- \) content, and hence \( n_i^- \) must also decrease. However because \( n_i^+ \) is constant, as \( n_i^- \) decreases \( n_e \) must increase in order for the plasma to remain electrically neutral, according to Eq. 6.4. So at \( t=0 \), when the plasma is initiated, \( n_e \) is depleted because of electron attachment, then \( n_e \) begins to increase as \( n_i^- \) decreases, resulting in the observed impedance transients.
6.3 Impedance Transients

In previous chapters $Z_p$ was expressed in polar coordinates by a magnitude and phase angle. Expressed in rectangular coordinates, the plasma impedance is:

$$Z_p = R_p + jX_p$$  \hspace{1cm} (6.5)

where the relations between polar and rectangular coordinates are: $|Z_p| = \sqrt{R_p^2 + X_p^2}$ and $\theta = \tan^{-1} \left( \frac{X_p}{R_p} \right)$. The plasma resistance $R_p$ is due to ohmic heating of electrons in the plasma bulk ($R_{ohm}$), and stochastic heating of electrons in the plasma sheaths ($R_{stoc}$). These two resistances are in series [18] such that:

$$R_p = R_{ohm} + R_{stoc}$$  \hspace{1cm} (6.6)

The plasma reactance $X_p$ is due to the capacitance of the plasma sheaths. For a capacitive reactance:

$$X_p = -\frac{1}{\omega C_s}$$  \hspace{1cm} (6.7)

where $C_s$ is the sheath capacitance.

Work done by Lieberman [19, 27] has shown that $R_{ohm}$, $R_{stoc}$, and $C_s$ can all be expressed in terms of $n_e$. From [27] $R_{ohm}$ and $R_{stoc}$ can be expressed as:

$$R_{ohm} = \frac{m \nu_m d}{e^2 n_e}$$  \hspace{1cm} (6.8)

$$R_{stoc} = \frac{m \bar{\nu}_e}{e^2 n_e}$$  \hspace{1cm} (6.9)

where $m = m_e$ is the electron mass, $\nu_m$ is the electron-neutral collision frequency, $d$ is the length of the bulk plasma region, $e$ is the charge on an electron, and $\bar{\nu}_e$ is the
average electron velocity. From Eqs. 6.8 and 6.9 it is evident that as \( n_e \) increases
\[ R_p = R_{ohm} + R_{stoc} \]
will decrease, leading to the resistive transient. An approximate expression for \( C_s \) from [19] is given by:
\[
C_s \approx \frac{1.226\varepsilon_o A}{s_m}
\]  
(6.10)

In this expression, \( \varepsilon_o \) is the permittivity of free space, \( A \) is the electrode surface area, and \( s_m \) is the ion sheath thickness, which is given by:
\[
s_m = \frac{5}{12} \left( \frac{J_1^3}{e^2\varepsilon_o T_e n_s^3} \right)
\]  
(6.11)

The ion sheath thickness depends upon a number of factors including: \( J_1 \) the measured RF current density, \( T_e \) the electron temperature (which is a measure of the electron's kinetic energy), and \( n_s \) the positive ion density at the plasma-sheath interface. Because of the negative self-bias acquired by the electrodes in an RF discharge, negative ions will be repelled from the sheaths. Since the net charge of the plasma must be zero, \( n_e \approx n_s \) at the plasma-sheath interface. Using this approximation and combining the expressions in Eqs. 6.7, 6.10, and 6.11 the plasma reactance becomes:
\[
X_p = \frac{-5}{12} \left( \frac{J_1^3}{1.226e^2\varepsilon_o T_e A n_e^2} \right)
\]  
(6.12)

Figure 5.4 in the previous chapter has shown that the RF peak-to-peak current (which is proportional to \( J_1 \)) remains essentially constant, therefore changes in \( J_1 \) are not responsible for changes in \( X_p \). From Eq. 6.12 the source of the reactance transient becomes apparent; as \( n_e \) increases the plasma reactance will decrease. Furthermore, since \( X_p \sim \frac{1}{n_e^2} \), the reactance transient should be larger than the resistive transient,
for which $R_p \sim \frac{1}{n_e}$. This was confirmed in the previous chapter by the many plots of resistance and reactance versus time, which all show a reactive transient that is larger than the resistive transient.

To summarize, impedance transients are probably due to increasing $n_e$, which would lead to decreasing $R_p$ and $X_p$ as seen from Eqs. 6.8, 6.9, and 6.12. Qualitatively, an increase in $n_e$ could be due to a decrease in the electro-negative molecule $H_2O$, as seen in Fig. 5.13, which subsequently leads to a decrease in $H^-$, according to the reaction given in Eq. 6.3. The electron density must increase as $H^-$ decreases if the plasma is to remain electrically neutral.

6.4 Suggestions for Future Work

Electrical characterization of the modified Tegal MCR-1 has enabled accurate measurement of the plasma impedance at 13.56 MHz. Impedance transients are just beginning to be investigated in detail. The next most important step in order to quantify the effects of $H_2O$ on the impedance transients is controlling the leak rate of the plasma chamber. This could be accomplished using high precision mass flow controllers, or a precise needle valve to introduce a controlled leak of air into the chamber. Experiments could then be performed to test the effect different air flows (and thus different $H_2O$ concentrations) have on the impedance transients. Currently, the flow of air into the plasma chamber is due to unintentional leaks in the o-ring
seals. The air flow is relatively constant, since the chamber base pressure does not vary much from experiment to experiment.

Another interesting, but perhaps more difficult experiment would involve measuring $n_e$ as a function of time using a Langmuir probe. If electron attachment is indeed responsible for the impedance transients, observing a change in $n_e$ would help confirm this quantitatively.

Finally, the effect of different system parameters on the impedance transients should be investigated. This should include such parameters as: RF power, gas mixtures, gas pressure, and gas flow. A factorial experiment involving the controlled variation of these system parameters may provide better insight into the mechanisms causing the impedance transients.
CHAPTER 7

Conclusion

This work has focused on electrical characterization and plasma impedance measurements of a single-wafer RF plasma etch system. All measurements and characterization were carried out at the fundamental frequency of 13.56 MHz. In calculating the plasma impedance from the measured RF voltage and current, transmission line effects were taken into account using the standard transmission line equation. The measurement probes were calibrated to the empty plasma chamber to correct for magnitude and phase errors. An LC equivalent circuit model for the empty plasma chamber was developed. This LC circuit is in shunt with the plasma impedance, and is accounted for when calculating the $Z_p$. All these corrections are necessary in order to accurately measure the plasma impedance.

Transients in the plasma impedance are observed during the first 5 minutes after the plasma is initiated. Impedance transients are observed under a variety of conditions, including: clean and dusty Ar plasmas, Ar/SF$_6$ plasmas, and for various electrode geometries and temperatures. The repeatability of these transients have been demonstrated. Water vapor and its atomic and molecular consituents, O and OH, have been observed in Ar plasmas using OES and RGA. Data from the
RGA system indicates that the H$_2$O ion current follows the same repeatable transient the impedance follows, and on approximately the same timescale. The impedance transients are thought to arise from electron attachment resulting from the reaction: \( e^- + H_2O \rightarrow OH + H^- \). Because the positive ion density remains constant, and assuming the H$^-$ concentration follows the same transient as the H$_2$O, then it becomes apparent that a decrease in H$^-$ must be accompanied by an equal increase in the electron density in order for the plasma to remain electrically neutral. It has been shown that the plasma resistance and reactance behave as: \( R_p \sim \frac{1}{n_e} \) and \( X_p \sim \frac{1}{n_e^2} \), and because of this impedance transients will occur as \( n_e \) increases over time. Although these results are based in part on speculation, it seems apparent that this impedance transient phenomena is not an artifact of the plasma system, but rather an effect that may be present in many plasma systems under similar conditions. If this is indeed true, impedance transients should be of considerable interest to the semiconductor manufacturing industry, since the impedance transients represent changes in fundamental plasma parameters occurring over a time period comparable to etch times used in industrial processes.
Appendix A

Data Acquisition Routine

Included here is the source code for the C program acquire.c which acquires the digitized voltage and current waveforms from the digital oscilloscope, and then saves this information to files on the computer's hard disk drive.

acquire.c

/* THIS PROGRAM SAVES A 2000 POINT DIGITIZED WAVEFORM */
/* FROM CHANNELS ONE & TWO OF THE HP54601A DIGITAL */
/* OSCILLOSCOPE TO SEPARATE ASCII DATA FILES. THE */
/* SCOPE TRIGGERS OFF CHANNEL TWO. SYSTEM IS FIRST */
/* AUTOSCALED AND THEN THE TIMEBASE IS SET FOR */
/* 500NS/DIV. */

#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include "decl.h"

char buffer1[9000]; /* channel 1 data buffer */
char buffer2[7500]; /* channel 2 data buffer */
char file1[50]; /* data filename variables */
char file2[50];
char s1[]="c0219"; /* current basename */
char s2[]="v0219"; /* voltage basename */
char index[50]; /* file index */

/* NOTE: BUFFER SIZE IN BITS NEEDS TO BE APPROXIMATELY*/
/*3.6X(TOTAL NUMBER OF DATA POINTS) OR LARGER. */

FILE *fp1;  /* file pointer channel 1 */
FILE *fp2;  /* file pointer channel 2 */

int hp=1;    /* HP Scope's GPIB address is 1*/
int gpib=0;  /* GPIB board address is 0 */
int m, i, j, l, k=1;  /* loop counters, etc. */

void main() {

    system("cls");  /* clears the computer screen */

    /* iteration loop; 41 iterations=20 minutes */
    for (i=1; i<=41; ++i) {

        strcpy(file1, s1);
        strcpy(file2, s2);
        SendIFC(gpib);  /* gives GPIB control of the bus*/

        /*Send is used to send device commands to the HP Scope*/

        DevClear(gpib, hp);  /* clear the HP Scope */
        Send(gpib, hp, ":autoscale", 10L, NLend);
        Send(gpib, hp, ":timebase:range 5000 ns", 23L, NLend);
        Send(gpib, hp, ":acquire:type normal", 20L, NLend);
        Send(gpib, hp, ":acquire:complete 100", 21L, NLend);
        Send(gpib, hp, ":waveform:source channel1", 25L, NLend);
        Send(gpib, hp, ":waveform:format ascii", 22L, NLend);
        Send(gpib, hp, ":waveform:points 2000", 21L, NLend);
        Send(gpib, hp, ":digitize channel1, channel2", 28L, NLend);

        /* Acquire waveform preamble and data from channel 1 and store*/
        /* in a data file sli, where s1 is the filename and i is the */
        /* loop index. */

        Send(gpib, hp, ":waveform:preamble?;data?", 25L, NLend);
        Receive(gpib, hp, buffer1, 9000L, STOPend);
        sprintf(index, "%d", i);
strcat(file1, index);
fp1=fopen(file1, "w");
for(m=0; m<=9000; m=m+1) {
    if(buffer1[m]==',' || buffer1[m]==';')
        fputc('
', fp1);
    else
        fputc(buffer1[m], fp1);
}
fclose(fp1);
printf("Data from channel 1 saved to file: \\

","file1);

/*Acquire waveform & preamble data from channel 2 and store*/
/*in a data file s2i, where s2 is the filename and i is the */
/*loop index.*/

SendIFC(gpib);
DevClear(gpib, hp);
Send(gpib, hp, ":acquire:type normal", 20L, NLend);
Send(gpib, hp, ":acquire:complete 100", 21L, NLend);
Send(gpib, hp, ":waveform:source channel2", 25L, NLend);
Send(gpib, hp, ":waveform:format ascii", 22L, NLend);
Send(gpib, hp, ":waveform:points 2000", 21L, NLend);
Send(gpib, hp, ":waveform:preamble?;data?", 25L, NLend);
Receive(gpib, hp, buffer2, 7500L, STOPend);
strcat(file2, index);
fp2=fopen(file2, "w");
for(m=0; m<=7500; m=m+1) {
    if(buffer2[m]==',' || buffer2[m]==';')
        fputc('
', fp2);
    else
        fputc(buffer2[m], fp2);
}
fclose(fp2);
printf("\nData from channel 2 saved to file: \\

","file2);
/* 10 second delay loop. */

for(j=0; j<=175; ++j) {
    l=0;
    while(l<10000)
        ++l;
}

/* 50 second delay loop. Acquire data once every 10s for the first*/
/* 25 iterations, and then once every minute (10s+50s) for*/
/* iterations 26-41. */

if(i>=25) {
    for(j=0; j<=4550; ++j) {
        l=0;
        while(l<10000)
            ++l;
    }
}

}
Appendix B

Plasma Impedance Routine

Included here are the Matlab® routines, convert.m and imp.m, used for calculating the plasma impedance. The convert.m routine converts the ASCII voltage and current data into their corresponding voltage and current values, based on the oscilloscope settings used when the data was digitized. The imp.m routine calculates the plasma impedance using the converted voltage and current waveform data from convert.m.

convert.m

% This routine converts ASCII characters taken from an HP54601A digital oscilloscope into their corresponding voltage values using information taken from the preamble, vector 'P', of the ASCII data file. Data is read from a vector 'A' and the converted data is saved in the vector 'B'. A time vector is generated and saved in the vector 't'.

%Preamble information
xinc=P(5);
xorg=P(6);
xref=P(7);
yinc=P(8);
yorg=P(9);
yref=P(10);
B=0;

for m=1:length(A),
    B(m)=((A(m)-yref).*yinc)+yorg;
    t(m)=((m-xref).*xinc)+xorg;
end

% This routine calculates the resistive and
% reactive components of a complex impedance
% at 13.6MHz and saves this data to two separate
% files: 'resistance' and 'reactance'. First
% the magnitude (Z) and phase angle (a) of the
% complex impedance are calculated. This data is
% then corrected, taking into account transmission
% line effects phase and magnitude errors in the
% measurement probes, and the intrinsic impedance
% of the plasma chamber.

B=20.*B; % 0.1 A/V probe, x2 for 50 ohm load
C=100.*C; % 100:1 voltage probe
n=1999;   % number of data points
div=500e-9; % time base on the oscilloscope
            % during data acq. in seconds
Fs=n/(div*10); % Sampling freq.
Fn=Fs/2; % Nyquist freq.
Y=(fft(B)); % A DFT of data B (current), C (voltage).
X=(fft(C));
Y=Y(1:n/2); % Use half of the pts. since DFT is symmetric
X=X(1:n/2);
amps=(2.*abs(Y))./(n/2); % Current & Voltage magnitudes
        % x2 since we used half the DFT pts.
volts=(2.*abs(X))./(n/2);

f=(0:((n/2)-1))/(n/2); % Set up freq. scale
f=f*Fn;
c=3e8; % speed of light m/s
e=2.26; % dielectric permittivity
L=1.27; % length of cable, meters
Zo=52; % characteristic impedance, ohms

% elect. length of cable in radians
el=((2*pi*f(69))*sqrt(e)*L)/c;

% mag. of impedance, w/ correction factor: 1.10
Z=(volts./amps).*1.10;

% phase angle of voltage with respect
% to the current, w/ correction factor:
% -11.95 degrees=-0.2085 radians.
% ar(angle(X)-angle(Y)-0.2085);

% impedance measured by the probes
Zb=Z.*(cos(a)+j.*sin(a));

% transmission line eqn. =Num/Den
Num=(Zb.*cos(el)-j*Zo*sin(el));
Den=(Zo*cos(el)-j.*Zb.*sin(el));

% impedance at chamber input
Zi=Zo.*(Num./Den);

Zc=6-j*97; % intrinsic chamber impedance

% Plasma impedance at 13.6MHz
Zp=(Zc*Zi(69))/(Zc-Zi(69));

R=real(Zp); % resistive component of Zi
I=imag(Zp); % reactive component of Zi

% open and write to file 'resistance'
% fid=fopen('resistance','at');
% fprintf('resistance', 'f\n', R);

% open and write to file 'reactance'
% fid=fopen('reactance','at');
% fprintf('reactance', 'f\n', I);
REFERENCES


