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Measurements of time varying plasma potential, temperature, and density in a 13.56 MHz radio-frequency discharge

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Argon plasma measurements were conducted in a commercial capacitively coupled etcher operating at 400 mTorr with 60-W coupled power at 13.56 MHz. Time varying floating potential was measured using a capacitively coupled probe which uses a capacitive voltage divider and a field effect transistor buffer amplifier. Average floating potential was obtained from a high-input-impedance Langmuir probe. The floating potential was found to be sinusoidal, \(21 \sin(\omega t) - 4 V \pm 1.5 V\), with a maximum of 17 \(\pm 1.5 V\) and a minimum of \(-25 \pm 1.5 V\). From these data and the use of a low-input-impedance Langmuir probe, a calibrated instantaneous \(I-V\) characteristic is used to obtain plasma potential and electron temperature. Plasma potential was found to be sinusoidal, \(21 \sin(\omega t) + 30 V \pm 1.6 V\), with a maximum of 51 \(\pm 1.6 V\) and a minimum of 9 \(\pm 1.6 V\). Electron temperatures were 6.58 \(\pm 0.19\) eV at maximum plasma potential and 6.49 \(\pm 0.19\) eV at minimum plasma potential. The electron density for this experiment was determined to be \(1.48 \pm 0.83 \times 10^{10}\) electrons/cm\(^3\).

I. INTRODUCTION

In this research the time varying plasma potential, electron temperature, and density in a rf discharge device were determined. These quantities are essential to the understanding of the process plasma. Accurate indication of temperature can lead to a better understanding of electron energy distribution and impact ionization reaction rate constants. Accurate indication of the plasma potential can lead to a better characterization of ion energies incident on the electrodes or substrates.

The current versus voltage \((I-V)\) characteristics of a Langmuir probe have proven to be a useful and practical plasma diagnostic technique. \(^1\,^8\) Popular Langmuir probe techniques include measuring \(I-V\) characteristics on a time scale which is short in comparison with the rf period, \(^5\,^7\,^8\) time averaged \(I-V\) characteristics, \(^4\) and double-probe methods. \(^5\,^7\,^8\) Another novel idea involves using a single Langmuir probe that simultaneously measures instantaneous current and floating potential to obtain a single instantaneous \(I-V\) characteristic. \(^12\) Effects of rf on the characteristic of a Langmuir probe has been considered by others. \(^5\,^9\,^11\) Other methods for measuring plasma potential in rf plasmas include the use of high-impedance capacitive voltage divider probes, \(^15\,^16\) and emissive probes. \(^10\,^11\) A recent comparison of measurements of plasma potential using collecting and emitting probes has been conducted. \(^22\) Also a comparison of various Langmuir probe techniques has recently been addressed by Chen. \(^12\) Our method of measurement involves a combination of a two shielded Langmuir probes and a capacitive probe.

II. THEORY

General probe theory \(^4\) uses a number of assumptions: the plasma is a homogeneous and quasineutral composition of electrons, and singly charged positive ions of the background gas; the electrons and ions possess Maxwellian velocity distributions with characteristic temperatures \(T_e\) and \(T_i\), respectively, with \(T_i \gg T_e\); the interaction mean free paths are large compared with both the probe dimension \(R_p\) and the plasma Debye shielding length \(\lambda_D\) (i.e., low-pressure, collisionless sheath approximation); electrons and ions which hit the probe surface are absorbed; well-defined space-charge sheaths surround the probe surface; and the probe does not perturb the plasma.

In order to more accurately reflect plasma behavior in this experiment, some of these assumptions need to be examined. To truly define an electron temperature a Maxwellian distribution must be assumed. But the electron energy distribution may deviate measurably from a Maxwellian. Therefore the electron temperatures obtained here are merely some measure of the mean electron energy. Another assumption is the "well-defined thin sheath formation." In general, the size of the sheath is voltage dependent, and especially for ion collection the sheath cannot be regarded as "thin." Hence the Bohm sheath criterion is incorporated to account for presheath effects \(^12\) and to provide a better estimate of ion saturation.

For the gas pressure used, 400 mTorr, the mean free path for interaction, \(\sim 0.39\) mm, is on the order of the probe characteristic dimension of \(0.19\) mm. Therefore to correct for moderate collisional effects in intermediate pressure discharges when determining the electron density from ion saturation, a scaling parameter based on the ratio \(R_p/\lambda_D\) should be used. \(^24\) When ion collection is not orbital motion limited, but is affected by presheath acceleration and assuming a collisionless sheath, a modified expression for ion saturation current can be obtained:

\[
I_{sat} = \left( eN_eA_p/4 \right) sqrt \left[ \left( 8kT_e/\pi M_i \right) \right] j_f^p,
\]

where \(j_f^p\) is a dimensionless ion current scale factor.

The dimensionless scale factor \(j_f^p\), takes into account the changing size of the ion sheath/presheath as probe voltage with respect to the reference electrode changes. The Laframboise results \(^25\) were employed, where, for large values of
$R_p/I_d$ represents the near sheath limited form of ion collection. When $R_p/I_d$ is zero, $f_p$ represents the orbital motion limited form of ion collection at the probe. The Laframboise technique is a numerical analysis based upon a Maxwellian electron energy distribution and assumes a collisionless limited form of ion collection at the probe. The Laframboise technique sheath. Notice also that Eq. (1) incorporates the Bohm criterion.

Figure 1 shows a typical $I-V$ characteristic curve for a dc discharge. When a probe is connected to a measuring resistor, the operating point of the circuit is given by the intersection of a load line with the $I-V$ characteristic. The load lines in Fig. 1 (a) have negative slope since electron current is defined as positive. For accurate current measurements the load resistor $R$ must be very small to establish a vertical load line. For accurate $V_f$ measurements $R$ must be very large to establish a horizontal load line. The actual current $I_A$ and measured current $I_m$ are shown in Fig. 1. Similarly, the actual floating potential $V_f$ versus measured $V_f'$ is also shown in Fig. 1.

For rf plasmas, the $I-V$ characteristic is sensitive to plasma sheath impedance and the probe circuits impedance to ground. The load line is a function of the probe circuits input impedance. For current measurements, $R$ should be much less than the characteristic impedance of the plasma sheath during the ion saturation region, and for $V_f$ measurements, $R$ should be much larger than the characteristic impedance of the plasma sheath at $V_f$. However, when high-frequency rf is present, stray capacitance to ground normally results in an ac impedance to ground which can be much smaller than the circuit input impedance. Therefore, when measuring fluctuations in $V_f$, the frequency response of the circuit is limited. To overcome this problem a capacitive probe was used to measure time varying $V_f$, rather than the standard capacitive neutralization technique. A high-input-impedance Langmuir probe was then used to obtain a dc reference to $V_f$, since the $V_f$ dc offset is not time-response limited by stray cable capacitance.

For 13.56-MHz discharges, plasma potential $V_p$ is generally thought to vary sinusoidally with some amplitude $V_{rf}$. Instantaneous current will fluctuate because $V_p$ is fluctuating. Thus the probe $I-V$ characteristic will shift back and forth along the $V$ axis' as shown in Fig. 2(a). The left-hand portion of this figure is the instantaneous $I-V$ characteristic when the plasma is at its minimum plasma potential $(V_p)_\text{min}$, and the right-hand portion is instantaneous $I-V$ at maximum plasma potential $(V_p)_\text{max}$. The actual $I-V$ characteristic sweeps back and forth between the two indicated extremes. The average $I-V$ of the two extremes is also shown in Fig. 2(a). Since the $I-V$ characteristic is nonlinear, the average current will not be the same as the instantaneous current at any given voltage $V$. Therefore, basing calculations on average probe current could lead to an erroneous indication of plasma parameters in some cases.

The instantaneous $I-V$ curve shown in Fig. 2(a) is derived from the instantaneous scope current trace shown on Fig. 2(b). Points $I_A$ and $I_m$ correspond to instantaneous current at minimum and maximum plasma potential for a specified probe bias. As probe bias is varied the instantaneous $I-V$ curve is mapped out.

### III. EXPERIMENTAL

Figure 3 shows the experimental arrangement used for this paper. A major component is the Davis and Wilder model 425 parallel-plate plasma etcher. This system consists of cylindrical process chamber, roughing pump, blower, motorized flow control valve, and water-cooled parallel plates that were ~70.1 cm in diameter and spaced 4 cm apart. The top plate was the powered electrode and the bottom the grounded electrode, which was electrically connected to the chamber chassis. A glass plate lies above the top electrode and radially along the inside cylindrical wall. Probe access was through three radial ports located approximately mid-plane between the two electrodes. Pressure was maintained within the chamber at 400 ± 5 mTorr as indicated by a Baratron gauge.

A Tegal 300-W 13.56-MHz generator supplied power through an associated Tegal matching network. The 13.56-MHz signal was generated within a 120-Hz sawtooth ramp. This was a peculiar characteristic of the power supply and care was taken to perform all measurements at the same...
Fig. 3. Experimental arrangement. All grounds are single point connected to the steel rod.

Point during this ramp cycle. Power was monitored by a Bird rf directional Thruline wattmeter, model 4342. The voltage waveform at the powered electrode was monitored through a capacitively coupled Bird waveform sampler and measured on a Tektronics model 475 oscilloscope. A blocking capacitor was located between the waveform sampler and the powered electrode. The dc offset bias between the powered electrode and ground was measured by a digital Fluke multimeter. Measurements of plasma parameters were taken within a double-shielded copper-screen room (Faraday cage). The power supply, rf matching network, grounded electrode, etcher chamber, cable shielding, screen room, and measurements were all referenced to a single-point ground system, which was a single 8-ft steel rod driven into the ground near the etching chamber. The grounding system greatly reduced the measurement signal noise interference associated with rf radiation. The power from the wall outlets into the screen room was passed through a low-pass filter.

Three types of probe arrangements were used to obtain plasma parameter data. A capacitive probe measured time varying floating potential, a high-input-impedance Langmuir probe obtained a reference to the time varying floating potential, and a low-input-impedance Langmuir probe measured instantaneous time varying current.

Figure 4(a) shows the capacitive probe construction and circuit schematic. This probe, when inserted within the plasma, behaves like a coaxial capacitor that tracks variations in $V_f$ without significantly loading the plasma.\textsuperscript{15} The probe consisted of a coaxial cable within a ceramic tubing having its extended center conductor capped with ceramic cement. A capacitive voltage divider network is formed by the probes tip capacitance and circuit capacitance from which the input signal is fed through a high input impedance field effect transistor (FET) buffer, and a NPN-transistor amplifier and delivered to a 50-Ω load. The effect of stray capacitance is minimized by locating the probe circuitry close to the probe tip. The measurement of time varying plasma potential is taken within a shielded room. This probe, its circuitry, associated power supply, and cabling were calibrated at 13.56 MHz.

The Langmuir probe construction is shown in Fig. 4(b). This probe consisted of a coaxial cable running the full length of the probe and terminated with a 15-mil tungsten tip. The coaxial cable is sleeved within a ceramic-coated stainless-steel tube which is welded to a $\frac{3}{4}$-in.-o.d. tube to match the probe port. The low input impedance probe had a 50-Ω load and the high input impedance used a 1M-Ω load. The bias for the low input impedance probe varied from $-50$ to $+56$ V. The probe, power supply, and cabling were calibrated at 13.56 MHz.

IV. RESULTS

An argon rf discharge was maintained at $400 \pm 5$ mTorr. Power to the plasma discharge was maintained at 100 W forward and 40 W reverse. The voltage to the powered electrode was $72 \pm 1$ V p-p with a dc offset of $-2 \pm 0.5$ V. From the calibrated capacitive probe measurement a time varying floating potential of $42.1 \pm 1.6$ V was obtained. Its waveform was sinusoidal and not affected by variations in bias potential. The dc reference was determined to be $-4 \pm 0.7$ V dc. In general $V_f = [21.05 \sin(\omega t) - 4] V \pm 1.5$ V.

Plasma potential was graphically determined from the
$I-V$ characteristic curve at a bias of $34 \pm 0.5$ V. By adding this voltage to the floating potential variation, the plasma potential was found to vary from a maximum of $51 \pm 1.6$ V to a minimum of $9 \pm 1.6$ V. In general the plasma potential can be characterized as $[21.05 \sin(\omega t) + 30]V \pm 1.6$ V. These measurements correspond to plasma potential variation at the midplane region between the two parallel plates. Figure 5 shows these results on a plot of a theoretical cross-sectional plasma variation between two parallel plates.

The $I-V$ curve was obtained from the low-input-impedance Langmuir probe. Depending upon the bias potential applied, a sinusoidal or sinusoidal-like waveform was traced on the oscilloscope. These results are shown in Fig. 6(a) without modification for time varying floating potential. Each curve corresponds to instantaneous total probe collection current as bias potential was varied from $-50$ to $+56$ V dc. The upper curve corresponds to plasma conditions at minimum plasma potential and the lower to maximum plasma potential.

From this plot it appears that plasma potential is reached when the bias is at $34$ V, since at this point there is clear indication of a discontinuity from an exponential region to a diverging linearlike region. Also note, since these data are uncalibrated with respect to measured floating potential, the left hand curve never goes below $0$. By definition at $V_f$ electron current and ion current are equal, i.e., total probe current is zero. Therefore an independent measurement of $V_f$ (the capacitive probe) is used to reference the $I-V$ characteristic curve. By adjusting total probe current to correspond to $(V_f)_{\text{min}} = -25.05 \pm 1.5$ V when plasma potential is at $(V_p)_{\text{min}}$ and to $(V_f)_{\text{max}} = 17.05 \pm 1.5$ V, when plasma potential is at $(V_p)_{\text{max}}$, the calibrated total probe current versus $(V_b + V_f)$ is obtained. From the above calibration procedure ion saturation current was determined to be $-23 \pm 11.6 \mu A$. The electron current is derived from the calibrated total probe current.

Electron current was obtained by subtracting out an esti-

![Figure 5: Theoretical cross-sectional plasma potential distribution between powered and grounded electrode showing measured values of $V_p$ and $V_r$ at maximum and minimum plasma potential at device midplane. $V_p = [21 \sin(\omega t) + 30]V \pm 1.5$ V, $V_r = [37.5 \sin(\omega t) - 2]V \pm 1.0$ V.](image1)

![Figure 6: (a) Unreferenced instantaneous total probe current vs $V_f$. Errors range from 25% for the low current values to 1% for high values of current. (b) Instantaneous and calculated average electron current vs $(V_b + V_f)$. (c) Log of instantaneous and calculated average electron current vs $(V_b + V_f)$. The slope of the line drawn through $\ln(I_e)$ at $(V_p)_{\text{min}}$ and $(V_p)_{\text{max}}$ in the exponential region is $T_e$ at the $V_p$ extrema. $T_e$ at $(V_p)_{\text{max}} = 6.49 \pm 0.19$ eV, $T_e$ at $(V_p)_{\text{min}} = 6.85 \pm 0.19$ eV, $T_{\text{ave}} = 6.46 \pm 0.24$ eV.](image2)
mation of ion current from the total probe current data. An analysis determining the ion current component and its effects on calculating $I_e$ and $\ln(I_e)$ has been conducted.\textsuperscript{24} A combination of the constant subtraction method and linear subtraction method was chosen for this work. The constant selected was the ion saturation value of $-23 \mu A$. The linear approximation was chosen from $V_{sat}$ to $V_p$ were $I_e = I_{sat}$ at $V_{sat}$, and $I_e = 0$ at $V_p$. Figure 6(b) is a plot of electron current, $(I_e)VS(V_p)$ at $V_p + V_f$. The left-hand side of each plot was instantaneous current at $(V_p)$max occurring at 9 ± 1.6 V, and the right-hand side is instantaneous current at $(V_p)$min = 51 ± 1.6 V. The calculated averages of $I_e$ and $\ln(I_e)$ between the two extremes of $(V_p)$min and $(V_p)$max are also shown in Fig. 6(a) and 6(b), respectively. Because each current data point, corresponding to a particular voltage for instantaneous current at $(V_p)$min, is not the same voltage for a current data point at $(V_p)$max, a linear approximation was used to acquire corresponding data points. From this expansion of data points an average current was derived. In this case the respective average plots closely approximate the shapes of the instantaneous curve for $(V_p)$min. This is because of the large spread along the $V$ axis between the instantaneous $I-V$ for $(V_p)$min and $(V_p)$max. Therefore, in this case the electron temperature obtained from the average $I-V$ trace is the same as that obtained from the instantaneous $I-V$ trace. However, if $(V_p)$max $-$ $(V_p)$min were smaller, the average $I-V$ trace would not provide an accurate determination of plasma parameters. The $V_p$ for the average $I-V$ curve is not equal to $[(V_p)$min $+$ $(V_p)$max]/2. To obtain average plasma potential the instantaneous plot of $I-V$ is required.

The electron temperatures obtained by linear regression analysis were $T_e$ at $(V_p)$min = 6.49 ± 0.19 eV, $T_e$ at $(V_p)$max = 6.58 ± 0.19 eV, and $T_{e,ave}$ = 6.46 ± 0.24 eV. Note that the electron temperature is the same at the plasma potential extrema.

The results from the Laframboise iteration method\textsuperscript{25} and Eq. (1) were used to calculate $N_e$. In this case $\beta = 2.9$ to obtain a density of $1.48 \pm 0.83 \times 10^{19}$ electrons/cm$^3$. $R_e/d$ and $l_{min}/l_p$ were determined to be 1.2 and 2.0, respectively. This implies that these measurements occurred in the conventional Langmuir probe and near orbital motion limited regime.\textsuperscript{24}

V. SUMMARY

Three probes were used to obtain plasma parameters for an argon plasma excited at 60-W coupled power at 13.56 MHz. Because of wide spread between $(V_p)$min and $(V_p)$max the average $I-V$ characteristic closely follows instantaneous $I-V$ at $(V_p)$min. Therefore, average $T_e$ equals instantaneous $T_e$ at plasma potential extrema. Plasma potential from the average $I-V$ curve is not the average of the plasma potential extrema. $V_p = [21 \sin (wt) + 30] \pm 1.6 V$ at the chamber midplane. An independent method of measuring $V_p$ is required to reference the $I-V$ characteristic. $V_p = [21 \sin (wt) - 4] \pm 1.5 V$. A consistency check for $V_p - V_f$ was obtained from\textsuperscript{5}

\[ V_p - V_f = \left( kT_e/2e \right) \{ \ln \left[ \left( 1/2\pi X^2 \right) \left( M_e/M_i \right) \right] \}, \]

where $X$ is a function of $T_e/T_i$, usually $= 0.6$, using $X = 0.575$ for $T_e/T_i = 0.004$, and $T_e = 6.5 \pm 0.3$ eV.

$V_p - V_f = 34 \pm 1.6 V$.

This falls within the measured value of 34 ± 0.5 V.

Future work will be conducted to determine variation in plasma potential throughout the device cross section, and $T_e$ and $N_e$ at the plasma potential null.

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