OFF-AXIS MEASUREMENTS OF ION KINETIC ENERGIES IN RF PLASMAS

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Introduction

In a plasma etching reactor, etching anisotropy and yield are often a function of ion bombardment energy and flux. This has motivated efforts to develop mass spectrometry and ion kinetic-energy analysis as diagnostics for monitoring rf discharges used for plasma processing [1]. Recent measurements [2-4], utilizing retarding potential analyzers mounted on grounded rf electrodes, indicate the existence of rich structure in ion kinetic-energy distributions for certain plasma systems. This structure is related to the chemistry which can occur as ions are accelerated by the oscillating electric fields present in the plasma sheath.

For argon discharges, Wild and Koidl [2] have demonstrated that ion-energy distributions exhibit pronounced peaks, and have been able to predict this structure using Monte Carlo simulations which assume a constant cross section for symmetric charge transfer in the sheath. Liu *et al.* [3] have shown that momentum transfer scattering in the sheath is essential to produce significant ion impact angles. More recently, Toups and Ernie [4] have determined that the ratio of the frequency of the applied rf potential and the reactor gas pressure is a critical parameter in determining the shape of the distribution.

In the present work a cylindrical ion-energy selector coupled to a quadrapole mass spectrometer is utilized to measure ion kinetic-energy distributions as a function of various discharge parameters in an argon plasma. The analyzer is oriented such that the sampling orifice is located on a plane equidistant between the two faces of the electrodes, and thus ions are sampled from the side of the plasma instead of through the grounded electrode. This allows ion energy distributions to be measured at varying distances from the bulk plasma. Ion-energy distributions obtained in this geometry are compared with previous measurements made through the grounded electrode. All results presented here were obtained using a GEC rf Reference Cell [5].

Experiment

The GEC rf Reference Cell electrode configuration is symmetric with two 4-inch diameter aluminum electrodes with 1-inch interelectrode spacing. RF power (13.56 MHz) is capacitively coupled to the upper electrode while the lower electrode is grounded. All experiments were performed using 99.999% argon at a pressure of 100 mtorr and a flow rate of 20 sccm.

The ion-energy analyzer is a VG SXP300-CMA† which consists of cylindrical mirror ion-energy analyzer [6] coupled to a 300 amu quadrapole mass spectrometer. Ions are sampled via a 200 micron aperture through a grounded stainless steel cone into the differentially pumped region of the analyzer. The orientation of the analyzer and sampling orifice with respect to the cell electrodes is shown in Figure 1. The ion-energy analyzer and mass spectrometer may be moved by means of a bellows assembly such that the distance from the sampling orifice to the edge of the electrode assembly may be varied from 0 to 10 cm.

†The identification of commercial materials and their sources is made to describe the experiment adequately. In no case does this identification imply recommendation by the National Institute of Standards and Technology, nor does it imply that the instrument is the best available.

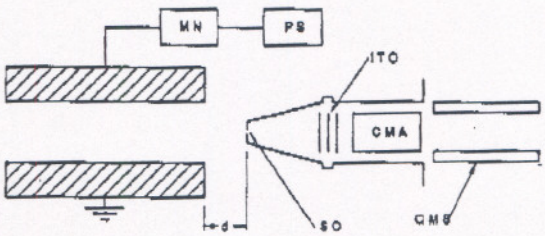

Figure 1. Schematic diagram showing the orientation of the ion-energy analyzer and mass spectrometer with respect to the GEC rf Reference Cell electrodes. The distance from the edge of the electrode assembly to the aperture is d, SO is the 200 micron sampling orifice, ITO are the ion transfer optics, CMA is the cylindrical mirror ion-energy analyzer, QMS is the quadrapole mass spectrometer, PS is the rf power supply, and MN is the matching network.

Ion-energy distributions were obtained by tuning the mass spectrometer to the ion mass of interest and then scanning the energy of the ions entering the energy analyzer. Several energy scans were averaged and then stored in a computer for analysis. Simultaneous measurements of discharge voltage and current waveforms were also obtained using voltage and current probes located on the powered electrode. Amplitudes and relative phases of the harmonics were then determined for each of these waveforms and were used to help characterize the plasma.

Results and Discussion

Shown in Figure 2 are ion kinetic energy distributions for Ar^+ as a function of probe position (d) for an applied peak-to-peak voltage (V_{pp}) of 200 volts. The distributions each exhibit a bimodal

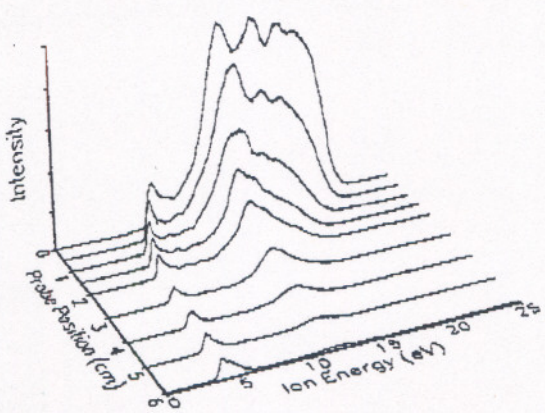

Figure 2. Ar^+ kinetic energy distributions as a function of distance of the aperture from the edge of the electrode assembly for a 200 V_{pp}, 100 mtorr argon plasma. All intensities are on the same arbitrary relative scale.

Table 1. Amplitudes of current and voltage harmonics and bias voltages (V_b) as a function of ion-energy probe position (d).

	Current (amps)				Voltage (volts)			
d	I_1	I_2	I_3	I_4	V_1	V_2	V_3	V_b
0 cm	0.22	0.05	0.21	0.03	96.4	1.9	0.6	−53.6
2 cm	0.22	0.05	0.21	0.03	96.0	1.6	0.6	−83.4
4 cm	0.22	0.05	0.21	0.03	97.8	1.8	0.6	−85.1
6 cm	0.22	0.05	0.21	0.03	98.0	1.5	0.5	−85.5

structure with a small peak at low energies and a peak of varying intensity at higher energies. A cut-off point is observed at low energies below which no ion intensity is observed. Table 1 indicates that the voltage and current waveforms as measured at the powered electrode are not significantly affected by the position of the ion-energy probe, despite the fact that the probe visibly perturbs the plasma as the probe is moved closer to the electrodes ($d \rightarrow 0$).

As d decreases a sheath develops around the end of the ion-energy probe and the grounded cone behaves as a part of the grounded electrode. It might then be expected that the ion kinetic energy distributions for $d = 0$ would exhibit characteristics similar to those seen in other experiments which sample ions through the grounded electrode. However, the low energy cut-off at 6 eV and the decreasing ion intensity below 10 eV observed in Figure 2 for $d = 0$ are not consistent with previous ion-energy distributions for Ar^+ measured through the grounded electrode [2–4]. This discrepancy may be associated with ion discrimination effects introduced by the "off-axis" ion sampling geometry utilized in the present experiment and is currently being investigated.

The observed structure for energies above 10 eV for $d = 0$ is consistent with other observations [2–4] and has been attributed to phase modulation effects associated with Ar^+ formation by resonant charge transfer in the sheath [2]. As the probe is moved away from the electrodes this structure disappears, the energy distribution narrows, and the mean ion-energy shifts to lower values. All of these effects are consistent with the diminishing influence of the probe in defining a sheath region near the aperture as the probe is removed from the vicinity of the powered electrode.

Measurements were also made for other ions present in the argon discharge including Ar^{++}, ArH^+, Ar_2^+, and H_2O^+ under the same conditions as for the data presented in Figure 2. Trends similar to those presented above for Ar^+ were found for Ar^{++} which is predominately formed in the sheath region by high energy electron collisions. However, ions such as H_2O^+ and Ar_2^+ that are formed predominantly in the glow region do not exhibit significant structure in their ion-energy distributions as shown by the example data presented in Figure 3. Additionally, substantially smaller shifts in mean energy and energy distribution widths are observed for Ar_2^+ and H_2O^+ as the probe position was varied.

Figure 4 shows kinetic energy distributions for Ar^+ as a function of the applied peak-to-peak rf voltage for $d = 0$. The mean kinetic energy is observed to decrease as V_{pp} decreases, and the structure attributed to charge exchange in the sheath is present at all voltages except the lowest. However, the structure becomes more pronounced as the bias voltage increases in accordance with the findings of Wild and Koidl [2].

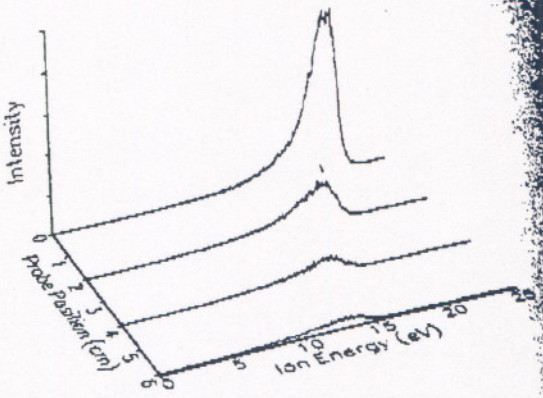

Figure 3. Ar_2^+ kinetic energy distributions as a function of the distance of the ion-energy probe from the electrode assemble for a 200 V_{pp}, 100 mtorr argon plasma. All intensities are on the same arbitrary relative scale.

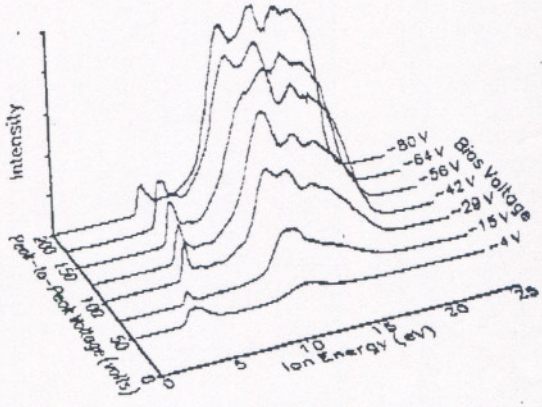

Figure 4. Ar^+ kinetic energy distributions as a function of applied rf voltage for a 100 mtorr argon plasma with the probe position at $d = 0$. All intensities are on the same arbitrary relative scale.

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