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Ion Energy and Angular Distributions in Inductively Driven RF Discharges in Chlorine

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Ion Energy and Angular Distributions in Inductively Driven RF Discharges in Chlorine

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Abstract

In this paper, we report values of ion energy distributions and ion angular distributions measured at the grounded electrode of an inductively-coupled discharge in pure chlorine gas. The inductive drive in our GEC reference cell produced high plasma densities ($10^{11}/\text{cm}^3$ electron densities) and stable plasma potentials. As a result, ion energy distributions typically consisted of a single peak well separated from zero energy. Mean ion energy varied inversely with pressure, decreasing from 13 to 9 eV as the discharge pressure increased from 20 to 60 millitorr. Half-widths of the ion angular distributions in these experiments varied from 6 to 7.5 degrees, corresponding to transverse energies from 0.13 to 0.21 eV. Ion energies gradually dropped with time, probably due to the buildup of contaminants on the chamber walls. Cell temperature also was an important variable, with ion fluxes to the lower electrode increasing and the ion angular distribution narrowing as the cell temperature increased.

I. Introduction.

Plasma discharges are widely used to etch semiconductors, oxides, and metals in the production of very-large-scale integrated circuits. Energetic ions in these discharges play a critical role in the process, influencing the etch rates, etch profiles, and selectivity to different materials.^{1,2,3} Several groups are actively engaged in developing computational models of these plasma processing discharges.⁴⁻⁸ In order to validate the predictions of these models, detailed experimental measurements of plasma parameters are required. As part of this validation effort, we report in this paper ion energy distributions and ion angular distributions measured with a gridded energy analyzer in an inductively-coupled discharge in chlorine gas.

Gridded "retarding field" energy analyzers have been used to measure ion energy spectra for several decades.^{9,10} A number of authors have examined the energy distributions using gridded energy analyzers in capacitively-driven¹¹⁻¹⁵ and inductively-driven^{16,17} RF discharges. More recently, gridded energy analyzers have been used to measure ion energies in electron-cyclotron-resonance driven plasmas^{18,19} and in plasmas for controlled fusion research.^{20,21} In addition to gridded energy analyzers, a number of other electrostatic detectors have been used to measure ion energies.²²⁻²⁷

The angular distribution of the ions striking the wafer strongly influences the etch anisotropy, which in turn influences the smallest possible feature size that can be etched on the wafer. Very few measurements have been reported on ion angular distributions in plasma etching discharges.¹¹ To our knowledge, no measurements have been reported of ion angular distributions in chlorine discharges. We have previously reported ion angular distributions in inductively-driven discharges in argon.²⁸ In this paper, we extend our ion energy and angular distribution measurements to chlorine gas.

II. Apparatus

GEC Reference Cell

Our experiments were carried out in a Gaseous Electronics Conference Reference Cell (GEC Ref. Cell)^{29,30} which had been modified to produce inductively-coupled discharges.³¹ The GEC Ref. Cell was developed to allow workers at a number of different laboratories to directly compare measurements in a cell which has good diagnostic access and is similar to plasma reactors used in the semiconductor industry. A schematic of our cell, including the five-turn planar rf-induction coil and the ion energy analyzer we used, is shown in Fig. 1. Our lower (grounded) electrode was 15.2 cm in diameter, slightly smaller than the 16.5 cm " standard " electrode diameter for the GEC Ref. Cell. In all of the data presented in this paper, the rf power given is net power to the matching circuit driving the induction coil. We estimate from other work³¹ that the actual rf power dissipated in the plasma is approximately 20% lower

than the powers listed here. All of our experiments were conducted with gas flowing in one of the side ports of the GEC Ref. cell and being pumped out both through the plenum at the bottom of the cell and through the large gate valve on the side of the cell. Typical flow rates ranged from 5.7 sccm at 20 millitorr to 39 sccm at 60 millitorr.

Ion Analyzer

The ion detector used in these experiments was a gridded energy analyzer, which was placed behind a pinhole in the lower electrode in a separate vacuum system. This detector was used to measure both ion energy spectra and ion angular distributions on the centerline of the discharge. This detector was built at Sandia, based on earlier designs at MIT.^{11,12} A schematic of the ion analyzer is shown in Fig. 2. The detector contains three screen grids and a series of annular collecting rings. The three grids and the collecting rings form sections of concentric hemispheres which are centered on the pinhole. The three screen grids³² were pressed over spherical brass mandrels and then tack-welded to stainless steel washers as described by Taylor.³³ The first grid (nearest the pinhole) and the third grid were of 50 lines per inch stainless steel woven screen and had 92% open area. The first grid was grounded to provide a field-free drift region between the pinhole and the detector. The third grid was held at a negative voltage (- 10.2 V) to repel discharge electrons and suppress secondary electron emission from the collecting rings. The second grid was made of 100 line-per-inch stainless steel screen which had 81% open area. This grid was scanned in voltage from 0 to + 40 V to sweep out the ion energy spectrum. The collecting rings were connected to ground through a picoammeter. Only ions with energies greater than the voltage on the second screen were passed by the grids and detected by the collecting rings. Thus, the ion energy spectrum was the derivative of the signal at the collecting rings as a function of voltage on the second grid.

The nine collecting rings were formed on a concave semispherical surface machined into a piece of VESPEL™ polyimide.³⁴ After nine small holes were drilled from the back side to the semispherical side of the polyimide piece, wires were glued through the holes to allow connection to the electrode rings. To form the electrodes, layers of chromium and copper were sputter-deposited over the polyimide and a layer of nickel was plated over the copper. We used a lathe to cut nine narrow (~ 0.25-mm wide) circular grooves through the conducting films to separate the nine annular electrodes. Each electrode subtended an angle of approximately 4 degrees to a normal through the pinhole.

Ion energy distributions were measured with either a 10 μm diameter pinhole in a 5 μm foil or a 6 μm diameter pinhole in a 2.5 μm thick foil as noted in the text. The ion angular data presented here were taken using a 3.5 μm pinhole in a 2.5- μm thick nickel foil.³⁵ Due to the finite-thickness of the pinhole foils, the pinholes looked slightly smaller to ions approaching the pinhole at large angles to the pinhole normal. We have corrected for this effect as explained in references 7 and 8. In most cases, the corrections changed the value of the signals by less than 10%.

The data collection system for the Sandia detector was controlled by a personal computer operating on LabVIEW for Windows. Voltages on the second and third grids of the detector were controlled by two Kepco PAT 100-0.2 power supplies which were in turn controlled by a Kepco SN-488 controller. Currents from the collector rings were measured with a HP 6512 electrometer. IEEE 488 cables connected the computer to the electrometer and the Kepco controller. Data points were collected at 0.25-volt intervals, with five measurements being averaged to comprise each data point. The data was then differentiated to obtain the ion energy distributions.

III. Results and Discussion

A. Ion Energies and Fluxes.

Figure 3 shows raw data and an ion energy distribution obtained with the ion analyzer for a 20 millitorr, 300 Watt RF discharge in chlorine. The raw data is signal in amps/cm^2 as a function of voltage on the second analyzer screen. The ion energy distribution is the derivative of the raw data with respect to voltage. Ideally, the raw signal should be flat, not slightly rising, before it begins to fall off. In simple analyzers in which the electrodes themselves are swept in voltage, Simpson³⁶ suggests this rise indicates emission of secondary electrons from the electrodes when the analyzer voltage is low. In our detector, in which the electrodes were at ground and the voltage on the second screen was swept, we feel this slight rise is more likely due to the build up of contaminants on the screens or the electrodes. We note that this rise could be reduced by cleaning the analyzer, either by baking it or running the second screen at negative voltage so the screens were bombarded by relatively high energy (~ 70 eV) ions.

Figures 4 and 5 show our measured ion energy distributions in chlorine discharges as a function of pressure and rf power. These ion energy distributions are similar in shape but 2 to 3 eV lower in energy than the argon ion energy distributions we reported previously.²⁸ The widths of the ion energy distributions were 1.4 eV FWHM independent of pressure or rf power. This is about half the 2.8 eV widths we reported earlier in argon discharges.²⁸

The data in figures 4 and 5 is summed over all nine collecting electrodes in the ion analyzer. We made separate measurements of ion energy distributions versus angle to the pinhole normal in a 30 millitorr, 200 Watt chlorine discharge. These showed no variation in the ion energy distributions versus angle for the first four collecting electrodes, (0° to 16° off axis), which contained most of the ion flux.

It is useful to compare our ion energies to the plasma potential measurements by Miller et. al.³¹ Miller used a Langmuir probe to measure plasma potentials in argon and chlorine discharges in a GEC Ref. Cell nominally identical to our own. Miller's plasma potentials are also 2 to 3 eV lower in chlorine than in argon. Miller reports a plasma

potential on the center of the discharge (centered azimuthally and halfway between the lower electrode and the window vertically) of 17 volts for a 20 millitorr, 230 Watt chlorine discharge, which is about 4 Volts higher than the ion energies we measure under similar conditions. Since we expect the plasma potential to drop as the measurement point is moved from the center of the discharge towards the lower, grounded, electrode (Miller's argon results drop by 5 Volts from the center of the discharge to the lower electrode) we consider our results to be in good agreement with Miller's data.

The ion energy distributions we measured for chlorine always consisted of a single, relatively narrow feature well separated from zero energy. This is in contrast to ion energy distributions measured in capacitive discharges¹¹ which typically showed a continuum of ion energies from a high energy limit down to near zero energy.

As discussed in our previous work involving argon discharges²⁸ and by other authors,¹⁶ the differences between our ion energy distributions and those seen in capacitive discharges arise from the differences in the plasma potentials, sheath dimensions and pressure ranges between the two cases. In capacitively-coupled discharges, the plasma potential varies from near zero to the full rf potential during each rf cycle. Also, capacitive discharges tend to be operated at relatively high pressures (up to 1 torr) and low electron densities ($n_e = 10^9$ to 10^{11} / cm^{-3}) which yields relatively wide, collisional sheaths. Charge exchange collisions in the sheath tend to drive the ion energy toward the gas temperature. Therefore, the energies of ions at the electrode in capacitive discharges can vary greatly, depending on the phase of the rf cycle when they start across the sheath and the number and location of collisions they experience in the sheath. In inductive discharges, the plasma potential is predominantly DC. Normally, this DC potential has only a small AC component superimposed on it due to stray capacitances between the rf induction coil and the plasma. Inductive discharges are normally operated at lower pressure (below 0.1 torr) and high electron density ($n_e = 10^{11}$ to 10^{12} / cm^{-3}) where the sheaths are narrow (~ 0.1 mm) and collisionless. In inductive discharges, ions will have a relatively narrow energy distribution (a few eV or less) at the edge of the sheath caused by collisions in the pre sheath, thermal energy, and spatial variations in the plasma potential. This distribution will then be uniformly shifted to higher energy, resulting in distributions like those in Fig. 4, as all the ions gain an energy equal to the DC sheath voltage in crossing the sheath.

During the data collection, it became evident that there were important parameters affecting the discharge that we were not controlling. The first parameter we call cell ageing - or the buildup of deposits on cell surfaces as a direct result of operating the chlorine discharge. Simple continuity tests with an ohmmeter indicated that these deposits included an insulating layer on the window holder separating the inductive coil from the discharge, which was presumably sputtered window material (SiO_2). It also included conducting deposits on the lower electrode and the chamber walls which were presumably mixtures of window material and chloride compounds. After enough deposits had built up on the chamber wall, the discharge became very hard to start and

operate in the “bright” or inductive³¹ discharge mode. The second parameter we call cell temperature, although this parameter may also involve chemistry of the wall surfaces as well as wall temperature. Hebner has measured gas and cell temperatures in argon discharges in a GEC Ref. Cell nominally identical to our own and finds that for 200 to 300 Watt discharges, the neutral gas temperatures^{37,38} are on the order of 600° C. Uncooled wall temperatures³⁹ are approximately 100° C. Our lower electrode was water cooled and remained at 15° C to 20° C during the experiments.

Figure 6 illustrates the effect of cell ageing on the ion energy distributions. As the cell aged, the mean ion energy dropped by one to two eV. Abrasive cleaning of the lower electrode and window holder returned the ion energy distributions to their original values at 300 Watts of rf power as shown in Fig. 6. At lower powers, this was not true. Figure 7 shows mean ion energies for 200 and 300 Watt rf discharges after the electrodes had been cleaned. At 30 millitorr, the 200 Watt data shows mean ion energies almost 2 eV below the 300 Watt data, in contrast to the “new cell” data of figure 5 in which the mean energies are identical at the two different powers.

Figure 8 shows total ion fluxes to the lower electrode in Amps/cm² as a function of rf power and pressure. The fluxes increase with both rf power and with pressure. We sometimes observed increases in total ion flux as large as a factor of two as the cell heated up from room temperature. Therefore, In order to minimize cell temperature effects on the data, before the chlorine data was taken, the cell was operated with a 30 millitorr argon discharge for one-half hour at the rf power we planned to use for the chlorine measurements.

B. Ion Angular Distributions:

Figure 9 shows raw data of ion angular distributions in 200 Watt chlorine discharges as a function of pressure. The data shows a broadening of the angular distribution as the pressure increases. In order to minimize cell ageing and cell temperature effects on the ion angular distributions, we used a new pinhole in a clean electrode for each series of angular distribution measurements and let the the GEC Ref. Cell warm up with an argon discharge for one-half hour before starting measurements as described in the preceeding paragraph.

If we assume that the distribution function of the ions at the pinhole can be approximated by a drifting Maxwellian distribution⁴⁰, we can derive estimates of the ratio of the transverse to longitudinal temperatures of the ions from our data. The measured ion current per detector electrode area is fit to a simple functional form:

$$J = A[\cos^4(d)]\exp[-B\sin^2(d)]$$

where d is the mean angle and A and B are to be determined by the fit. B is defined as E_d / kT_t where E_d and T_t are the directed energy ($E_d = 1/2 mv^2$) and the transverse temperature (kT_t).

Figure 10 shows drifting Maxwellian fits to ion angular distributions in 200 Watt rf discharges. Again, the data clearly shows a broadening of the data and hence an increase in the transverse temperature, as the pressure increases. Figure 11 shows our measured values of transverse energy versus pressure and rf power. The transverse temperatures increase both with pressure and power. The values of E_d used in determining kT_t in Fig. 11 came from the data in Fig. 10, which was taken the same day as the data in Fig. 11. The transverse temperatures shown in Fig. 11 of 0.13 to 0.21 eV are significantly lower than the 0.18 to 0.29 eV transverse temperatures we reported earlier for argon discharges.²⁶ The values we obtained for transverse temperatures appeared to depend on cell temperature. On several occasions, we observed the total ion flux increase with time and the ion angular distribution narrow with time as the cell heated up from room temperature. We can also present our data as an angular spread of the ion distribution. Figure 12 shows the half angle of the cone containing 63% of the ion flux as a function of chlorine pressure and rf power.

In measuring ion angular distributions, it is important to determine that the ion trajectories are not perturbed by fringing electric fields around the pinhole. In general, the pinhole size needs to be much smaller than the sheath size to avoid perturbing the ions. This problem is particularly severe in the high density discharges studied here since the sheaths are very narrow and the resulting sheath E-fields are very high. In previous work with argon discharges²⁸ we determined that pinholes needed to be smaller than 10 microns in diameter to avoid perturbing the angular distributions - i.e. 5 micron pinholes gave narrower distributions than 10 micron pinholes, but 3.5 micron and 6 micron pinholes gave identical angular distributions. Fig. 13 compares angular distributions measured with 3.5 and 6 micron diameter pinholes. The 6 micron pinhole data gives temperatures that are only about 12% higher than the 3.5 micron data. We conclude from these results that the 3.5 micron data were not significantly affected by fringing fields around the pinhole.

IV. Conclusions

During the course of these experiments we discovered two important variables that we were not controlling. First, the buildup of materials on the cell walls lowers the energies of the ions striking the bottom electrode in our cell. This may be due simply to charging of the materials on the cell walls or through changes in the discharge itself. Second, we found that the temperature of the GEC ref cell affects both the total ion fluxes striking the electrode and the ion angular distributions. The total flux sometimes increased as much as a factor of two as the cell heated up from room temperature to its stable operating temperature. The ion angular distributions narrowed slightly but repeatably (transverse temperatures varied by about 20%) as the cell heated up.

The ion energy distributions that we observed in chlorine discharges consisted of a single feature which was well separated from zero energy. This is quite different from the spectra seen in capacitively-coupled discharges and reflects the quiescent nature of the plasma potential in inductively-coupled discharges as well as the lack of charge-exchange collisions in the sheath. The mean ion energies seen in our experiments ranged from 9 to 13 eV, which is slightly lower than the plasma potentials measured in the center of the discharge by Langmuir probes³¹ and 2 to 3 eV lower than our results in argon.²⁸ The full-width-at-half-maxima of the ion energy distributions we measured was 1.4 eV, independent of discharge pressure or rf power, about half the 2.8-eV widths we measured in argon.

The ion energies varied inversely with discharge pressure. The effects of rf power variations, however, were more complex. In experiments with a clean cell, ion energies were independent of RF power, but after running discharges in the cell for extended periods, the ion energies increased slightly with increases in rf power.

In measurements taken after discharges had been run long enough for the GEC Ref. Cell to come to operating temperature, the total ion fluxes to the center of the lower electrode varied directly with discharge pressure and rf power, increasing from 5 mA/cm² at 20 millitorr and 200 Watts rf to 20 mA/cm² at 60 millitorr and 300 Watts rf.

The widths of the ion angular distributions seen in these experiments increased both with increases in pressure and rf power. Fitting our ion angular distribution data to drifting Maxwellian distributions yields transverse ion energies ranging from 0.13 to 0.21 eV, somewhat lower than the results previously reported for argon discharges. The fact that the ion energies (directed normal to the electrode) were lower in chlorine than in argon however, means that the angular half-widths measured for the chlorine distributions, at 6 to 7.5 degrees, are comparable to the half widths seen in argon discharges.

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References:

1. Dry Etching for VLSI, A. J. vanRoosmalen, J. A. G. Baggerman, and S. J. H. Brader. Plenum Press, New York, 1991.
2. Principles of Plasma Discharges and Materials Processing, Michael A. Lieberman, Allan J. Lichtenberg, John Wiley & Sons, New York, 1994
3. Silicon Processing for the VLSI Era: Volume I - Process Technology, S. Wolf and R. N. Tauber, Lattice Press, Sunset Beach, California, 1987
4. J. E. Johannes, T. J. Bartel, R. S. Wise, D. J. Economou, paper PS-MoM7: Comparison of Low Pressure Cl_2 Plasma Simulations With Experimental Data in an Inductively Coupled Source, 42nd National Symposium of the American Vacuum Society, Minneapolis MN, October 16, 1995
5. R. J. Hoekstra and M. J. Kushner, Predictions of Ion Energy Distributions and Radical Fluxes in Radio Frequency Biased Inductively Coupled Plasma Etching Reactors, Journal of Applied Physics, in press 1996.
6. C. Lee and M. A. Lieberman, J. Vac. Sci. Technol. A (13)2, March/April 1995, p 368
7. E. F. Jaeger, L. A. Berry, J. S. Tolliver and D. B. Batchelor, Physics of Plasmas 2 (6) June 1995, p. 2597
8. E. Meeks and J. W. Shon, J. Vac. Sci. Tech. A 13, (1995), p. 2884
9. B. Lipschultz, I. Hutchenson, B. LaBombard, and A. Wan, J. Vac. Sci. Technol. A4 (3) May/ June 1986, p. 1810
10. Principles of Plasma Diagnostics, I. H. Hutchenson, Cambridge University Press, New York, 1992, p. 80
11. J. Liu, G. L. Huppert, and H. H. Sawin, J. Appl. Phys 68 (8), 15 Oct. 1990, p. 3916
12. Scaling Relationships for Power Deposition and Ion Bombardment in Radio-Frequency Plasmas, Joanne Liu, MIT PhD thesis, 1993, Available from MIT Document Services, Rm 14-0551, 77 Mass. Ave Cambridge, Mass. 02139-4307, (617)-253-5668

13. B. E. Thompson, K. D. Allen, A. D. Richards, and H. H. Sawin, J. Appl. Phys. **59** (6), 15 March 1986, p. 1890
14. U. Flender and K. Wiesemann, J. Phys. D: Appl. Phys **27** (1994) p. 509
15. A. Wild and P. Koidl, J. Appl Phys. **69** (5) 1 March 1991, p. 2909
16. U. Kortshagen and M. Zethoff, Plasma Sources Science & Technology, **4** (1995), p. 541
17. J. Hopwood, Appl. Phys. Lett. **62** (9) 1 March 1993, p 940
18. Radial Ion Transport in a limited Axisymmetric ECR Plasma, Gerald Gibson, Jr., MIT PhD. thesis, 1994,
19. Ion Energy Distribution Functions Perpendicular and Parrallel to the Magnetic Field in ECR Plasmas, Minh Sy Le, MIT B.S. Thesis, 1995
20. F. Matthews, J. Phys. D: Appl. Phys. **17** (1984), p. 2243
21. A. W. Molvik, Rev. Sci. Instrumen. **52** (5) May 1981, P. 704
22. Ion Energy Measurements in an Inductive RF Plasma with RF Bias, John Trow, Applied Materials, 47th Annual Gaseous Electronics Conference, Gaithersburg MD, October 1994
23. W. D. Davis and T. A. Vanderslice, Phys. Rev, **131** (1) July 1, 1963, p. 219
24. A. Manenschijn, E. van der Drift, G. C. A. M. Janssen and S. Radelaar, J. Appl. Phys. **69** (12), June 15, 1992, p. 7996
25. W. M. Greene, M. A. Hartney, W. G. Oldham and D. W. Hess, J. Appl. Phys. **63** (5) March 1, 1988, p. 1367
26. J. K. Olthoff, R. J. VanBrunt, and S. B. Radovanov, J. Appl, Phys, **72** (1992) p. 4566
27. J. K. Olthoff, R. J. VanBrunt, and S. B. Radovanov "Studies of Ion Kinetic Energy Distributions in the Gaseous Electronics Conference RF Reference Cell", Journal of Research, National Inst. of Standards & Technology, **100** (4) July-August 1995
28. J. R. Woodworth, M. E. Riley, D. C. Meister, B. P. Aragon, H. H. Sawin, M. S. Le; Ion Energy and Angular Distributions in Inductively Driven Argon Discharges, Journal of Appl. Phys, in press 1996

29. P. J. Hargis, Jr. , K. E. Greenberg, P. A. Miller, J. B. Gerardo, J. R. Torczynski, M. E. Riley, G. A. Hebner, J. R. Roberts, J. K. Olthoff, J. R. Whetstone, R. J. Van Brunt, M. A. Sobolewski, H. M. Anderson, M. P. Splichal, J. L. Mock, P. Bletzing, A. Garscadden, R. A. Gottscho, G. Selwyn, M. Dalvie, J. E. Heidenreich, J. W. Butterbaugh, M. L. Brake, M. L. Passow, J. Pender, A. Lujan, M. E. Elta, D. B. Graves, H. H. Sawin, M. J. Kushner, J. T. Verdeyen, R. Horwath and T. R. Turner, *Rev. Sci. Instruments*, **65**, (1994) p. 140
30. J. K. Olthoff and K. E. Greenberg, *Journal of Reserach, National Institute of Standards and Technology* **100** (4) July-August, 1995, p. 327
31. P. A. Miller, G. A. Hebner, K. E. Greenberg, P. D. Pochan, and B. P. Aragon, *Journal of Research, National Institute of Standards and Technology* **100** (4), July-August 1995, p. 427
32. The wire screen grids for the Sandia detector were obtained from the Unique Wire Weaving Co, Inc, 762 Ramsey Ave. Hillside, HJ 07205, (908)-688-4600
33. P. A. Taylor, *J. Vac. Sci. Technology A* **6**, (4), July - August, 1988, p. 2583
34. VESPEL™ is a trademark of the DuPont Corporation.
35. Pinholes were obtained from National Apertures, Inc. 26 Keewaydin Dr. Suite B, Salem NH, (603) 893-7857
36. J. A. Simpson, *Rev. Sci. Instruments*, **32** (12), Dec. 1961, p. 1283
37. G. A. Hebner, Spatially resolved, excited state density and neutral temperatures in inductively coupled argon plasmas, *J. Appl. Phys*, in press 1966
38. G. A. Hebner, Neutral and ion translational temperatures in inductively coupled argon plasmas, *J. Appl. Phys*, in press 1966
39. G. A. Hebner, private communication
40. C. F. Chen, Introduction to Plasma Physics and Controlled Fusion, 2nd Edition, Vol. I: Plasma Physics , p. 231, Plenum Press, New York, 1984

Figure Captions:

Figure 1: schematic of the GEC Ref. cell with inductive rf drive coil. The ion analyzer was located below a pinhole in the lower electrode.

Figure 2. Schematic of the gridded energy and angle analyzer used in these experiments. The collection electrodes and the screens were sections of concentric hemispheres with the pinhole at their center. Voltage on the middle grid was varied to sweep out the ion energy distribution. The distance from the pinhole to the annular collection electrodes was 2.29 cm.

Figure 3. Raw data and ion energy distribution in a 20 millitorr, 300 Watt chlorine discharge. The ion energy distribution is obtained by differentiating the raw data with respect to voltage.

Figure 4. Ion energy distributions in 300 Watt discharges in chlorine as a function of discharge pressure. Ion energy decreases as pressure increases.

Figure 5. Ion energy distributions in 30 millitorr discharges in chlorine as a function of rf power to the matching network. The power dissipated in the plasma is approximately 80% of the power to the matching network.

Figure 6. Mean ion energies in 300 Watt chlorine discharges as a function of cell ageing. Data taken on the first three days that chlorine discharges were operated in the GEC Ref. Cell show a clear decline in ion energies as contaminants built up on the cell walls. Data taken on a fourth day, after the electrodes had been cleaned, recovered the original energies.

Figure 7. Mean ion energies versus pressure and rf power in chlorine discharges. In the data shown here ion energy does increase slightly as power is raised, in contrast to the data shown in figure 6, pointing out the importance of contaminants on the cell walls in determining exact ion energies.

Figure 8. Total ion fluxes to the grounded electrode in chlorine discharges as a function of pressure and rf power. To reduce the effect of cell temperature variations on the ion flux, the cell was allowed to warm up by running 30 millitorr discharges for one-half hour before this data was taken.

Figure 9. Raw data of ion angular distributions in 200 Watt chlorine discharges as a function of pressure. This data was taken through a 3.5micron diameter pinhole in a 2.5-micron thick nickel foil. The data clearly shows a broadening of the distributions as pressure increases.

Figure 10. Drifting Maxwellian fits to ion angular distributions in 200 Watt chlorine discharges. The transverse temperatures calculated from these fits vary from 0.15 eV at 20 millitorr to 0.17 eV at 50 millitorr.

Figure 11. Transverse ion temperatures at the grounded electrode in chlorine discharges, as determined from drifting Maxwellian fits. The transverse temperatures increase with both pressure and rf power.

Figure 12. Angular spread of positive ions striking lower electrode in Cl discharges. The figure shows the half-angle of the cone containing 63% of the ion flux as a function of pressure and rf power. Angles are measured from the normal to the lower electrode surface.

Figure 13. Transverse ion temperatures measured at the lower electrode in 300 Watt chlorine discharges for two different pinhole sizes.

Figure 1: schematic of the GEC Ref. cell with inductive rf drive coil. The ion analyzer was located below a pinhole in the lower electrode.

Figure 2. Schematic of the gridded energy and angle analyzer used in these experiments. The collection electrodes and the screens were sections of concentric hemispheres with the pinhole at their center. Voltage on the middle grid was varied to sweep out the ion energy distribution. The distance from the pinhole to the annular collection electrodes was 2.29 cm.

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Chart3

Raw Signals and Ion Energy Distribution in 20 millitorr, 300 Watt Chlorine Discharge

Figure 3. Raw data and ion energy distribution in a 20 millitorr, 300 Watt chlorine discharge. The ion energy distribution is obtained by differentiating the raw data with respect to voltage.

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Figure 4. Ion energy distributions in 300 Watt discharges in chlorine as a function of discharge pressure. Ion energy decreases as pressure increases.

Figure 5. Ion energy distributions in 30 millitorr discharges in chlorine as a function of rf power to the matching network. The power dissipated in the plasma is approximately 80% of the power to the matching network.

Ion Energy Distributions in 300-Watt Cl Discharges vs cell ageing

Figure 6. Mean ion energies in 300 Watt chlorine discharges as a function of cell ageing. Data taken on the first three days that chlorine discharges were operated in the GEC Ref. Cell show a clear decline in ion energies as contaminants built up on the cell walls. Data taken on a fourth day, after the electrodes had been cleaned, recovered the original energies.

Figure 7. Mean ion energies versus pressure and rf power in chlorine discharges. In the data shown here ion energy does increase slightly as power is raised, in contrast to the data shown in figure 6, pointing out the importance of contaminants on the cell walls in determining exact ion energies.

Figure 8. Total ion fluxes to the grounded electrode in chlorine discharges as a function of pressure and rf power. To reduce the effect of cell temperature variations on the ion flux, the cell was allowed to warm up by running 30 millitorr discharges for one-half hour before this data was taken.

Figure 9. Raw data of ion angular distributions in 200 Watt chlorine discharges as a function of pressure. This data was taken through a 3.5micron diameter pinhole in a 2.5-micron thick nickel foil. The data clearly shows a broadening of the distributions as pressure increases.

Figure 10. Drifting Maxwellian fits to ion angular distributions in 200 Watt chlorine discharges. The transverse temperatures calculated from these fits vary from these fits vary from 0.15 eV at 20 millitorr to 0.17 eV at 50 millitorr.

Figure 11. Transverse ion temperatures at the grounded electrode in chlorine discharges, as determined from drifting Maxwellian fits. The transverse temperatures increase with both pressure and rf power.

Figure 12. Angular spread of positive ions striking lower electrode in CI discharges. The figure shows the half-angle of the cone containing 63% of the ion flux as a function of pressure and rf power. Angles are measured from the normal to the lower electrode surface.

**Transverse Ion Temperatures measured at lower electrode
vs pinhole size for 200 Watt Cl Discharges**

Figure 13. Transverse ion temperatures measured at the lower electrode in 300 Watt chlorine discharges for two different pinhole sizes.

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