DOE/ER/13727--T2

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DE92 018558

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SELF-GENERATED STOCHASTIC HEATING IN AN RF DISCHARGE

DOE Grant DE-FG03-87ER13727

ANNUAL REPORT May 15, 1991–May 14, 1992

I. TECHNICAL PROGRESS

We have studied the nonlinear dynamics of stochastic heating arising from the reflection of electrons from moving sheaths as an underlying mechanism for electron power deposition in r.f. discharges. We examined the dynamics of the electron collisions with the sheaths in the regime in which the sheath motion is small compared to the average electron velocity to derive a map that describes the electron motion. We have shown that for high frequency, ($\omega/2\pi \gtrsim 50$ MHz), the electrons will strike the moving wall with random phase. At low pressures this stochasticity is an intrinsic property of the dynamics. The stochastic electron heating leads to a power law electron distribution.

The stochastic heating was determined in both the slow sheath and fast sheath velocity regimes assuming an incident Maxwellian distribution. In the slow sheath regime, we showed analytically that the stochastic heating power

$P_s \propto V_s$, the sheath voltage, which leads to a scaling of discharge density with voltage as $n_e \propto V_s$. In the fast sheath regime we found $P_s \propto n_e \propto V_s^{7/6}$. The usual experimental regime for low pressure materials processing discharges is $u_s \sim u_e$, which spans both fast and slow regimes. During the last grant period we have numerically investigated this intermediate regime, to obtain a complete picture of the scaling over the entire range of applied voltages. The work has been reported [1, 2] and a paper is in preparation.

The sheath motion in a capacitively coupled RF discharge is highly nonlinear. We have measured the voltage on a floating probe placed in the sheath region, as a function of position and time. A circuit model of the probe-discharge system is used to relate the observed probe voltage to the sheath motion. The results indicate that the primary nonlinear motion is quite similar to the theoretical model. We also have observed oscillations related to the plasma frequency, whose peak harmonic component can be calculated from a simple resonant plasma model. These oscillations can be a useful plasma diagnostic for determining plasma density. The presence of these high frequency oscillations may also significantly enhance the rate of stochastic heating of electrons. These results have been published [3].

The scaling of the density and absorbed power with voltage were obtained experimentally and compared with the theoretical scaling. Although the scaling was similar there was an absolute discrepancy between the theory and experiment [4]. Furthermore, experiments done by another group and in some simulations have indicated steeper scaling with V_s. This has led to a critical examination of the assumptions, including the very important shape of the electron energy distribution.

Simulations are very useful, both in checking the results of analytic calculations under similar conditions, and in interpreting experimental results with detailed computer diagnostics. The effect of various physical phenomena can also be investigated by changing the model to either include or exclude the particular phenomena, such as collisions in the sheath. The discharge was simulated using PDP1, a 1-d 3-v, planar, bounded electrostatic PIC code developed by C. K. Birdsall's group in U.C. Berkeley's EECS Department. Simulations were done on a Sun Sparcstation for a 3 mTorr symmetric argon discharge of length 10 cm, driven by a 13.56 MHz signal applied to one electrode. Approximately 10,000 computer particles were used in the discharge, with 1500 timesteps per r.f. cycle. The statistics presented were typically averaged over 100 r.f. cycles.

A key question concerns the electron distribution function. The velocity distribution is found to vary in time, showing some beamlike behavior. A time average of the distributions can be interpreted as a two-temperature

Maxwellian with $T_c = 0.97$ eV and $T_h = 4.2$ eV, but can be fitted equally well with a power-law distribution. This is in reasonable agreement with the experimental measurements of Godyak and Piejak, and with our theoretical study of stochastic heating at an oscillating sheath, done previously in our group. Another very important characteristic of the electron distribution is its scaling with V_s. In the simulation we found that both the cool and warm components scale with V_s as $T_e \propto V_s^{0.4}$. This additional scaling, used in the one-temperature analytic calculation, modifies the analytic scalings. The scaling of the plasma density and power can also be found from the simulations. For a 10 cm discharge we found $n_e \propto V_s^{1.5}$, in rough agreement with the experimental observations of a 10 cm discharge by Godyak and Piejak, and higher than found in our experiment or in the analytic model.

Using the simulations as a guide revisions were made to the collisionless sheath model to include the effects of the non-Maxwellian electron distribution, the spatial and temporal variations in the electron temperature, the faster drift of the electron velocity distribution, and the higher energy of the electrons lost at the electrode. With these modifications, and using the numerical integration of the sheath dynamics in the intermediate sheath velocity regime, the density and power were calculated. The values obtained were compared with the results of simulations and experiments, with the analytic results quite close to those found by both simulation and experiments for symmetric discharges [4]. Our experimental results were for an asymmetric discharge where significant differences can be expected due to the effects of asymmetry. A paper presenting these results is in preparation.

Magnetically enhanced, capacitive RF discharges (so-called RF magnetrons or MERIE discharges) are playing an increasing role in thin film etching for materials processing. In these discharges, a weak DC magnetic field is imposed lying parallel to the powered electrode surface. We determined the RF power transferred to the discharge electrons by the oscillating electron sheath in the presence of the magnetic field finding that the stochastic heating can be strongly enhanced. Using this heating, along with particle and energy conservation, we obtained discharge parameters such as the ion flux and ion bombarding energy at the powered electrode as functions of RF power, pressure and magnetic field. Some results of the model show good agreement with experiments have been performed on a commercial MERIE reactor. The work has been published [5].

A helical resonator plasma source is a slow wave, high Q structure that may be used for plasma-assisted materials processing at very low pressure ($P \lesssim 1$ mTorr). The resonator consists of a helical coil surrounded by a grounded coaxial cylinder. The coil is grounded at one end and opencircuited at the other end, with RF power coupled to the coil via a movable clip. During operation, resonance is achieved by tuning the RF power supply frequency. The source can produce high plasma densities over a wide pressure range, requires no external matching network, and uses no external magnetic field coils. Source operation at low pressures should allow us to isolate the effects of stochastic heating in the absence of competing effects due to electron-neutral collisions. It also should allow exploration of a regime in which high electric fields exist over most of the discharge cross-section.

During the previous grant periods we have characterized the helical resonator by measuring the plasma density, resonance frequency, helix voltage, electric field, and Q, for varying pressures and RF powers. We have compared these measurements to a model of the resonator operation which predicts the dispersion relation, the field structure, and the scaling of the ohmic and stochastic heating. The scaling of density with helix voltage observed experimentally is not consistent with theoretical calculations in which stochastic heating is the dominant overall electron heating mechanism in the low pressure regime. We conclude that a more detailed theoretical model is required [6].

II. PROPOSED RESEARCH

During the coming grant period, we plan to develop a self-consistent model of the overall power balance in the helical resonator discharge, in which we consider the new effects that have proved necessary to our complete understanding of the capacitive discharge. The model will incorporate the non-sinusoidal sheath motion that enhances the stochastic heating energy deposition in the discharge, and the electron-neutral collisions that lead to phase randomization and ohmic electron heating. The effects of a fast sheath and a non-Maxwellian electron distribution, which proved important for resolving the capacitive discharge anomalies, will also be considered. In addition, at low pressures, with high electric fields and lower densities, the discharge region is penetrated by the electric fields, which can lead to enhanced power loss. Enhanced power loss was observed leading us to believe that we were in this regime. A major modification of the overall discharge model will be made to incorporate this effect.

The critical parameters such as plasma density and absorbed power will be be measured more carefully to be sure that the discrepancies between theory and experiment are well characterized. An important parameter in understanding the total dynamics is the sheath width. An attempt will be made to measure this width using the techniques developed for the measurement in the capacitive discharge, in the geometrically restrictive configuration of the helical device.

Another critical parameter that will be measured is the DC floating potential of the plasma, which is related to the bombarding energy of ions on the substrate surface. This measurement will yield information on the role of the capacitive, radially-oscillating sheaths in producing stochastically heated electrons within the discharge. In addition to direct measurement of the floating potential with a Langmuir probe, we plan to use a gridded electrostatic ion energy analyzer, already developed, to determine the ion energies.

There is much that can be understood about resonator operation by examining the effect of chemically reactive discharges on substrates placed within the helical resonator process chamber. We plan to study the etching of resist materials (polymers) in oxygen discharges, using the etching as a vehicle to determine the radial uniformity of the resonator plasma, the ion bombarding energies, and the ion and reactive neutral fluxes, generated in the plasma, that are incident on the wafer. This is a longer range project and will probably not be attempted during the coming year.

III. PUBLICATIONS AND ABSTRACTS

1. B. P. Wood, M. A. Lieberman, and A. J. Lichtenberg, "Heating by RF Sheaths in Capacitive Discharges," Abstract 5P-13, presented at the 18th IEEE International Conference on Plasma Science, June 3–5, 1991, Williamsburg, Virginia.
2. M. A. Lieberman, "Heating by RF Sheaths in Low Pressure Discharges," Invited Talk 4C5-6, presented at the 18th IEEE International Conference on Plasma Science, June 3–5, 1991, Williamsburg, Virginia.
3. B. P. Wood, M. A. Lieberman, and A. J. Lichtenberg, "Sheath Motion in a Capacitively Coupled Radio Frequency Discharge," *IEEE Transactions on Plasma Science*, **19**, 619 (1991).
4. B. P. Wood, "Sheath Heating in Low Pressure Capacitive R.F. Discharges," Ph.D Dissertation, Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, (1991).
5. M. A. Lieberman, A. J. Lichtenberg, and S. E. Savas, "Model of Magnetically Enhanced, Capacitive RF Discharges," *IEEE Transactions on Plasma Science*, **19**, 189 (1991).
6. M. A. Lieberman, A. J. Lichtenberg, D. L. Flamm, and K. Niazi, "Helical Resonator Plasma Source," Abstract R-9, p. 152, Conference Abstracts, 43rd Annual Gaseous Electronics Conference, 16–19 October 1990, Champaign-Urbana, Illinois; K. Niazi, D. L. Flamm, and M. A. Lieberman, "A Network Model for the Helical Resonator Plasma Source," 44th Annual Gaseous Electronics Conference, October 1991, Albuquerque, New Mexico.
7. M. A. Lieberman, "Modeling of High Density Plasma Sources for Materials Processing," Invited Talk PS-ThM2, 38th National Symposium of the American Vacuum Society, November 11–15, 1991, Seattle, Washington.
8. M. A. Lieberman, "Analytical Modeling of Materials Processing Plasmas — Where's the Beef?," Invited Talk, 33rd Annual Meeting of the Division of Plasma Physics of the American Physical Society, 4–8 November 1991, Tampa, Florida.

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