Characterization of Electron Cyclotron Resonance Hydrogen Plasmas

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Electron cyclotron resonance (ECR) plasmas yield low energy and high ion density plasmas. The characteristics downstream of an ECR hydrogen plasma were investigated as a function of microwave power and magnetic field. A fast-injection Langmuir probe and a carbon resistance probe were used to determine plasma potential (V_p), electron density (N_e), electron temperature (T_e), ion energy (T_i), and ion fluence. Langmuir probe results showed that at 17 cm downstream from the ECR chamber the plasma characteristics are approximately constant across the center 7 cm of the plasma for 50 Watts of absorbed power. These results gave $V_p = 30 \pm 5$ eV, $N_e = 1 \times 10^8$ cm⁻³, and $T_e = 10$ -13 eV. In good agreement with the Langmuir probe results, carbon resistance probes have shown that $T_i \leq 50$ eV. Also, based on hydrogen chemical sputtering of carbon, the hydrogen (ion and energetic neutrals) fluence rate was determined to be 1×10^{16} /cm²-sec at a pressure of 1×10^{-4} Torr and for 50 Watts of absorbed power.

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I. Introduction

Hydrogen plasmas are important for both fusion and electronic materials processing. Specifically, electron cyclotron resonance (ECR) hydrogen plasmas can be used for passivation of dopants or defects, and for cleaning of impurities from surfaces (e.g., C or O). For example, Ditzio et al.¹ examined hydrogen passivation of grain boundaries in thin-film polycrystalline silicon transistors by comparing an ECR plasma with an rf plasma and a Kaufman ion-source technique. Their results showed that the ECR source was the most effective in passivating electrically active defects due to the large quantity of passivating species and the absence of ion-beam damage effects. The ECR plasmas are of interest because of the low ion energy (low ion-beam damage) and the low pressures afforded these plasmas. Typical ion energies² are thought to be from 10 to 50 eV, however little work has been done to directly measure the ion energy distribution downstream from an ECR plasma source. Further, Hussein et al.³ suggests that a high energy tail in the electron distribution is characteristic of ECR sources; a point which also questions the presence of and fluence rate for a high energy tail in the ion distribution.

In this paper, a Langmuir probe and carbon resistance probe were used to determine the energy and fluence of ions and neutrals in an ECR hydrogen plasma. In particular, we have adapted carbon resistance probes, previously used for plasma edge studies in Tokamaks⁴, to measure the energy and flux of neutrals and ions. The resistance probe technique is based upon the observation that lattice damage caused by energetic particles incident on a thin carbon film increases the electrical resistivity of the film. A comparison of ion energies determined from both Langmuir probe and carbon

probe data will be shown to be in good agreement with theoretical ion energies which are based upon the magnitude of the divergent magnetic field.

II. Diagnostic techniques and experimental apparatus

Microwave power at a frequency of 2.45 GHz was introduced into the ECR chamber through a quartz vacuum window. The forward microwave power (P_f) was adjustable from 0-1000 Watts and the reflected microwave power (P_r) was minimized by a three-stub tuner which acted as a matching network, adjacent to the vacuum window. Both forward and reflected microwave power were monitored using a directional coupler. The ECR chamber has an inner diameter of approximately 14 cm and a length of 16.5 cm. The ECR chamber was mounted on a UHV stainless-steel vacuum chamber such that the plasma stream was extracted into the chamber by a divergent magnetic field². The vacuum chamber was pumped by a 1500 l/sec turbomolecular pump to achieve a base pressure of 1×10^{-8} Torr. The hydrogen gas was introduced into the ECR chamber near the quartz window at a throughput of 20 sccm producing a pressure of $1-2 \times 10^{-4}$ Torr.

A mirror magnetic field configuration was produced by two separate coils surrounding the ECR chamber, with one coil (current I_1) centered about the end of the ECR chamber (at the quartz vacuum window) and the other coil (current I_2) separated by a distance of 8 cm. For these experiments, the magnetic field was maximum at the vacuum window and decreased along the chamber axis. The resonant magnetic field (875 Gauss) was established at the midpoint of the ECR chamber. This field configuration created a magnetic beach⁵ in which the microwaves were launched into the ECR chamber from a region with a magnetic field greater than the resonance value. Therefore,

plasma densities greater than the critical density for cut-off of the microwaves were possible in the high field region near the quartz window.

A fast-injection Langmuir probe was used to measure plasma conditions both in the ECR region and 17 cm downstream from the ECR source. The Langmuir probe was oriented perpendicular to the static magnetic field in order to minimize distortion of the current-voltage (I-V) curve⁶. In this configuration, the electron saturation current can be low⁶ by a factor of 1.5 to 2.5; and in this study, the electron densities were not corrected for possible suppression by the magnetic field. The Langmuir probe is pneumatically injected into the plasma at ≈ 80 cm/sec from one edge of the plasma cone across the center of the plasma to the other edge of the plasma (≈ 14 cm). Simultaneously, the voltage is scanned from -100 to 100 V at 200 Hz and I-V curves are obtained as a function of radial position for each injection of the probe at different levels of microwave power.

The procedure for fabrication of the carbon probes follows that described in reference⁴. The probe is illustrated in Fig. 1. A silicon film of 2 nm is evaporated onto a quartz substrate to provide adhesion. Then, a carbon film is evaporated onto the thin silicon film and annealed at 700 °C in vacuum for 1.5 h. This procedure gives carbon films with a reproducible resistivity of 1.6 ± 0.2 m Ω -cm. Metal pads, 10 nm thick, composed of a Cr-Ni alloy are then evaporated onto the carbon film to provide for electrical contacts to measure the resistance of the carbon film. Finally, silicon overlayers are deposited to provide energy discrimination. The probe was electrically isolated from the chamber at 17 cm downstream from the ECR source.

The resistance change in carbon films caused by ion bombardment has been well characterized⁴. The dependence of the resistance change on energy and fluence of the particles and on their mass and atomic number has been

examined and from these studies a model was developed to describe the resistance change. The basic assumption is that the resistance of the film can be described by a local resistivity:

$$\rho(x) = \rho_0 + \alpha\phi\Gamma(x) \quad (1)$$

which increases linearly with the amount of energy deposited into atomic displacements of the carbon atoms at depth x where ρ_0 is the initial resistivity of the carbon, ϕ is the particle fluence, and α is the change in resistivity per unit damage. The damage profiles $\Gamma(x)$ used in this model are calculated using a version of the TRIM Monte Carlo particle transport code⁷ modified by Brice⁸ for multilayer targets and to include a monoenergetic distribution for the energy of the incident particles and an isotropic distribution for the angle of incidence. Integrating over depth, the resistance R of a film of thickness τ is given by:

$$R = \frac{1}{\tau} \int_0^\tau \rho(x) dx \quad (2)$$

Lateral dimensions cancel out here since length = width for the samples used in this study. In the limit for low fluences ($\alpha\phi\Gamma \ll \rho_0$), the change in resistance is given approximately by:

$$\Delta R \approx \frac{\alpha\phi}{\tau^2} \epsilon E \quad (3)$$

where E is the energy of the incident particle and ϵ is the fraction of this energy which goes into damage in the carbon. Calibrations⁴ have been done to determine the energy dependence of ΔR . The value giving the best fit here was $\alpha = 1.1 \times 10^{-26} \Omega \text{ cm}^4/\text{eV}$. The model predicts a cutoff when the maximum energy transferred in collisions is less than the displacement threshold. From the calibration data, the model fits fairly closely to the energy

dependence calculated using a displacement threshold of 5 eV. A fuller discussion of the displacement threshold is given in references 4. To a first approximation the resistance change at low doses is nearly proportional to the incident particle energy in the range 30 to 1600 eV. In this range, the fraction ϵ of energy into damage is 0.2 ± 0.05 for hydrogen. Thus if the particle energy is known, the fluence can be determined from the measured resistance change using Eq. (3) and the calibration curves in reference 4.

Resistance probes can be used to determine particle energy either from the saturation of the resistance change at high fluences when the carbon thickness is greater than the range of the particles, or at low doses using a Si overlayer comparable in thickness to the range of the particles as illustrated in Fig. 1. Since the particles lose some of their energy in passing through the overlayer, the damage and the resulting change in the resistance is less for the carbon with the overlayer than for the adjacent uncovered carbon. The ratio between the resistance change for the carbon with and without the overlayer can therefore be used to determine the incident particle energy. At sufficiently low energies, the particles are stopped by the overlayer and there is no change in the underlying carbon giving a low energy cutoff. The configuration that was used in this study was a triple probe with 2 nm, 3 nm, and 4 nm silicon overlayers. At high fluences ($\phi \geq 10^{16} \text{ cm}^{-2}$), the resistance change saturates for uncovered carbon films thicker than the range of the particles because the resistivity of the damaged region becomes much larger than that of the underlying undamaged portion of the film. In the high fluence limit, the resistance of the carbon film is determined primarily by the thickness of the undamaged portion of the film and is insensitive to changes in the fluence.

Results from both Langmuir probe and carbon resistance probe techniques will be compared for the same plasma conditions downstream from the ECR source.

III. Results

A. Langmuir Probe

The plasma conditions near the ECR layer were studied as a function of microwave power (P_f) and are shown in Fig. 2. The magnetic field configuration ($I_1 = 115$ A and $I_2 = 134$ A) was held constant for each measurement. Both curves indicate that above 150 Watts, the electron density (N_e) and temperature (T_e) are nearly constant for increasing microwave power. This "saturation" behavior may be due to the cut-off of right-hand circularly polarized (RHCP) waves in an overdense plasma. Experimentally, this phenomena was observed by measuring the transmitted microwave power. Above 150 Watts, the transmitted microwave power increased with increasing forward microwave power. Therefore, the overdense plasma had saturated its ability to absorb the applied microwave power.

The variation of both N_e and T_e , at 17 cm downstream, is shown in Fig. 3 as a function of microwave power. Both plots are mirror reflections of each other. This phenomena is related to the dependence of the electron temperature on the mean free path between collisions. As the density increases, the mean free path decreases between collisional events. Therefore, an electron loses more of its energy on average in a high density plasma than in a low density plasma. The "saturation" effect which was observed near the ECR region is not prominent downstream, and both T_e and N_e

are lower downstream than in the ECR chamber. The complicated recombination processes occurring in the extracted plasma stream have a profound influence on the plasma conditions downstream. Also, microwave absorption is not determined by downstream plasma conditions. Therefore, saturation behavior is not necessarily expected in the downstream plasma. Radial Langmuir probe results in the downstream position indicate that the electron density and temperature are constant 7 cm across the center of the vacuum chamber. This is indicative of the quality of our plasma confinement conditions in the extraction region.

To estimate the energy of the ions extracted from the divergent magnetic field, the plasma potential (V_p) and the floating potential (V_f) were determined from the Langmuir probe I-V characteristics. The ion energy (T_i) is roughly equal to the difference between V_p and V_f . Near the ECR region, T_i is 50 ± 5 eV at 50-300 Watts; and in the downstream region, T_i is 30 ± 5 eV at 50-300 Watts.

B. Carbon Probe

A carbon triple-probe was designed with the ability to detect particle energies greater than 30 eV. The silicon overlayer thicknesses were chosen to range out the following ion energies: (a) 2 nm Si $\Rightarrow T_i \leq 30$ eV, (b) 3 nm Si $\Rightarrow T_i \leq 40$ eV, (c) 4 nm Si $\Rightarrow T_i \leq 50$ eV. Hence, the separate energy bins defined by the different overlayers yield the capability to investigate the presence of a high-energy tail (e.g., 50-100 eV). The underlying carbon film was 50 nm thick. The change in resistance for this probe for 50 Watts of power are presented in Fig. 4 as a function of time which is directly proportional to the H fluence. After 6 mins, the carbon film with a 4 nm Si overlayer has experienced no resistance change. Therefore, the number of particles with

energies ≥ 50 eV are negligible for this fluence regime (the level of fluence shall be described below). In comparison, the resistance change for the both the 3 nm and 2 nm Si overlayers is indicative of the presence of particles with energies ≤ 40 eV. Also, the large fractional resistance change for these overlayers was a result of high fluences of $3\text{-}4 \times 10^{18}$ ions/cm². For times greater than 6 mins, the fractional resistance change increases markedly for all the overlayers. Rutherford backscattering spectrometry (RBS) showed that for $\phi \geq 4 \times 10^{18}$ H/cm² the Si overlayer was eroded at a rate of 1.25 nm/min. In the time range of 6-14 min, the sputtering of the Si overlayers increases the particle fluence onto the underlying carbon film, and eventually the Si overlayers become so thin (less than 1 nm) that the carbon film is directly attacked by the incident particles. Elastic recoil detection (ERD) of the carbon probe indicated that approximately 10.6 nm of the carbon film had been sputtered after 32 min.

To confirm these results, another carbon triple-probe was placed in the plasma edge region at ≈ 2 cm outside the plasma stream. This probe was exposed to smaller fluences and therefore operates as a resistance probe for which particle energies can be measured from the saturation of the resistance change. The normalized resistance change for this probe, with a 3 nm Si overlayer, saturated at a value of 0.02. Figure 5 shows the calculated resistance changes as a function of fluence corresponding to different H ion energies; and compared to the measured saturation value of 0.02, the particles have energies of 30 to 35 eV. Although the angle of incidence of particles impinging on the probe is complicated by both the ion gyration orbits and the neutral random orbits, this result is a reliable estimate of the particle energies and is in agreement with the previous carbon triple-probe results.

In order to directly measure the large hydrogen fluence in the plasma stream, a carbon probe was developed which was based solely upon sputtering. Roth and Bohdanský⁹ have examined the physical and chemical sputtering of graphite as a function of H-ion energy and they showed that for H particle energies ≤ 50 eV the predominant sputtering mechanism was chemical. The chemical sputtering yield is approximately constant at 5×10^{-3} atoms/ion. For high fluences, the resistance change of an uncovered C layer is based upon the change in the thickness of the carbon film due to sputtering as a function of fluence (fluence rate times time). The fractional resistance change caused by particle damage saturates after a few minutes (≈ 2 min) and contributes a negligible amount to the observed resistance change. Thus, a simple relationship can correlate resistance (or conductance) changes for uncovered C probes and the H fluence based upon chemical sputtering.

The resistance (R) of the carbon film can be expressed in terms of the resistivity (ρ), the length of the film (L), and the cross-sectional area ($A = \text{width} \times \tau$):

$$R = \rho L / A = \rho L / w \tau \quad (4).$$

If all quantities except the thickness (τ) are constant with time (t), then the change in the normalized conductance ($S = 1/R$) with time is given by:

$$\Delta S / S_0 = - \Delta \tau / \tau_0 \quad (5),$$

where S_0 is the initial conductance at the beginning of the experiment and τ_0 is initial thickness of the film. Figure 6 shows the change in the normalized conductance increases linearly with time for an uncovered carbon resistance probe at the downstream position in a 50 Watt ECR hydrogen plasma. The hydrogen (ion and neutral) fluence rate, $\Delta \phi / \Delta t$, can then be determined from the slope of the curve in Fig. 6 as follows. $Y_H \Delta \phi = N \Delta \tau$, where $N = 10^{23} / \text{cm}^3$ is the atomic density of carbon, $Y_H = 5 \times 10^{-3}$ is the chemical sputtering yield. Therefore, $\Delta \phi / \Delta t = (N / Y_H) \Delta \tau / \Delta t = - (N \tau_0 / Y_H S_0) \Delta S' / \Delta t$, i.e. the change in the

normalized conductance is directly proportional to time with a proportionality constant equal to: Y_{HSO}/Nr_o . This simple model gives an accurate sputtered thickness when compared with ERD analyses of exposed carbon resistance probes and yields $\Delta\phi/\Delta t = 1 \times 10^{16} \pm 2 \times 10^{15}$ H/cm²-sec.

IV. Discussion

The fluence rate determined from the carbon resistance probe results can be directly compared to the fluence rate determined from Langmuir probe measurements. Both the measured ion density (N_i) and ion energy ($T_i \approx V_p - V_f$) are used from the Langmuir probe I-V characteristics. The ion density, calculated from the ion saturation current, was 8×10^8 cm⁻³ and T_i was 30 eV. The ion fluence rate is given by: $\Delta\phi/\Delta t = N_i v$. The ion velocity (v) was calculated from T_i yielding $v = 8 \times 10^6$ cm/sec. Therefore the ion fluence rate determined from the Langmuir probe is: $\Delta\phi/\Delta t = 5 \times 10^{15} \pm 2.5 \times 10^{15}$ ions/cm²-sec. This ion fluence rate agrees extremely well with the fluence rate given by the carbon probe for both ions and energetic neutrals. In general, the fluence rate determined from the carbon probe is expected to be larger than that determined from the Langmuir probe because of the additional energetic neutrals, however further measurements are needed to accurately determine the partition between ions and energetic neutrals.

Both diagnostics (Langmuir probe and carbon resistance probe) yielded a measured ion energy of 30 ± 5 eV downstream from the ECR region for the same magnetic field configurations. This measured T_i can be compared to a theoretical value given by Matsuo² based upon divergent magnetic field extraction:

$$T_i \approx -T_e (1 - B/B_0) \quad (11)$$

where T_e is the electron energy in the ECR region, B is the magnetic field at the downstream position, and B_0 is the magnetic field in the ECR region. At 50 Watts and for the magnetic field configuration given above ($B=30$ Gauss), the theoretical ion energy is $T_i \approx 28$ eV (for $T_e \approx 30$ eV from Fig. 2), which is in excellent agreement with the experimentally determined ion energy.

V. Conclusion

Electron Cyclotron Resonance (ECR) hydrogen plasmas are sources of high fluence and low energy particles. This study has developed the use of carbon probes for characterizing ECR hydrogen plasmas. Measurements of the fluence rate and ion energy from the carbon resistance probes agreed well with analyses from a fast-injection Langmuir probe. The measured ion energy 17 cm downstream from the ECR chamber at a magnetic field of 30 Gauss was 30 ± 5 eV. Also, the fluence rate was determined to be between 5×10^{15} and 1×10^{16} /cm²-sec. Finally, the measured ion energy was consistent with the ion energy predicted by the theory developed by Matsuo².

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Figure Captions

Fig. 1. Resistance probe consists of a quartz substrate with a thin carbon film covered on one side by a silicon overlayer (side view above with expanded vertical scale, top view below). A constant current is supplied through the two outer contacts and the voltage drop is measured across the two inner pairs of contacts.

Fig. 2. Electron density (n_e) and electron temperature (T_e) as a function of forward microwave power (P_f) in the ECR chamber. The magnetic field configuration was $I_1 = 115$ A and $I_2 = 134$ A.

Fig. 3. Electron density (n_e) and electron temperature (T_e) as a function of forward microwave power (P_f) downstream from the ECR chamber. The magnetic field configuration was $I_1 = 115$ A and $I_2 = 134$ A.

Fig. 4. Normalized resistance change for a carbon resistance probe with silicon overlayers for energy discrimination as a function of time. The probe was oriented normal to the plasma stream and in the downstream position. The magnetic field configuration was $I_1 = 115$ A and $I_2 = 134$ A.

Fig. 5. TRIM calculated normalized resistance change as a function of fluence for a carbon resistance probe with a silicon overlayer of 3 nm.

Fig. 6. Normalized resistance change as a function of time for a carbon sputter probe. The probe was oriented normal to the plasma stream and in the downstream position. The magnetic field configuration was $I_1 = 115$ A and $I_2 = 134$ A.

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Fig. 1

Fig. 2

Fig. 3

Fig. 6

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