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Measurements of the presheath in an electron cyclotron resonance etching device

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Abstract. The first direct measurement of a collisional Bohm presheath from plasma potential measurements is given. By measuring the presheath thickness in front of a grounded wafer stage, a determination of the collision mean free path for ions in an electron cyclotron resonance etching tool has been made. Presheaths were measured in N_2 and CF_4 plasma using an emissive probe. The presheath thickness in N_2 was found to be linearly dependent on the mean free path. Measurements of CF_4 plasmas, for which the collision cross sections are unknown, have shown results similar to those found for nitrogen. This result has enabled an extrapolation to be made of the effective cross section for collisions in plasmas created from CF_4.

1. Introduction

In recent years, the drive for smaller, more powerful electronic devices has pushed industry toward smaller etched features on wafer substrates. These small features are easily eroded in the etching process, so anisotropic etching is very desirable. Etch anisotropy is limited by the distribution of ion trajectories bombarding the wafer [1]. These trajectories are largely determined in the sheath region in front of the wafer where the ions gain most of their energy. Collisions between ions and neutrals in the sheath are particularly troublesome because they tend to randomize the ion trajectories.

Low pressure etching tools such as electron cyclotron resonance (ECR) plasma devices have demonstrated high etch anisotropy due to the nearly normal incident bombardment of energetic ions [2]. This result is due mainly to the lack of collisions in the sheath at lower pressures.

The number of collisions an ion will encounter is characterized by the mean-free path for collisions. In ECR tools, the collision mean-free path for typical etching pressures is many times larger than the sheath thickness. On the other hand, higher pressure etching tools, such as reactive ion etchers, exhibit mean-free paths many times smaller than the sheath [3].

Generally, plasmas exhibit three regions: the sheath, the presheath and the bulk region. The bulk region, which is closest to the source, is mobility limited in ECR tools [1] and characterized by a small ambipolar electric field. The region closest to the wafer stage is the sheath with a large potential drop. The bulk region and sheath are connected by a presheath with an intermediate electric field.

A presheath is a quasi-neutral transition region between the sheath and the bulk plasma which the plasma creates to satisfy the Bohm sheath criterion [4]. To satisfy this criterion, the ion velocity at the presheath-sheath boundary needs to be at least the ion acoustic speed:

$$c_s \equiv \sqrt{\frac{T_e}{M}}$$

where T_e is the electron temperature and M is the ion mass. This assumes that the electron temperature is much greater than the ion temperature. As a result, there exists a potential drop in the presheath of

$$\varphi \geqslant \frac{T_e}{2e}$$

In general, the total dimension of the presheath can depend on the size of the device, the ionization mechanism, the collision mean-free path, etc. Much theoretical research has been published on the subject of presheaths. A recent review article by Riemann [5] summarizes some of these investigations and provides many references.

To our knowledge, only two experimental efforts have been published on the measurements of presheaths. One of these was an emissive probe study of a presheath in a multidipole confined filament discharge in argon [6]. The device was operated at pressures ranging from 0.8×10^{-4} to 4×10^{-4} Torr resulting in densities from 3.4×10^9 to 2.75×10^{10} cm^{-3} and electron temperatures from 0.75 to 2.2 eV. The plasma potential measured in the presheath was found to agree with a simplified version of the plasma-sheath equation. A laser-induced fluorescence measurement of the ion flow velocities in an ECR device has also been published [7]. Using Doppler shifts in the fluorescence of singly ionized argon ions, the measured presheath velocities at an electron temperature of 14 eV and density of 3×10^{11} cm^{-3} were found to satisfy the Bohm sheath criterion.

The current work is the first direct measurement taken of the presheath thickness by investigating the plasma potential profile in an ECR device. It was found that the presheath spatial dimension is approximately proportional to the collisional mean-free path. This result enables mean-free paths to be determined, in systems where the mean-free path is unknown, by measuring the presheath width. The apparatus and diagnostics used in this investigation will be discussed in section 2. Section 3 lists the results of these measurements and a discussion of these results is contained in section 4.

2. Experimental apparatus and diagnostics

These experiments were performed in an electron cyclotron resonance (ECR) etching device with a grounded wafer stage. This device is made up of two regions: a source region, where the electron cyclotron resonance is maintained and a downstream target region, where the wafer is placed for etching (figure 1). The plasma is produced by a commercial ECR source (ASTeX S1000). A thin anodized aluminum liner has been placed inside the source chamber to reduce sputtering from the stainless steel walls. The magnetic field varies as shown in figure 1. Microwave power of up to 1000 W at 2.45 GHz is input to the source through a quartz window at the end of the chamber. The plasma drifts from the source, more or less following the magnetic field lines, into the target or downstream chamber. (Ionization also occurs in the downstream chamber from electrons in the tail of the Maxwellian.) Plasma can be maintained at neutral pressures ranging from 0.5 to 4 m Torr with flow rates of 10 to 100 sccm without throttling the diffusion pump.

In the experiment, a silicon wafer was attached to the stainless steel wafer stage which was then positioned 10 cm outside the source region (see figure 1). Although the stage has the capability of being RF self-biased to increase the energy of the bombarding ions, the stage was grounded for these experiments.

Measurements of plasma potential were taken using an emissive probe utilizing the inflection point method in the limit of zero emission [8]. We were able to resolve potentials to within 0.1 V with the probe. Positions were resolved to 0.1 cm using a mechanical driver. The probe was a filament of 2% thoriated tungsten, 25 μm in diameter, oriented perpendicular to the magnetic field. It was constructed to make it possible to get within 2.5 mm of the wafer stage. Other plasma parameters were determined using a Langmuir probe [9]. This probe was a one-sided, 6.3 mm diameter tantalum planer disc oriented to face the source.

3. Results

This work was performed in N_2 and CF_4 plasmas with 800 W of microwave power. Neutral pressures of 0.5, 0.75, 1 and 2 mTorr during plasma operation were maintained with nitrogen flow rates of about 12, 19, 25 and 55 sccm and CF_4 flow rates of about 6, 9, 13, and 32 sccm respectively. Plasma potentials were measured point by point along the axis of the device from 0.25 cm to 8.5 cm from the wafer. The plasma potential measurements were made several times at each pressure. A typical set of plasma potential profiles for N_2 is shown in figure 2 and for CF_4 in figure 3.

Axial profiles of other plasma parameters were determined in N_2 with the Langmuir collecting probes. The ion density as a function of pressure (at 800 W) was found to be 1.8×10^{11} cm^{-3} at the source aperture for 2 mTorr and 1.4×10^{11} cm^{-3} for 0.5 mTorr. The densities

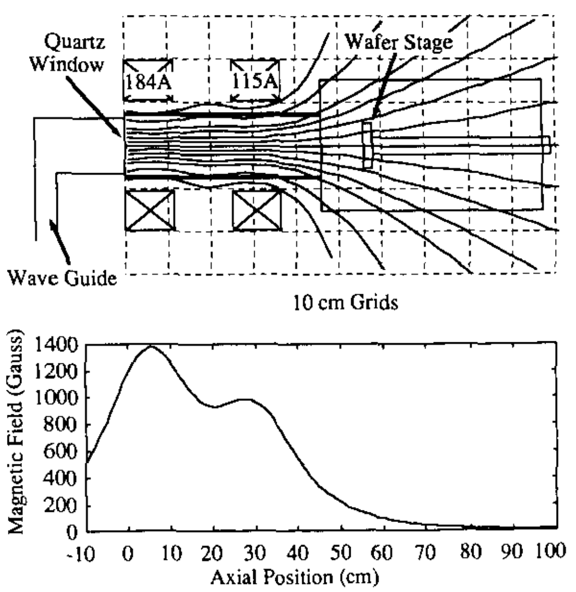

Figure 1. The electron cyclotron resonance etching device showing the position of the wafer stage with magnetic field lines and the field magnitude along the axis.

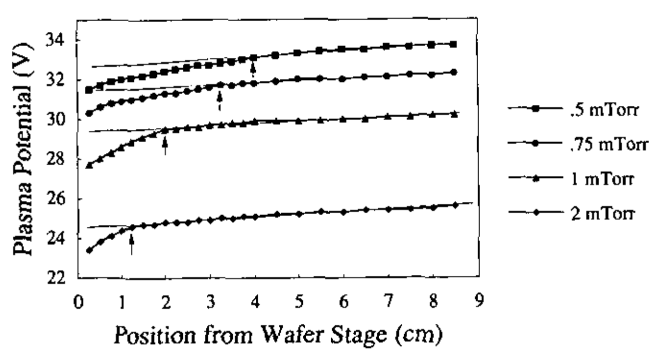

Figure 2. The plasma potential versus position from the wafer stage in an 800 W, nitrogen discharge, measured at the pressures shown, with arrows indicating the point at which the slope changes.

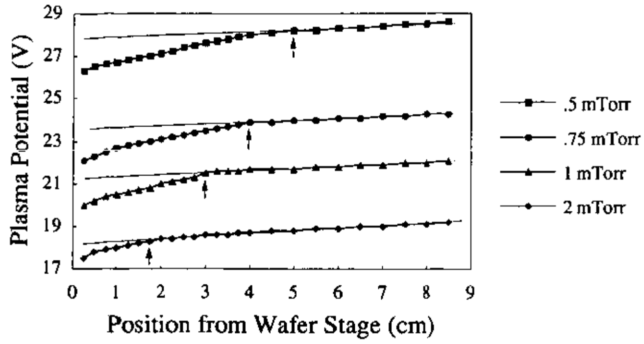

Figure 3. The plasma potential versus position from the wafer stage in an 800 W, carbon tetrafluoride discharge measured at the pressures shown, with arrows indicating the point at which the slope changes.

fell by a factor of 2 from the source to the wafer stage. The electron temperature along the axis was approximately 3.3 eV for 2 mTorr and 4 eV for 0.5 mTorr, both dropping by approximately 10% from the source to the wafer stage. For the given temperatures and densities, the Debye length was approximately 0.003 cm, giving a sheath width at the wafer stage of 0.01 cm.

The plasma potential profiles, shown in figures 2 and 3, exhibit several interesting trends. The plasma potential decreases with pressure from 33.7 to 25.6 V at the aperture, while the ambipolar electric field shows little pressure dependence with a nearly constant value of $0.12\ \mathrm{V\,cm^{-1}}$. The presheath region, characterized by a change in the slope of the plasma potential, has a nearly constant electric field at each pressure. The beginning of the presheath region was taken to be the intersection of the linear slopes of the ambipolar potential and the presheath potential, shown by the arrows in the figures. Because of the small spatial size of the sheath compared with the presheath, the presheath thickness was taken to be the distance from the wafer surface to the intersection. In the N_2 plasma, the presheath width was found to increase linearly with $1/p$, where p is the pressure, from 1.25 cm at 2 mTorr to 4 cm at 0.5 mTorr. In CF_4, the presheath width was 1.75 cm at 2 mTorr and 5 cm at 0.5 mTorr.

The exact plasma potential, ambipolar electric field, and presheath dimensions have been found to be dependent on the chamber wall conditions. However, after many runs with various wall conditions, the linear nature of the presheath dependence on inverse pressure was maintained.

4. Discussion

The mean free path for collisions can be calculated using

$$\lambda = \frac{1}{n_n \sigma}$$

where n_n is the neutral density and σ is the collision cross section. Using the equation for drift velocity in an electric field, $v = KE$, where

$$K \approx \frac{e\lambda}{Mv}$$

one can calculate the cross section for collisions:

$$\sigma = \frac{e}{MK^2En_n}.$$

This assumes the ion velocity with respect to the neutrals to be dominated by the electric field drift velocity. Here K is the mobility of ions in a gas and v is the velocity of the ions with respect to the gas. The mobility of N_2^+ in nitrogen can be determined using data found in the literature for the reduced mobility (K_0) [10], where

$$K_0 = K\left(\frac{P(\mathrm{Torr})}{760}\right)\left(\frac{273}{T}\right).$$

The reduced mobility is dependent on the electric field and the neutral pressure. At each pressure, the electric field, calculated to be $T_e/(2eL)$, where L is the presheath thickness, was used to determine the reduced mobility. Using these values, and assuming a gas temperature of 300 K, the cross section was calculated for each potential profile. The average cross section was $8.7 \times 10^{-15}\ \mathrm{cm^2}$. These values for the cross section were used to calculate the mean free paths.

Figure 4 suggests that there is a simple dependence of the presheath thickness on the mean free path in N_2 with a slope of 1.5. The errors in determining the beginning of the presheath are reflected in the figure. The linear relationship between the mean free path and presheath width makes it possible to determine the mean free path for other gases in this system by measuring the presheath thickness.

Plasma potential axial profiles for CF_4 (shown in figure 3) are similar to those for nitrogen. The collision cross section for CF_4 is difficult to determine because of the complex nature of the ion species after the CF_4 dissociates [11]. Therefore, the similarity between CF_4 and N_2 can be used to estimate the mean free path in CF_4. The presheath widths in CF_4 are approximately 1.35 times the widths in N_2 (figure 5), which gives an effective collision cross section of approximately $6.4 \times 10^{-15}\ \mathrm{cm^2}$.

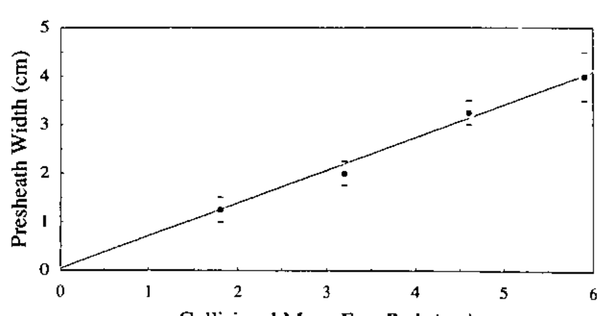

Figure 4. Presheath thickness versus mean free path for collisions in nitrogen with error bars indicating the uncertainty in determining the position for the beginning of the presheath.

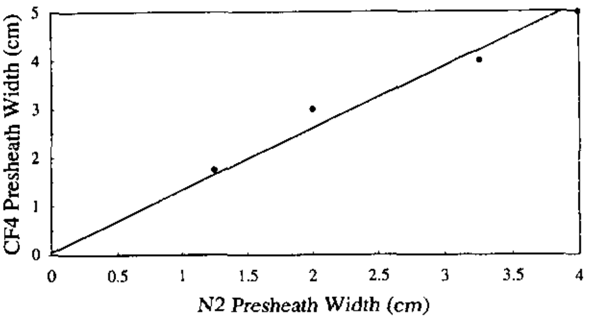

Figure 5. CF_4 presheath thickness versus N_2 presheath thickness.

5. Conclusions

The first direct measurements of collisional Bohm presheaths from plasma potential measurements have been accomplished in an ECR plasma etching tool. The first presheath measurements in an etching gas were also performed. Measurements were taken in N_2 and CF_4 with similar results for each. The thickness of the N_2 presheath was found to be proportional to the mean free path for collisions between ions and neutrals so that the electric field,

$$E \approx \frac{3T_e}{4e\lambda}.$$

Using this dependence on the mean-free path and the similarity between the presheaths in CF_4 and N_2 the previously unknown cross section for collisions in CF_4 was estimated. This is a new technique that can be applied to nearly all etching gases and will help to further the understanding of plasma processes in etching devices.

Acknowledgments

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References

[1] Den Hartog E A, Pershing H and Woods R C 1990 *Appl. Phys. Lett.* **57** 661
[2] Suzuki K, Okudaira S, Sakudo N and Kanomata I 1977 *Japan. J. Appl. Phys.* **16** 1979
[3] Mutsukura N, Kobayashi K and Machi Y 1990 *J. Appl. Phys.* **68** 2657
[4] Bohm D 1949 *Characteristics of Electrical Discharges in Magnetic Fields* ed A Guthrie and R K Wakerling (New York: McGraw-Hill)
[5] Riemann K-U 1991 *J. Phys. D: Appl. Phys.* **24** 493
[6] Meassick S, Cho M H and Hershkowitz N 1985 *IEEE Trans. Plasma Sci.* **13** 115
[7] Gulick S L, Stansfield B L, Abou-Assaleh Z, Boucher C, Matte J P, Johnston T W and Marchand R 1990 *J. Nucl. Mat.* **176/177** 1059
[8] Smith J R, Hershkowitz N and Coakley P 1979 *Rev. Sci. Instrum.* **50** 210
[9] Hershkowitz N 1989 *Plasma Diagnostics Discharge Parameters and Chemistry* ed D Auciello and D L Flamm (New York: Academic)
[10] McDaniel E W and Mason E 1973 *The Mobility and Diffusion of Ions in Gases*, (New York: Wiley)
[11] Plumb I C and Ryan K R 1986 *Plasma Chem. Proc.* **6** 205