Diagnostics of Downstream Microwave Electron Cyclotron Resonance (ECR) Plasma

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Abstract. Diagnostics of downstream plasma generated in a microwave ECR plasma chemical vapour deposition (CVD) facility (a 2.45 GHz, 1.5 KW) is done using a Langmuir probe. The probe is inserted near the substrate location (640 mm away from main ECR zone). The objective is to see the extent of uniformity in the plasma parameters of generated plasma near the substrate location. For this purpose I-V probe characteristics were recorded at four different operating pressures for four different power levels for each pressure to cover the operating range of parameters that are used during thin film deposition. Data was analysed to obtain the radial electron energy distribution function (EEDF) and radial variation of plasma parameters such as electron number density (nₑ), average electron energy (∥E∥), and plasma potential (Vₚ). Ion number density (nᵢ) was also estimated by Orbital Motion Limited Theory (OML) using a Graphical User Interface (GUI) developed for this purpose and compared with nₑ calculated from electron energy distribution function (EEDF). The results obtained by the different methods are compared and observed differences are explained.

1. Introduction
Large volume plasma generated by the microwave ECR mechanism plays an important role in various plasma processing applications. This has large number of applications in the areas of thin film deposition and plasma etching technologies. ECR plasma sources have attracted a lot of attention as they can generate uniform plasma on large area with features like: high degree of ionization / high plasma densities even at low processing pressure (<1mTorr) and efficient gas utilization [1]. Further advantages of the ECR plasmas are low sputtering rates by the incident charged particles and an electrode less design. The physics of ECR microwave plasma discharges have been reviewed by Asmussen [2]. Due to electrode less nature of the ECR plasma, it is also possible to obtain an independent control on ion energy and flux by application of suitable bias (rf or dc bias) on the substrate [3]. We have set up a 2.45 GHz, 1.5 kW microwave ECR plasma processing facility in our laboratory. The plasma diagnostics of the microwave ECR generated plasma is performed by inserting Langmuir probe in the plasma in downstream region near substrate location (640 mm away from main ECR zone) that is used during thin film deposition. Analysis of the spatial distribution of plasma parameters in the reactor chamber by earlier investigators show that the ECR plasma in the upper region (high magnetic field region) has poor radial and axial uniformity of plasma density and electron temperature, whereas the plasma in the down stream region (low magnetic field region) has a...
reasonably good radial uniformity [4]. In the upper part of the source where the magnetic field is high, the ECR plasma is continuously accelerated in the decreasing B direction by a force \( F_z = \mu \nabla B \) (where \( \mu \) is the magnetic moment) and fills the entire processing chamber. Under the influence of strong magnetic field gradient the plasma has poor radial and axial uniformities for both \( n_e \) and \( \langle E \rangle \). However, in the downstream region (processing chamber) the diffusion of ECR plasma is mainly governed by particle collisions, such as ion-neutral and neutral-neutral collisions. As a result of this phenomenon, the plasma in the downstream region is expected to have a radial uniformity. Here we have investigated the radial uniformity of different plasma parameters like \( V_p \), \( \langle E \rangle \), and \( n_e \) at various operating pressures with different microwave power levels for each pressure. Ion number density \( (n_i) \) was also calculated by OML theory and \( n_e \) was calculated from EEDF. Differences that are observed in values of the parameters are explained.

The investigations reported here are useful from the practical point of view as this source is routinely being used for various materials processing applications including thin film deposition on large areas and objective here is to know the maximum area over which plasma parameters remain fairly uniform without affecting the uniformity of the deposited film.

2. Experimental Details

Fig.1: The schematic diagram of the microwave ECR plasma processing system

The schematic of the microwave ECR plasma processing system is shown in Figure 1. The details regarding instrumentation are discussed elsewhere [5]. Cylindrical Langmuir probe made of a tungsten wire of 1.6 mm length and 0.5 mm diameter was inserted radially (perpendicular to the magnetic field) into the processing chamber near the substrate location (820 mm from the quartz isolation window).
This location (where the substrate is located) is at a far away distance (640 mm) from the main ECR zone where the magnetic field is reduced considerably. The grounded chamber was used as a reference and the probe bias was swept from –120 to +20 V with respect to the chamber. Radial variation in the plasma parameters such as \( V_p, <E>, \) and \( n_e \) at the substrate location were estimated by different methods from the I-V characteristics of a Langmuir probe inserted in plasma. The data were taken with variation in microwave power levels (240–420 Watt) at a fixed pressure for different operating pressures (0.9x10^{-4} – 4x10^{-4} mbar) that are typically used during thin film deposition experiments.

3. Analysis of the I V Curves

A typical I–V characteristic of a single Langmuir probe is shown in Figure 2. Plasma potential is found from the zero crossing of the second derivative of I–V curve as shown in Figure 3. The second derivative of I–V curve is also related to the EEDF by a relation given by Druyvesteyn [6-8].

\[
f_e(\epsilon) = \frac{2m_e}{eA} \left( \frac{2e\epsilon}{m_e} \right)^{1/2} \frac{d^2I}{dV^2}
\]

(1)

Where \( f_e(\epsilon) \) is the electron energy distribution function (EEDF), energy \( \epsilon = e(V_p - V) \) given in eV, \( e \) is the charge of an electron, \( A \) is the probe area and \( m_e \) is the mass of an electron. The electron energy probability function (EEPF) as given by the equation (2) is used to verify the nature of the plasma (Maxwellian or non-Maxwellian).

\[
f_p(\epsilon) = \epsilon^{-\frac{1}{2}} \cdot f_e(\epsilon)
\]

(2)

For Maxwellian distribution In EEPF vs E graph shows a linear nature whereas for Druyvesteyn distribution In EEPF vs \( E^2 \) is linear. The plot shown in Figure 4 (In EEDF vs (Electron energy)^2)
clearly indicates Druyvesteyn nature of plasma studied here. To calculate the average electron energy \(<E>\) and electron no. density \((n_e)\) from Druyvesteyn EEPF, we have used the following equations [9]:

\[
\langle E \rangle = 0.55 \left( \frac{d\ln f_p(E)}{dE^2} \right)
\]

\[
n = I_{eo} \sqrt{\frac{m_e}{2 \times <E>}} \times \frac{1}{0.45 Ae}
\]

Where \(I_{eo}\) is the electron saturation current obtained from plasma potential of I-V characteristics [9-10]. The ion density \((n_i)\) was also determined from the Orbital Motion Limited (OML) probe theory [6, 8, 11, 12] using GUI (Graphical User Interface) that was developed to analyze the data. The advantage of using OML theory is that the ion density can be determined without the knowledge of the electron temperature. Here it is assumed that the plasma is isotropic, electron temperature is much higher than the ion temperature \((T_e >> T_i)\) and probe sheath is thick and non collisional. Assuming a maxwellian energy distribution in the unperturbed plasma, the following formula for a cylindrical probe is used to determine the ion current in the OML regime.

\[
I_i = A n_i e^\sqrt{\frac{2}{\pi}} \left( \frac{-eV}{M_i} \right)^{\frac{3}{2}}
\]

where \(I_i\) is the ion current, \(A\) is the area of the probe; \(e\) is the electronic charge; \(M_i\) is the ionic mass (mass of \(Ar^+\) in this study). The slope of the linear relationship between the square of ion current \(I_i^2\) vs the probe voltage in the ion saturation region yields the plasma ion density \(n_i\) without knowledge of the electron temperature.

4. Results and Discussions

Experiments to generate plasma with variation of operating pressure indicate that a stable plasma is generated only when the operating pressure is in the range of \(10^{-3} – 10^{-4}\) mbar. The radial variation in...
the charged particle density \( n_e \) and \( n_i \) at substrate location estimated by different methods is shown in Figure 5.

The values shown here are without the error bars on it. However, it must be mentioned here that the relative standard uncertainty is less than 15 \% for electron temperature, 10 \% for plasma potential and floating potential and 20 \% for plasma density. Taking into account the uncertainty of probe surface area of about 5 \%, the total relative standard uncertainty for the plasma density measurement is around 25 \% [13]. Presence of the magnetic field may lead to reduction in the current drawn from the plasma by the Langmuir probe in the direction perpendicular to the magnetic field because electron tries to follow the magnetic field lines. However, for the conditions of our experiments and for cylindrical probe used during these measurements, this effect can be treated as “large Debye length” collisionless plasma [14, 15]. While using a cylindrical probe for measurements in a magnetized plasma the collisionless conditions can be described as a function of four parameters namely: electron mean free path \( \lambda_e \), probe radius \( r_p \), Debye length \( \lambda_D \) and Larmor radius \( r_L \), that is, \( \lambda_e \gg r_p >\lambda_D \) and \( r_L > r_p \). For the magnetic field at the substrate location between 270 to 340 Gauss and the typical operating pressure ~ 10^{-4} \text{ mbar}; electron mean free path is ~ 1 meter, Debye length is ~ 49 – 93 \( \mu \text{m} \) and Larmor radius for electrons is ~ 124 – 191 \( \mu \text{m} \). Since the ion mass is much higher than the electron mass, the Larmor radius of ions is also much larger, so with a reasonably good approximation, one can also neglect the influence of the magnetic field on the I-V characteristic of the probe.

Plasma potential \( V_p \) calculated from 2\textsuperscript{nd} derivative of I-V characteristic of Langmuir probe data is shown in Figure 6. Considering the uncertainty / errors in the measurements, variation in plasma potential with applied microwave powers for each operating pressure show fair amount of uniformity in the pressure and microwave power range studied here. It means that during the thin film deposition experiments the ions are hitting the substrate with fairly uniform energy indicating uniformity in the coating over the entire pressure and power range investigated here. Figure 7 shows the radial variation in \( <E> \) with different pressure for fixed microwave power levels and also with different microwave powers for fixed pressures.

The observed results show that fairly uniform plasma is generated in the processing chamber over an area having ~ 200 mm diameter (indicating that one can have a uniform deposition of thin films over an area of ~ 200 mm diameter with this source).
Fig 6: (a) Radial variation of plasma potential ($V_p$) with operating pressures for fixed microwave powers. (b) Radial variation of plasma potential ($V_p$) at fixed operating pressure.

Fig 7: (a) Variation of $\langle E \rangle$ with different pressures for fixed microwave powers. (b) Variation of $\langle E \rangle$ with different microwave powers for fixed pressures.

The ion density ($n_i$) calculated using OML theory shows one order of magnitude higher values compared to the electron density ($n_e$) calculated from the EEDF. Earlier investigators have shown that ion-ion and ion-atom collisions within the space charge sheath surrounding the cylindrical probe, as well as the finite length of the cylindrical probe, significantly affect the ion orbital motion and tend to destroy it [6,15,16]. OML theory also assumes that charged particles inside the plasma of all energy graze the probe surface, which is not the case here. Further, there is no concept of absorption radius in this theory [12]. This explains the experimentally observed overestimation of the ion density from the probe data compared to electron densities.
5. Conclusions:
The results of these investigations indicate that the ECR plasma at a far away distance from the ECR zone shows Druyvesteyn distribution of electrons even though its diffusion is mainly controlled by particle collisions such as ion-neutral and neutral-neutral collisions. Actually, this typical Druyvesteyn like distribution is not commonly observed in low pressure ECR plasma in downstream region. These results are interesting and may be due to the change in the boundary conditions at the chamber walls during thin film deposition experiments. The plasma parameters such as charged particle density (n_e and n_i), plasma potential (V_p) and average electron energy (<E>) show a fair amount of uniformity in the central region of processing chamber over an area having ~ 200 mm diameter. In the range of power levels (240-420 Watt) and operating pressures (0.9x10^{-4} – 4x10^{-4} mbar) these parameters do not change significantly indicating that one can deposit thin films over area of ~ 200 mm diameter with fair amount of uniformity. Comparison of electron density (n_e) from EEDF measurement and ion density (n_i) from OML theory confirms that estimation made by OML theory are slightly higher.

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