Impedans Langmuir Probe used to analyse 13.56 MHz and 40 MHz capacitively coupled nitrogen plasmas

INTRODUCTION:

Radio frequency (RF) discharges, microwave discharges and dielectric discharges are employed in various applications such as surface etching, surface modifications and film deposition. RF plasma discharges tend to be more controllable in terms of ion and electron densities - which generally regulates the chemistry during plasma processing. In RF plasma processing, favourable uniformity is commonly achieved along with exceptional stability. Capacitively coupled RF plasma discharges are frequently employed for various types of processing but have certain mode transitions that occur at different power levels and gas pressures that are not fully understood.

To investigate these mode transitions in more detail it is important to establish the key plasma parameters such as electron temperature, the plasma density, and the electron energy distribution function (EEDF). As the RF power is increased, a change is observed between the low current α (low RF power) mode to high current γ mode (high RF power). At low gas pressure, the electrons indicate a bi-Maxwellian type EEDF typical of the collisionless stochastic heating mode while at high gas pressure the EEDF is Druyvesteyn or Maxwellian typical of the collisional Ohmic heating mode. A transition is noticed between these electron heating modes as a function of the gas pressure.

The desired plasma density and ion impact energy can be obtained by controlling the RF driving frequency and the RF power level. While 13.56 MHz is the most commonly used frequency, higher frequencies have begun to be used for various applications in recent years due to evidence of better control of the plasma density as well as the ion flux. The driving frequency strongly impacts the chemical reactions between the active plasma species due to its impact on the dissociation, excitation, and ionization rates. Therefore, understanding the influence of the driving frequency is necessary for determining the physical and chemical properties of RF plasma processing. Hence in this study, nitrogen plasma characteristics are investigated in a capacitively coupled radio frequency plasma driven by two different exciting frequencies of 13.56 MHz and 40 MHz.

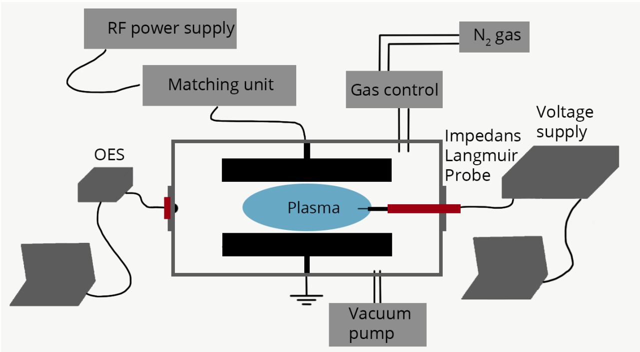

Figure 1. Schematic of the cyclic ALE process.

Nitrogen is a commonly used gas for certain types of plasma process. The Langmuir probe diagnostic along with optical emission spectroscopy have been reported previously at the exciting frequency of 13.56 MHz. However, there is insufficient literature at 40 MHz.

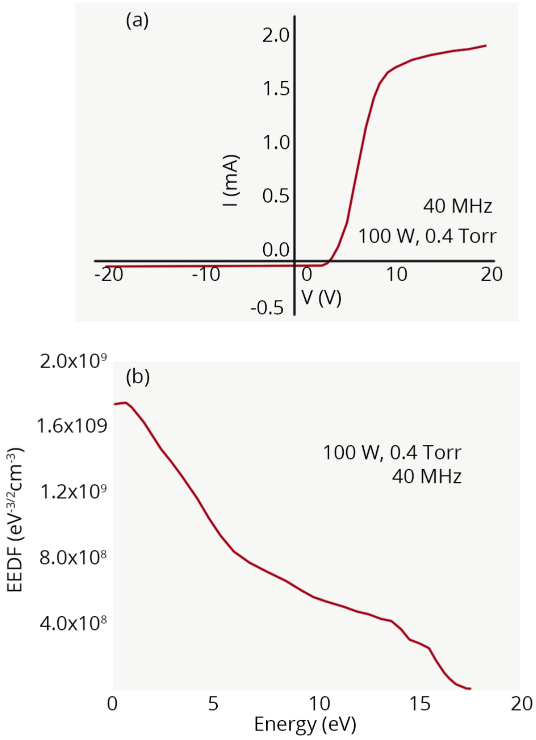

Figure 2. I-V curve (a) and EEDF (b) are shown for 40 MHz frequency.

A previous study by Abdel-Fattah et al investigated the effects of driving frequency changing between 13.56 MHz and 50 MHz, their work is done at limited pressure values (0.06, 0.1, and 0.2 Torr) and at a fixed voltage of 140 V. While this study includes a parametric scan of the RF input power from 25 W to 200 W with an increment of 25 W and the gas pressure from 0.1 Torr to 1 Torr with an increase of 0.1 Torr. Optical emission spectroscopy is performed to characterize the variation of the vibrational temperatures corresponding to the N2 second positive system (C 3Πu − B 3Πg) and the N2 + first negative system (B 2Σ + u − X 2Σ + g). The vibrational temperature is associated with the concentration of the vibrational excitation particles depending on the electron energy loss. The vibrational temperature plays a vital role in defining the shape of the EEDF. A single Langmuir probe is used to measure the electron temperature and the electron density of the nitrogen plasma discharge. All results are discussed in detail.

EXPERIMENT:

The experimental setup consists of a capacitively coupled RF plasma discharge system including two

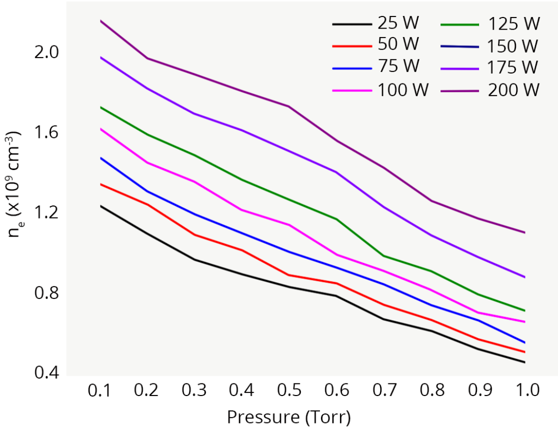

Figure 3. Electron density n_e is shown for 13.56 MHz.

parallel stainless-steel electrodes. The diameter of the electrodes is 20 cm, and the electrode distance is 3 cm. Two RF power generators (13.56 MHz and 40 MHz) supply power through a matching network. RF input power is applied to the upper electrode, and the lower electrode is grounded as shown in Figure 1. The optical emission of the plasma discharge is measured using an optical emission spectrometer. It is a high-resolution miniature UV-Vis broadband fiber optic spectrometer. The current – voltage (I – V) characteristics of the discharge is measured using an Impedans Langmuir Probe System. The probe consists of a tungsten wire with a diameter of 0.4 mm and a length of 10 mm which is inserted into the plasma discharge. The system has a computer controlled voltage power supply with a maximum scan range of -150 V to +150 V and the resolution of the data acquisition is 4.5 mV for the voltage and 4.5 nA for the current.

A. Langmuir Probe:

A single RF-compensated Langmuir probe is used to determine the electron density and the effective electron temperature from the current – voltage (I – V) characteristics. The electron energy distribution function (EEDF) is defined as $F(\varepsilon) = \varepsilon^{1/2} f(\varepsilon)$, where ε is the electron energy in eV, and f(ε) is the electron energy probability function proportional to the measured second derivative of the I – V characteristics, d^2I/dV^2 . Figure 2 shows a sample for the I – V curve and EEDF measured for the RF exciting frequency of 40 MHz at 100 W and 0.4 Torr - where the bi-Maxwellian shape is clearly evident. The electron density n_e and

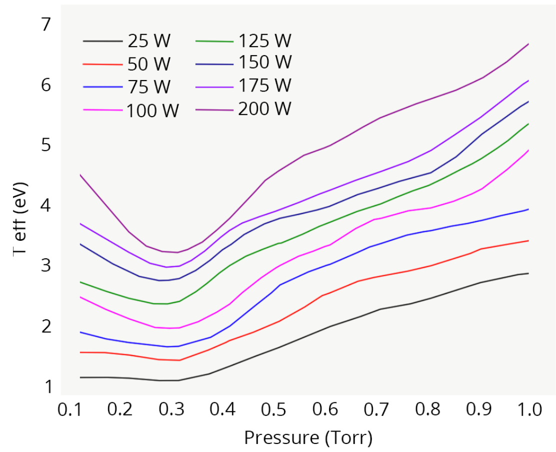

Figure 4. Effective electron temperature (Teff) is shown for 13.56 MHz.

the effective electron temperature T_{eff} were measured for the driving frequency of 13.56 MHz as a function of discharge pressure for a range of discharge power, the results of which are shown in figure 3 and 4 respectively. The electron density n_e decreases gradually as the gas pressure increases from 0.1 Torr to 1 Torr, where there is not sufficient energy for effective ionization. The effective electron temperature T_{eff} firstly shows a decrease up to 0.3 Torr, and then it increases gradually in the pressure range from 0.3 Torr to 1 Torr. The reduction in the electron temperature shows that the vibrational collisions between the electrons and molecules are significant.

The results for T_{eff} for the exciting frequency of 40 MHz demonstrates that with increasing the exciting frequency, the electron density n_e increases while the effective electron temperature T_{eff} decreases. The increase in n_e leads to an increase in the electron collision frequency, and this leads to a reduction of T_{eff} with increasing frequency. At lower exciting frequency a thicker plasma sheath is obtained, and thus the electric field extends deeper into the bulk plasma as compared to the higher frequency. Similar to 13.56 MHz, the electron density decreases with increasing gas pressure. The effective electron temperature drops up to 0.2 Torr and then increases gradually with increasing gas pressure and RF input power. A decrease in the electron temperature is observed due to the higher population of inelastic collisions at low gas pressure. The mode shift from collisionless heating to collisional bulk heating is observed at the gas pressure of 0.2 Torr. Moreover, the mode transition

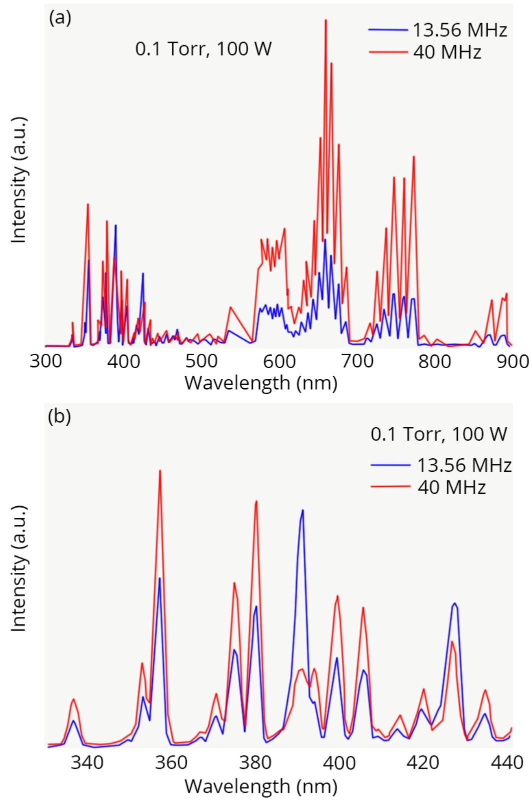

Figure 5. Two frequencies 13.56 MHz and 40 MHz for the whole spectrum (a) and zoomed spectrum (b).

is observed more effectively with increasing RF input power due to the higher energy electrons at high power.

B. Optical Emission Spectroscopy:

The emission of N2 plasma is captured using optical emission spectroscopy with a range of wavelengths between 300 nm and 900 nm (figure 5a). This technique is a non-invasive and an extremely sensitive way to determine the atomic and molecular species obtained in the plasma discharge. Different vibration transitions (v′ -> v″) are observed at the line bands of 337.1 nm, 353.0 nm, 357.7 nm, 366.8 nm and 399.8 nm are shown in figure 5b. Also, the vibrational temperature of N22 is estimated using the Boltzmann plot method which is shown in figure 6.

CONCLUSION:

This study focuses on the characterization of a nitrogen capacitively coupled plasma discharge produced with two different frequencies of 13.56 MHz and 40 MHz using a Langmuir probe and optical emission spectroscopy.

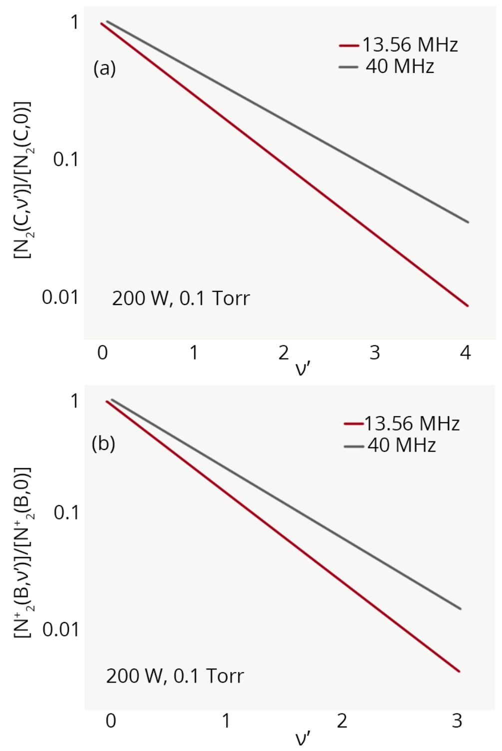

Figure 6. Boltzmann plots for N2(C, ν') vibrational distribution (a) and N2+(C, ν') vibrational distribution (b) at 200W and 0.1 Torr for frequencies 13.56 MHz and 40 MHz.

This study aims to interpret nitrogen plasma discharges at 40 MHz and compare the results with 13.56 MHz discharges, which has not been studied previously in literature using these diagnostics. The electron density n_e, the effective electron temperature T_{eff}, and vibrational temperatures of N2 and N2 + are calculated for different RF input powers and gas pressures. The results show that increasing the RF input power causes a transition from the α-mode to the γ-mode. Between 0.1 Torr and 1 Torr the effective electron temperature T_{eff} decreases up to a certain pressure value and then increases steadily. This behavior is correlated to the transition from a bi-Maxwellian or non-Maxwellian type EEDF corresponding to collisionless stochastic heating mode to a Druyvesteyn type EEDF corresponding to collisional Ohmic heating mode into the bulk plasma - which occurs at 0.3 Torr for 13.56 MHz and 0.2 Torr for 40 MHz. The calculated vibrational temperatures of N2 and N2 + have a gradual decrease after 0.3 Torr for 13.56 MHz and 0.2 Torr for 40 MHz due to the reduction of the relative population of N2(C 3Πu) and N+ 2 (B 2Σ + u) states. The results of Langmuir probe diagnostics are in a good agreement with the optical emission spectroscopy measurements.

REFERENCES:

* D. Mansuroglu, "Capacitively coupled radio frequency nitrogen plasma generated at two different exciting frequencies 13.56 MHz and 40 MHz analyzed using Langmuir probe along with optical emission spectroscopy."

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