Comparative Study of Plasma Parameters in Magnetic Pole Enhanced Inductively Coupled Argon Plasmas*

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Abstract Langmuir probe measurements of radio frequency (RF) magnetic pole enhanced inductively coupled (MaPE-ICP) argon plasma were accomplished to obtain the electron number densities and electron temperatures. The measurements were carried out with a fixed RF frequency of 13.56 MHz in a pressure range of 7.5 mTorr to 75 mTorr at an applied RF power of 10 W and 100 W. These results are compared with a global (volume average) model. The results show good agreement between theoretical and experimental measurements. The electron number density shows an increasing trend with both RF power and pressure while the electron temperature shows decreasing trend as the pressure increases. The difference in the plasma potential and floating potential as a function of electron temperature measured from the electrical probe and that obtained theoretically shows a linear relation with a small difference in the coefficient of proportionality. The intensity of the emission line at 750.4 nm due to 2p\1{}\rightarrow{}1s\2{} (Paschen's notation) transition closely follows the variation of $n_e$ with RF power and filling gas pressure. Measured electron energy probability function (EEPF) shows that electron occupation changes mostly in the high-energy tail, which highlights close similarity of 750.4 nm argon line to $n_e$.

Keywords: MaPE-ICP, Langmuir probe, global model

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1 Introduction

Inductively coupled plasmas (ICPs) have the distinctive features of independently controllable ion energy by RF-bias \textsuperscript{[1\textasciitilde3]}, relatively high plasma number density and low sheath voltage. These properties make ICPs an attractive industrial plasma source. Another distinctive feature of ICPs is the presence of two operational modes, called capacitive mode (E mode) and inductive mode (H mode). The two operating modes are different in their plasmas and electrical properties. At low RF power the discharge represents the E mode, shows a weaker light intensity, relatively low electron number density ($\sim 10^9$ cm\textsuperscript{-3}), and high plasma potential. The E mode is understood to be sustained by the electrostatic field that is produced between the powered end of the RF coil and the ground surrounding. In contrast the H mode, excited by high RF power is characterized by brighter light intensity, high electron number density ($\approx 10^{11}$ cm\textsuperscript{-3}) and low plasma potential. The H mode was studied comprehensively in many papers, while limited numbers of reports were presented for the study of E mode. There are many experimental and theoretical studies on the E to H mode transition \textsuperscript{[4\textasciitilde15]}. LEE et al. \textsuperscript{[12]} presented the skin depths for the stable H mode operation. The critical coil current required for the operation of the H mode is studied by KORTSHAGEN et al \textsuperscript{[4]}. LIEBERMAN and GOTTSCHO \textsuperscript{[16]} developed the global model for high-density discharges of noble gases, and for molecular gases the model is extended by LEE et al \textsuperscript{[17,18]}. The key idea of the global model is to avoid the complication which arises due to spatial variations and to devise a model that contains a large number of reactions in order to model processing plasma with limited computing capacity. The plasma parameters determined from the global model are a suitable tool to predict the dependence of one parameter on the other, and to study the plasma chemistry. It should be emphasized that the global model is not meant to give precise values of the plasma parameters. A comparative study of the simple noble gas model and Langmuir probe measurements performed on a planar inductive argon discharge with varying aspect ratios (length/diameter) was reported in Ref. \textsuperscript{[19]}. In the global model, the reaction rate coefficients for electron collisions were calculated by integrating the collision cross sections over a Maxwellian electron energy distribution \textsuperscript{[17,19]}. Magnetic Pole Enhanced inductively coupled plasma (MaPE-ICP) source is designed for large area \textsuperscript{[20]} plasma generation with high plasma uniformity as well as low ion energy. The MaPE - ICP source is mainly used in the semiconductor industry especially for dry etching. The development of the MaPE-ICP source also has useful applications in so-

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lar cells and flat display panels (FDPs). The dry etching of indium tin oxide (ITO) layers deposited on glass substrates was investigated in the magnetic pole enhanced ICP source showing high resolution structured shapes, good profiles without damaging the layer properties [21]. MEZIANI et al. [22] used a transformer circuit model to illustrate the MaPE-ICP source electrically; this allows describing the microscopical parameters of a MaPE-ICP source by relating them to the electrical parameters calculated on the coil antenna. But very little work has been done to understand the behaviour of different plasma parameters [20] and hardly any reports are presented on EEPFs in two operational modes.

The purpose of this article is to study various plasma parameters in two operational modes in comparison with the volume-averaged global model in a MaPE-ICP source at various pressures (7.5 ~ 75 mTorr) and applied power (10 W to 100 W) with a fixed gas flow rate of 20 sccm. In section 2 we present a description of the global model, experimental setup will be presented in section 3, results and discussion in section 4 followed by conclusions in section 5.

2 Global model

For this model we consider only four reactions shown in Table 1. The neutral particle and charged particle densities are calculated in a cylindrical chamber given below in section 3.

2.1 Particle balance

Two main reactions are considered to evaluate desired plasma parameters. For neutral particle generation the main source is gas flow into the chamber, thus the rate equation for argon neutral species \( n_0 \) can be written as:

\[
\frac{dn_0}{dt} = \frac{Q_{\text{atomic}}}{V} + k_{\text{loss}} n_p - k_{\text{iz}} n_0 n_0 - \frac{n_0 S_p}{V}.
\]  

Here \( Q_{\text{atomic}} \) is the argon atomic density flowing into the chamber per second, \( S_p \) is the pumping speed in m³/s and \( V \) is the volume of the chamber in m³.

The particles balance equation for positive argon species \( n_p \) is obtained by considering the main generation of positive argon atoms due to direct ionization collisions between electron and argon atoms, and the only loss of positive ions considered here is due to wall neutralization, and is given as:

\[
\frac{dn_p}{dt} = k_{\text{iz}} n_p n_0 - k_{\text{loss}} n_p. \tag{2}
\]

2.2 Power balance

It is assumed that the RF power supplied to the system is dissipated in parts, part of the power is utilized in collision processes between neutral atoms and electrons while the surplus power is used in kinetic energy of electrons and ions flowing into the walls of the reactor, thus the power balance equation can be written with the above effects taken in consideration:

\[
\frac{dP_e}{dt} = \frac{P_{\text{abs}}}{V} = e \varepsilon_c k_{\text{iz}} n_0 n_e - e k_{\text{loss}} (\varepsilon_{ew} + \varepsilon_{ew}) n_c, \tag{3}
\]

where
- \( P_{\text{abs}} \) is the total power absorbed (assumed that the RF power absorbed is known).
- \( \varepsilon_c \) is the collisional energy loss per electron-ion pair generated given as:

\[
\varepsilon_c = \varepsilon_{iz} + \frac{k_{\text{exc}}}{k_{\text{iz}}} \varepsilon_{\text{exc}} + \left( \frac{3m_e}{m_{\text{Ar}}} \right) \frac{k_{\text{elas}}}{k_{\text{iz}}} T_e. \tag{4}
\]

- The mean kinetic energy lost per electron loss to the wall is given by \( \varepsilon_{ew} = 2T_e \).
- The loss in mean kinetic energy per ion lost to the wall is the sum of the ion energy entering the sheath and the energy gained by the ion as it crosses the sheath, and is given by \( \varepsilon_{iw} = T_e/2 + V_s \).

The ion velocity entering the sheath is \( v_B \), corresponding to a directed energy of \( T_e/2 \). In Eq. (6), \( \varepsilon_{\text{exc}} = 11.5 \) eV and \( \varepsilon_{iz} = 15.76 \) eV are the threshold energies of the excitation and ionization [24], respectively, and \( k_{\text{elas}}, k_{\text{iz}} \) and \( k_{\text{exc}} \) are the rate constants of elastic, ionization and excitation processes, respectively (see Table 1 for rate coefficients).

2.3 Losses to the wall

The ion flux to the walls is assumed to have a rate coefficient \( k_{\text{loss}} \) given in Table 1, where \( U_B = \sqrt{\frac{e T_e}{m_{\text{Ar}}}} \) is the Bohm velocity, \( m_{\text{Ar}} \) is the ion mass and \( h_L \) and \( h_R \) are the edge to centre positive ion density ratios given as [23]

<table>
<thead>
<tr>
<th>No.</th>
<th>Reaction</th>
<th>Rate coefficients</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>Ar + e → Ar + + 2e</td>
<td>( k_{\text{iz}} = 2.3 \times 10^{-14} T_e^{0.68} \exp(-15.76/T_e) )</td>
<td>25</td>
</tr>
<tr>
<td>(2)</td>
<td>Ar + e → Ar + + e</td>
<td>( k_{\text{exc}} = 2.5 \times 10^{-15} T_e^{0.74} \exp(-11.56/T_e) )</td>
<td>25</td>
</tr>
<tr>
<td>(3)</td>
<td>Ar + e → Ar + + e</td>
<td>( k_{\text{elas}} = 2.3 \times 10^{-14} T_e^{1.61} \exp[0.06(\ln T_e)^2 - 0.12(\ln T_e)^3] )</td>
<td>25</td>
</tr>
<tr>
<td>(4)</td>
<td>Ar + e → Ar (wall loss)</td>
<td>( k_{\text{loss}} = 2U_B(R^2 h_L + RL h_R)/R^2 L )</td>
<td>22</td>
</tr>
</tbody>
</table>

Table 1. Reactions taken in the global mode
that the plasma is quasi-neutral, given as:

\[ h_R = 0.80 \left( 4 + \frac{R}{2 \lambda_i} \right)^{-1/2}, \]  
\[ h_L = 0.86 \left( 3 + \frac{L}{2 \lambda_i} \right)^{-1/2}. \]  

Here, \( \lambda_i \) is the ion-neutral mean free path given by,

\[ \lambda_i = \frac{1}{n_e \sigma_{Ar}}. \]  

The total ion-neutral collision cross section for the argon ions is given by \( \sigma_{Ar} = 1 \times 10^{-18} \text{ m}^2 \) [24].

Balance equation for charged particles is, considered that the plasma is quasi-neutral, given as:

\[ n_c = n_p. \]  

Eqs. (1)~(3) along with Eq. (8) are solved using the modified Rosenbrock formula to obtain the desired plasma parameters.

### 3 Experimental setup

The experimental setup is shown in Fig. 1. In a “Magnetic Pole Enhanced-Inductively Coupled Plasma (MaPE-ICP 200)” source a patented ferrite core is used (Operating manual FHR Anlagenbau GmbH).

![Fig. 1 Schematic diagram of the MaPE-ICP 200 source set-up with magnetic pole enhancement and thin dielectric window](image)

This core concentrates the magnetic field of the induction coil in the plasma chamber and has the effect of increasing intensity in the process, similar to the core of a transformer. Secondly the mechanical strength of the core is used to support the dielectric window which serves as vacuum partition as well the protection between coil and plasma. Because of the ferrite core, the window can be made significantly thinner; as a result the magnetic field strength on the load (i.e. plasma) is increased.

A Langmuir probe is used as a diagnostic tool. The acquisition unit includes its own on-board microcontroller via a co-axial cable that is shielded from the plasma by a ceramic shaft. The reference probe is used to compensate any low frequency DC shift in the plasma potential. The SmartProbe system is operated using the Smart Soft™ program. The DRUYVESTEYN’s method was used for the determination of EEPF [25]. It is extracted from the second derivative of the Langmuir probe characteristic in the electron retardation regime \( (V_e << V_p) \) according to

\[ f(\varepsilon) = \frac{2\sqrt{2m_e}}{e^3} \frac{d^2 I}{dU^2}, \]  

where \( I \) and \( A_p \) are the probe current and probe tip area, \( e \) and \( m_e \) are electron charge and mass, respectively; and \( U = V_p - V_i \) is the probe potential referenced to the plasma potential. The plasma potential is calculated as the zero crossing of the second derivative of the probe current. The EEPF is related to electron energy distribution function EEDF \( F(\varepsilon) \) as:

\[ F(\varepsilon) = \sqrt{\varepsilon} f(\varepsilon). \]  

The chamber is made up of stainless steel, with inner diameter of 340 mm and height of 250 mm and the probe is positioned at the midway (vertically) between the coil and substrate holder (200 mm diameter) and horizontally 90 mm from the edge of the substrate. The separation between coil and substrate is 50 mm.

The inductive (Planner coil) source is powered by a 13.56 MHz (PGF-RF Generator-1600 watt) RF supply. The Matchbox is set in automatic mode so that the capacitors automatically adjust to reach an optimum for minimum reflected power. The chamber is evacuated by a Turbo molecular pump in back up to reach a base pressure of \( 0.075 \text{ mTorr} \). Water is used for cooling the chamber. A Hastings flow meter was used to measure the argon flow rate which was set to 20 sccm. Fiber optics were placed outside the chamber in front of one of the windows of the plasma chamber, collecting the light from the volume of the plasma centre approximately. This fiber is connected to an optical spectrometer (HR4000 CG-UV-NIR) which measures the intensity of the emitted light as a function of wavelength. The wavelength resolution of the spectrometer is 0.5 nm. For the measurement of the argon lines the light was integrated over the full width of the individual lines. We selected argon 750 nm lines for comparison with the probe and global model data.

### 4 Results and discussions

The measurements were carried out in argon discharge in a pressure range of \( 7.5 \text{ mTorr} \) to \( 75 \text{ mTorr} \), each in the power range dissipated in plasma of \( 10 \text{ W} \) to \( 100 \text{ W} \). The plasma parameters are compared with the global (volume-averaged) model. The measured EEPF and OES are shown which support the behaviour of the discharge in E or H mode.
4.1 Effect of RF power on plasma parameters

Fig. 2 demonstrates the change in electron density with RF power at an argon gas pressure of 7.5 mTorr and 75 mTorr. These results were compared with the global model. It is observed that the electron number density increases with increasing RF power, which shows a smooth transition from E to H mode. The variation in electron density is in agreement with the results reported by HOPWOOD et al. [26] and IKADA et al. [27] but with much higher electron density. The higher electron number density in inductive mode is speculated due to the high coupling efficiency resulting from the significantly thin window and the ferrite core used in antenna [28]. At lower RF power the global model is not in good agreement with the measured electron density because of non Maxwellian distribution function as shown in Fig. 3; this corresponds to E mode. At RF power beyond 30 W the measured electron density showed good agreement with the calculated results, this corresponds to H mode and EEPF evolves to the Maxwellian distribution, as shown in Fig. 3.

![Fig.2](image)

**Fig.2** Global model and experimental results showing electron number density as a function of RF power at 7.5 mTorr and 75 mTorr argon gas pressure

![Fig.3](image)

**Fig.3** Measured EEPFs in E and H modes at (a) 7.5 mTorr, (b) 75 mTorr showing bi-Maxwellian distribution in E mode (10 W) and Maxwellian distribution in H mode (100 W)

4.2 Effect of filling gas pressure on plasma parameters

Figs. 4 and 5 show the electron number density and electron temperature as a function of gas pressure, respectively. These figures establish a comparison between the experimental data and the calculated results obtained by the use of the global model. It is observed that experimental results in inductive mode (100 W) are in good agreement with the model while in the capacitive mode (10 W) there is a deviation from the measured values. These results reflect the deviation from the Maxwellian distribution that occurs at RF power lower than 30 W, as can be observed in Fig. 3. In fact, the global model considers a Maxwellian distribution throughout the power and pressure range that makes it inaccurate at low RF power and pressures [23]. The other possible reason of disagreement at low power (E mode) may be due to power coupling efficiency which is about 30% in E mode which is much smaller than the power coupling efficiency in H mode. The measured and calculated electron number densities \( n_e \) increase as the pressure increases, while the electron temperature \( T_e \) decreases. The measured electron temperature at 10 W and 100 W as a function of pressure in Fig. 5 shows weak dependence of electron temperature on RF applied power. Note that at higher pressure the slope of EEPF becomes steeper at the same absorbed power, reflecting the decrease in electron temperature \( T_e \) shown in Fig. 6. At low pressure there is no signifi
The temperature $T_e$ is primarily determined by the charged particle balance. The decrease of the wall loss of the electron-ion pair and the increase of the step ionization frequency with the increase of pressure ($p$) may cause the decrease of the direct ionization frequency, resulting in the decrease of $T_e$. Therefore, the electron number density $n_e$, which is determined by the power balance, increases with pressure ($p$) under the condition of constant RF power. The sheath potential can be related to the difference in plasma potential and floating potential. The difference in plasma potential and floating potential as a function of electron temperature shows a linear relation with a proportionate constant of 4.1, indicating that the sheath potential decreases with the decrease in electron temperature. The comparison of experimental and theoretical results is shown in Fig. 7. Theoretically the difference in plasma potential and floating potential is given by

$$V_p - V_f = \frac{k T_e}{2e} \ln\left(\frac{M_i}{2e}\right),$$

where $M_i$ and $k$ is the ion mass and the Boltzmann constant, respectively.

**4.3 Comparison of OES with Langmuir probe and calculated results (electron density and EEPF)**

Furthermore, the Argon 750.4 nm line, which arises due to transition $2p_{1} \rightarrow 1s_{2}$ (in Paschen’s notation), requires high energy ($\varepsilon_e > 13.48$ eV) electrons. The cascade contribution of 750.4 nm line from higher levels is much smaller and direct excitation from the ground state is larger than other transitions between the $3p^{5}4p$ and $3p^{5}4s$ levels. Due to a shorter radiative lifetime and large transition probability the intensity of this line is quite high. It is observed that the high energy tail of EEPF at 7.5 mTorr and 75 mTorr increases with increasing RF power, which is appropriate to the enhancement of the 750.4 nm line, as observed in Fig. 2. The distortion in the high energy tail of EEPF might be due to signal to noise ratio (SNR) [29]. Therefore Argon 750.4 nm line serves as a good indicator of the high-energy electron number density in argon plasma and supports the results of the global model shown in Fig. 8.

**5 Conclusion**

In this paper we report the behaviour of electron number density and electron temperature at various pressures in pure E mode and dominant H mode in Magnetic Pole Enhanced Inductively Coupled (MaPE-ICP) argon plasma, and compared the results with the global (volume-averaged) model that consists of rate
equations for neutral and charged particles, and an energy balance equation for electrons. The model calculation approximates the experimental results. It is found that the measured and calculated electron number density and electron temperature in H mode are in good agreement, while in E mode the model results deviate from that of experiments. The results show close similarity between argon 750.4 nm line intensity due to $2p_1 \rightarrow 1s_2$ (Paschen’s notation) transition and electron number density ($n_e$) with RF power and filling gas pressure.

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References

25. Druyvesteyn M J. 1930, Phys., 64: 781

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