Measurements of plasma parameters in capacitively coupled radio frequency plasma from discharge characteristics: Correlation with optical emission spectroscopy

B. Bora\textsuperscript{a,b,\,*}, H. Bhuyan\textsuperscript{a}, M. Favre\textsuperscript{a}, E. Wyndham\textsuperscript{a}, H. Chuaqui\textsuperscript{a}, C.S. Wong\textsuperscript{c}

\textsuperscript{a}Department of Physics, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, Santiago, Chile
\textsuperscript{b}Comisión Chilena de Energía Nuclear (CCHEN), Casilla 188-D, Santiago, Chile
\textsuperscript{c}Plasma Technology Research Centre, Physics Department, University of Malaya, 50603 Kuala Lumpur, Malaysia

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A B S T R A C T

Plasma parameters from the discharge characteristics of a 13.56 MHz capacitively coupled radio frequency Ar plasma are evaluated on the basis of homogeneous discharge model for wide range of operating pressure. The homogeneous discharge model of capacitively coupled radio frequency discharge is modified to take into account the nonlinear plasma series resonance effect. The effect of drift velocity of the electron due to change in radio frequency electric field and operating pressure is also considered. Considerable dependent of plasma parameters on the drift velocity of the electron as well as on the plasma series resonance effect are observed in low pressure. An irregular variation of calculated plasma density with operating pressure is observed, which is reconfirmed with optical emission spectroscopy. © 2013 Elsevier B.V. All rights reserved.

1. Introduction

Radio-frequency (rf) plasma is widely used as a low temperature plasma-processing medium for material processing in many fields including microelectronics, aerospace, and biology [1–4]. Being a source of energetic ions, chemically active species, radicals and also energetic neutral species, rf discharges are widely used in etching, deposition and surface treatment, particularly in the semiconductor industries. Although, several processing work is done on an empirical basis for a particular device, a full characterization is desirable for reproducibility, consistency, better understanding the process, and more importantly transformation of processes from one device to another [5]. The yield of ion implantation in different plasma-processing techniques like plasma enhanced chemical vapour deposition; plasma immersion ion implantation etc. strongly depends on the plasma parameters [6]. It is therefore important to investigate the plasma parameters, namely electron density \(n_e\) and temperature \(T_e\) in such plasmas.

There are several diagnostic techniques employed to study the plasma parameters which includes Langmuir probe, plasma spectroscopy, microwave and laser interferometries, and Thomson scattering [7–11]. In addition, several techniques have also been reported in the recent years to characterize atmospheric pressure capacitively coupled radio frequency (CCRF) plasma in different experimental conditions [12–15]. In atmospheric pressure CCRF plasma, the electrical discharge characteristic can be used to estimate the plasma parameters, which is simpler, easier, quicker, and without the use of any additional equipment. Li et al. [12] estimated the plasma parameters from the discharge characteristics of atmospheric pressure CCRF plasma by using equivalent circuit model (ECM). They have estimated \(n_e\) in a mode of atmospheric pressure CCRF plasma by considering that \(n_e\) is only proportional to the rms value of current \(I_{\text{rms}}\), i.e. \(n_e = a I_{\text{rms}}\), assuming the proportionality coefficient \(a\) depends trivially on the drift velocity of the electrons in the bulk of the plasma. It is known that due to higher plasma frequency than the typical applied rf frequency in CCRF plasma, the rf electric field influences the electron velocity, which is known as drift velocity. However, the acceleration of the electrons by rf electric field is restricted by collisions in atmospheric pressure, which of course limit the increase of the drift velocity. Thus, the drift velocity of the electrons has very little effect on the discharge characteristics in atmospheric pressure CCRF plasma and the
assumptions $\alpha = \text{constant}$ is suitably valid. But, in low pressure, which is important in material processing works, when the electron gain more energy from the applied electric field by increasing its drift velocity due to the less electron neutral collision, this assumption would not be valid and the method adopted in ECM could not be used suitably to evaluate the plasma parameters. In addition, the nonlinear plasma series resonance (PSR) effect is also dominant and produces several harmonics to the rf current in low pressure, particularly in mTorr range [16–19], which also need to be considered while evaluating the plasma parameters. It is worth to mention here that the homogeneous discharge model has been suitably used to study the plasma series resonance effect in low pressure CCRF plasma [20] along with characterization of the atmospheric pressure glow discharge plasma [21] and microplasma device [22].

In this paper, we report a CCRF plasma characterization results evaluated from the electrical discharge characteristics on the basis of homogeneous discharge model in Ar environment for wide range of pressure. The homogeneous discharge model of CCRF is modified to make it applicable for wide range of operating pressure including mTorr range by adopting the nonlinear PSR effect. In this modified model, the effect of drift velocity of the electrons is also considered. The influence of PSR effect and the variation of the drift velocity of the electrons with rf electric field on the plasma parameters are also discussed. The variation of the plasma parameters with operating parameters is also verified by optical emission spectroscopy.

2. Experimental details

The experiment is carried out in a 13.56 MHz CCRF system. The experimental setup of the CCRF system is shown in Fig. 1. The electrode assembly of the rf discharge consists of two circular disc-shaped parallel stainless steel electrodes separated by 11 cm. The diameter of the lower powered electrode is 8 cm and the upper grounded electrode is 10 cm. The pressure in the stainless steel vacuum chamber was maintained by a combination of rotary and turbo molecular pumps. Series of mass flow controller are also used for maintaining gas flow rates. The discharge current and voltage are measured by a Tektronix TCP0150 current probe and Tektronix HVP-15HF voltage probe. The voltage probe has very high impedance (100 MΩ/1 pF) and therefore it is considered that the voltage probe hardly affect the voltage or current waveforms. The capacitance between the powered electrode and the ground (parasitic capacitance) is found out to be 0.4 pF. The signals are recorded in a Tektronix DPO-4104 oscilloscope for further analysis. An automatic matching network (ENI MWH-5-01) is connected in between the rf power supply and the electrodes to deliver maximum power to the load. The rf power generator (ENI ACG-6B) can deliver up to a maximum of 600 W and is equipped with a pair of meters to monitor simultaneously the forward power and reflected power. Electrical signals from the plasma are recorded only when there is no reflected power from the load. Bulk plasma is produced and filled in the space between the electrodes and the electrodes are covered by sheath regions. The experimental parameters varied are the rf power (10 W–120 W) and Ar pressure (10 mTorr–350 mTorr). The three measured quantities i.e. $I_{\text{rms}}$, $V_{\text{rms}}$, and average power $P$ are used to calculate the plasma parameters from the modified homogeneous discharge model. To study the optical emission spectroscopy (OES) a spectrometer (Ocean Optics USB2000) was used.

3. Modified homogeneous discharge model

In homogeneous discharge model of CCRF, the plasma is divided in two parts: sheath plasma near the electrodes and the bulk plasma. The sheaths near the electrodes contribute a sheath capacitor ($C_s$) and the bulk plasma contributes a bulk plasma resistor ($R_p$) and a bulk plasma inductor ($L_p$). Thus, the CCRF discharge can be considered as a parallel parasitic capacitor ($C_{\text{par}}$) with the plasma as shown in Fig. 2. In the bulk of the plasma, the electron frequency, $\omega_p = n_e e^2 / \varepsilon_0 m$ and the capacitance of the parallel electrodes $C_0$. Can be used to express the inductance of the bulk plasma electron due to the inertia as follows [12,16]

$$L_p = \frac{1}{\omega_p^2 C_0} = \frac{md}{A n_e e^2}$$  \hspace{1cm} (1)

where, $m$ is the mass of electron, $d$ is the distance between the electrodes, $A$ is the surface area of the powered electrode. The plasma bulk is assumed to be quasi-neutral and (for simplicity) homogeneous. The radio frequency current through the bulk of the plasma is carried by electron conduction alone. The dependence of the current density inside the plasma bulk on the electric field can thus be modelled by a generalized Ohm’s law. It takes into account the acceleration of the electrons by the electric field and their momentum loss due to elastic collisions with the neutrals of the background gas. It is well known that the Ohmic and stochastic heating are the main heating mechanism for sustaining plasma in

![Fig. 1. Experimental setup of the 13.56 MHz CCRF system.](Image)

![Fig. 2. Equivalent circuit for the homogeneous discharge model of CCRF plasma.](Image)
low pressure CCRF discharge [15]. The major contribution in Ohmic heating is due to the bulk and edge plasma, whereas the stochastic heating is due to the oscillating plasma–sheath interface. The Ohmic heating is dominant at a high operating pressure for \( \varepsilon_0/d < 1 \) while the stochastic heating is dominant at a low operating pressure for \( \varepsilon_0/d \geq 1 \), where \( \varepsilon_0 \) is the mean free path of the electron in electron neutral collision [15,16,23]. We have here considered the Ohmic as well as stochastic heating since the experiment was performed in wide range of pressure. Thus, considering the Ohmic and hard wall model for stochastic heating, the resistance of the plasma bulk \( R_p \) can be expressed as [12,16,18]

\[
R_p = \frac{(v_m + v_e/l_p)l_p}{\varepsilon_f}
\]  

where, \( v_m \) and \( v_e \) are the electron neutral collision frequency and the mean thermal speed, respectively, \( l_p \) is the length of the plasma bulk. \( \varepsilon_f \) is a correction factor introduced to the plasma resistance to take into account the PSR effect. The reason behind the incorporation of this correction factor is explained below. It was reported that due to the PSR effect the measured rms current is higher than the current predicted by homogeneous discharge interface [17,18]. It has also been experimentally observed that at the beginning of the rf cycle the plasma sheath expands and as a result energetic electron beams are generated [24,25]. The PSR effect enhances the generation of these highly energetic electron beams due to the rapid expansion of the sheath. These electrons travel from the sheath region and propagate through the bulk plasma and enhance the total plasma current. In other words, for time average measurements, this mechanism indicates a reduction in the time average plasma resistance. Thus we anticipated that the measurement in the reduction of plasma resistance will give the quantitative behaviour of PSR effect and its need to be considered while calculating the plasma parameters from the discharge characteristics. The electron neutral collision frequency, \( v_m \) and the mean thermal speed, \( v_e \) can be express in terms of \( n_e \) and \( T_e \) as [13,16,18]

\[
v_m = n_e\pi\sigma^2\left(\frac{8kT_e}{m}\right)^{\frac{3}{2}}
\]

\[
v_e = \frac{8eT_e}{\pi m}^{\frac{3}{2}}
\]

where, \( \sigma \) is the electron neutral collision crosssection. Combining Eqs. (1)–(4), the resistance of the plasma bulk can be expressed as,

\[
R_p = \frac{\sigma}{A\varepsilon_f}\left(8m\pi kT_e\right)^{\frac{3}{2}}\left(1 + \frac{(e/k)^2}{\pi\sigma^2} \frac{1}{n_e}\right)^{\frac{3}{2}}
\]

In homogeneous discharge model, the sheath capacitance can be expressed as [12,16]

\[
C_s = \frac{en_0\varepsilon_0A^2}{2V_{rms}}
\]

where, \( \varepsilon_0 \) is the applied rf frequency. In our experiment, we have found the maximum plasma impedance around 220 \( \Omega \) for the entire experimental ranges varied in this work. On the other hand, the impedance of the parasitic capacitance at 13.56 MHz is calculated to be 29 \( \Omega \), which is sufficiently higher than the plasma impedance for considering the effect of the parasitic capacitor on the current and voltage waveforms. Now, according to the equivalent circuit (Fig. 2) \( I_{rms} \) and \( V_{rms} \) can be correlated as,

\[
V^2_{rms} = I^2_{rms}\left[\frac{8m\pi k}{A\varepsilon_f}\left(\frac{\sigma}{A\varepsilon_f}\right)^{\frac{3}{2}}\left(1 + \frac{(e/k)^2}{\pi\sigma^2} \frac{1}{n_e}\right)^{\frac{3}{2}} + \frac{md\omega}{A\varepsilon_f}\left(2e\varepsilon_0\sigma^3Am\right)^{\frac{3}{2}}\left(1 + \frac{(e/k)^2}{\pi\sigma^2} \frac{1}{n_e}\right)^{\frac{3}{2}}\right]
\]  

Li et al. [12] show that for atmospheric pressure CCRF plasma the variation of the rms value of voltage with current is nonlinear but varies according to one branch of a hyperbola. This is a special case of Eq. (7) in atmospheric pressure, when the drift velocity of the electrons in the plasma bulk depends trivially on the variation of electric field and the PSR effect is negligible. The average dissipated power in the plasma and the rms values of current and voltage can be correlated in terms of the power factor as

\[
P = V_{rms}I_{rms}\cos \phi
\]

where, \( \phi \) is the phase difference between the current and voltage. Based on the equivalent circuit as shown in Fig. 2, Eq. (8) can be expressed as

\[
\cos^{-1}\left(\frac{P}{V_{rms}I_{rms}}\right) = \tan^{-1}\left[\frac{m_0\varepsilon_f}{(8m\pi k)^{\frac{3}{2}}}\left(1 + \frac{(e/k)^2}{\pi\sigma^2} \frac{1}{n_e}\right)^{-1}\times\left(1 - \frac{2e}{e\varepsilon_0\sigma^3Am}\frac{1}{n_e}\frac{T_e}{T_e^{-\frac{1}{2}}}\right)^{\frac{3}{2}}\right]^{\frac{3}{2}}
\]

The power density \( p \) (W/cm\(^3\)) of the plasma can be expressed in terms of \( n_e \) and \( T_e \) as power balance equation [12,16]

\[
p = n_e\varepsilon_0K_{iz}e^{\varepsilon_iz} + n_e\varepsilon_0K_{ex}e^{\varepsilon_iz} + n_e\varepsilon_0K_{el,e-a}e^{3mM}T_e
\]

where, \( K_{iz}, K_{ex} \) and \( K_{el,e-a} \) are the ionization coefficient, excitation coefficient and the electron–atom elastic collision rate coefficient, respectively. These terms along with other terms in Eq. (10) are
described in details elsewhere [12,16,26]. Eqs. (7), (9) and (10) were solved simultaneously to determine \( n_e \), \( T_e \), and \( c_f \).

4. Results and discussions

To characterize the CCRF plasma on the basis of the above mentioned modified homogeneous discharge model, we have performed the experiment in different rf power (10 W–120 W) and Ar operating pressure (10 mTorr–350 mTorr). Following sub-sections explain the dependence of the discharge characteristics and plasma parameters on the rf power and pressure.

4.1. Dependence on rf power

Typical current and voltage waveforms for different rf power at an operating pressure of 35 mTorr are shown in Fig. 3. Considerable distortions in the current waveform are observed probably due to the PSR effect, which is known to be more prominent in low pressure, particularly in mTorr range [17–19]. To study the PSR effect, Fast Fourier Transform (FFT) of the current waveform is performed and is shown in Fig. 4. Several harmonics of the applied frequency are observed in the current waveforms. The intensities of all the harmonics are seen to increase proportionally with increasing rf power with a maximum intensity of the third harmonic. The measured \( I_{rms} \) and \( V_{rms} \) for different rf power at an operating pressure of 35 mTorr are shown in Fig. 5. The plasma impedance (\( X_T = V_{rms}/I_{rms} \)) is found to decrease from 175 \( \Omega \) to 155 \( \Omega \) as the power increased from 10 W to 120 W. Comparing the \( V_{rms} - I_{rms} \) characteristic (inset in Fig. 5) with the previously reported characteristics of atmospheric pressure CCRF plasma [12–14], it is observed that the \( V_{rms} - I_{rms} \) characteristic obtained in our experiment is almost similar with that obtained in atmospheric pressure CCRF plasma for higher current densities. However, for lower current densities the \( V_{rms} - I_{rms} \) characteristic obtained in our experiment is different from atmospheric pressure CCRF plasma. This difference for lower current densities may be due to the change in the bulk plasma resistance with the variation of the electric field at low pressure and the existence of the PSR effect.

The calculated values of \( n_e \) and \( T_e \) for different rf power at an operating pressure of 35 mTorr are shown in Fig. 6. These results are
quite generic for CCRF plasma and the ranges of the plasma parameters are well agreed with the rf compensated Langmuir probe measurements for the same experimental system [2]. It is observed that $T_e$ is initially increased rapidly with increasing rf power and slow down the rate of increment as the rf power increased further. The nonlinear increment of $T_e$ with increase in rf power is probably due to the increasing collisions. Similar trend in variation of $T_e$ and $n_e$ measured by optical emission spectroscopy with operating power was also reported for low frequency hydrogen glow discharge plasma [26]. Unlike the atmospheric pressure rf discharge where $n_e$ only depends linearly on current ($\alpha = \text{constant}$) [12], $n_e$ shows considerable nonlinear dependency with current in low pressure (inset of Fig. 6). The dependency factor $\alpha$ in low pressure initially increases with increasing current and the rate of increment is reduces as the current increases further. The computed values of the $\alpha$ are found to lie in between 6 and 8.

4.2. Dependence on operating pressure

The rf current waveforms recorded at 50 W rf power for different operating pressure are shown in Fig. 7. The distortions in the current waveforms are seen to increase with decreasing operating pressure. It may be probably due to the existence of the PSR effect [17,18]. The increasing number of harmonics with decreasing pressure in the FFT of the current waveforms (Fig. 8) clearly indicates the crucial role played by the PSR effect in the rf discharge at low pressure. The measured values of $I_{\text{rms}}$ and $V_{\text{rms}}$ for different operating pressure at 50 W rf power are shown in Fig. 9. The $V_{\text{rms}}$ decreases with increasing pressure, while the $I_{\text{rms}}$ initially increases with increasing pressure and then decreases with further increase in pressure making $I_{\text{rms}}$ higher in intermediate pressure range. The higher values of $I_{\text{rms}}$ in the intermediate pressure range probably due to the higher contribution of the harmonics current (Fig. 8) [18,27].

The calculated values of $n_e$ and $T_e$ for different operating pressure at 50 W rf power are shown in Fig. 10. It is observed that $T_e$ decreases with increasing pressure. The decrease in $T_e$ is probably due to the increase in collision with increasing pressure. The variation of $n_e$ with pressure shows an irregular trend. It is found that $n_e$ initially increases rapidly with increasing pressure and reaches a maximum value at an intermediate pressure after which it decreases with further increase in pressure. The reason behind this irregular variation in $n_e$ with increasing pressure is probably the combined affect of the collision and the PSR effect. It is customary to assume that the $n_e$ should increase with increase in pressure due to increasing collision. But in lower pressure range, the PSR effect...
plays a significant role and enhances the $n_e$. Recent experimental measurements on CCRF plasma show that at the beginning of the rf cycle the plasma sheath expands and as a result energetic electron beams are generated. The PSR effect enhances the generation of highly energetic electron beams due to the rapid expansion of the sheath. These electrons travel from the sheath region propagate through the bulk of the plasma and enhance $n_e$. As the pressure increases the PSR effect starts diminishing and as a result $n_e$ decreases significantly due to the reduction in PSR effect compared to the increases in $n_e$ due to the collision. As a result $n_e$ decreases with increasing pressure after an intermediate pressure. Recently, it has been pointed out that the measurements of the excitation temperature ($T_{exc}$) by OES could be an efficient characterization of low pressure plasma [28]. The measurements on the variation of $T_{exc}$ with operating parameters may provide some vital variations of $T_e$ with the same operating parameters [28]. In addition, spectral line intensities of emission have been investigated to study the bounce resonance heating in dual frequency CCRF plasma [28]. It has been reported that the variation of the spectral line intensity of Ar (811.4 nm) reflects the variation of the plasma density [29]. Thus, the OES studies of the CCRF plasma are carried out to reconfirm the irregular trend of the variation of $n_e$ with operating pressure. Fig. 11 shows the typical optical emission spectra recorded for three operating pressure at 50 W rf power. The variation of $T_{exc}$ calculated on the basis of Boltzmann plot method [28,30] and spectral line intensity of Ar (811.4 nm) with operating pressure are shown in Fig. 12. Similar with the variation of $T_e$ with operating pressure, the calculated $T_{exc}$ from OES is also found to decrease with increasing pressure. Although, the values of the intermediate pressure for maximum $n_e$ and maximum spectral light intensity are different, a similar trend in variation for both the $n_e$ and light intensity is observed, which reconfirm the irregular variation of $n_e$ with operating pressure as a consequence of PSR effect. The different values of the operating pressure for maximum light intensity and $n_e$ are probably due to the combine effect of $n_e$ and $T_e$ on the spectral light intensities.

5. Conclusions

In summary, a CCRF Ar plasma has been characterized on the basis of homogeneous discharge model for wide range of pressure. The homogeneous discharge model of CCRF discharge is modified to make it applicable in low operating pressure by adopting the nonlinear PSR effect and considering the effect of rf electric field on the drift velocity of the electron. Considerable influence of PSR effect and the variation of the drift velocity of the electron with rf electric field on the plasma parameters were observed in low pressure. The technique used in this study does not interrupt the plasma compared to other plasma characterization techniques like Langmuir probe, which may be considered as one of advantage for this measurement technique. Since the information from the plasma are collected by the discharge characteristics itself, simultaneous measurement of the plasma parameters is suitably possible in processing plasmas without interrupting the plasma and also probably could be coupled with the rf generator or matching unit.

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