INDEPENDENT CONTROL OF ION ENERGY AND ION FLUX IN CAPACITIVELY COUPLED RADIO FREQUENCY PLASMA: A STUDY ON HARMONIC RATIO

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Abstract - Capacitively coupled radio frequency (CCRF) is widely studied in recent years because of its simpler design and high efficiency for different material processing applications. A negative dc potential develops between the bulk plasma and the power electrodes, which is termed as 'self-bias' in RF plasma. This self-bias is generated because of the geometrical asymmetry of the electrodes, which can be achieved by appropriately design the area of the powered and the grounded electrodes. However, independent control of the dc self-bias in single frequency CCRF plasma is not possible, since the changing in any operating parameters change the plasma parameters. In these circumstances, dual frequency CCRF plasma could be useful in controlling the separate control of the dc self-bias and plasma density, which respectively determine the ion energy and ion flux. In addition, the dc self-bias could be artificially generated by an electrical asymmetry effect by means of dual frequency CCRF plasma even though the electrodes are geometrically symmetric. It has been observed recently that the polarity of the dc self-bias could be controlled by adjusting the phase angle between the applied radio frequency voltage waveforms. Based on nonlinear global model, a dual frequency capacitively coupled radio frequency plasma driven by different frequencies of harmonic ratio 1 to 12 has been studied. Fluid equations for the ions inside the plasma sheath have been considered to determine the voltage-charge relations of the plasma sheath. Geometrically symmetric as well as asymmetric cases with finite geometrical asymmetry of 1.2 (ratio of electrodes area) have been considered to make the study more reasonable to experiment. In this presentation, details of the model and the results will be discussed. It has been found that the control of dc-self bias is possible only with the even numbers of frequency ratio. It has been also observed that the influence of phase angle between the two waveforms are prominent in lower harmonic ratio and the influence is almost negligible for higher harmonic ratio. So, for the higher harmonic ratio, only the driving voltages of the waveforms can be used as a controlled parameter, whereas for lower harmonic ratio, the phase angle can be also used as one of the controlled parameters.

I. INTRODUCTION

Capacitively coupled radio frequency (CCRF) plasma have beenextensively used in industrial plasma processing applications in recent years. 1-6. In conventional geometrically asymmetric RF discharge, a dc self-bias is generated naturally because of the different electrode sizes to compensate the total flux of the charge particles to each electrode within one rf period. But, in geometrically symmetric discharge, no such dc self-bias is generated naturally. Recently, it has been shown that the dc self-bias could be artificially generate by applying electrical asymmetry effect (EAE) by means of dual frequency CCRF plasma even though the electrodes are symmetric[7- 9]. The EAE could be achieved by applying an even harmonic of the fundamental. If the applied, temporally symmetric voltage waveform contains an EAE, the sheaths in front of the two electrodes are necessarily asymmetric. In this case, a dc self-bias develops and leads to nonlinear plasma series resonance (PSR) heating even if the electrodes are geometrically symmetric. The basic advantage of the dual frequency CCRF plasma over the single frequency CCRF plasma is the possible independent control of ion energy and ion flux. The driving voltages or power of the two frequencies could be utilized to control the EAE and as a result independent control of ion energy and ion flux may be possible. It has been also reported that the polarity of the dc self-bias also could be control by adjusting the phase angle between the two applied rfvoltage waveforms [9-14]. However, some literature suggests that the increased of high frequency voltage increase the ion flux and some literature suggest the increased of high frequency voltage decrease the ion flux[15-20], which is still not understood clearly. The self-excitation of the PSR may significantly alter the heating of the plasma and need to take into account in order to describe quantitatively correct the heating mechanisms of electrons in CCRF discharges[21, 22]. It have been also revealed that PSR effect is also arises in symmetrically symmetric CCRF plasma if EAE is applied, which lead to enhance the plasma heating [9-14,23].

Several numerical and modeling studies have been reported [10-14, 21] to study the heating mechanism in asymmetric CCRF plasma, ignoring the plasma sheath at the grounded electrode by considering that the grounded electrode is infinitely larger than the powered electrode. It is worth to mention here that, in our previous studies, we have developed a plasma model for geometrically symmetric CCRF plasma on the based on nonlinear global model[21] by considering

the second sheath at the grounded electrodes [9,23,24]. In this work, based on the nonlinear global model, we have studied the influences of harmonic ratios of the applied RF sources on the generation of the dc self-bias and plasma heating in geometrically symmetric dual frequency CCRF plasma. In addition, it was realized that most of the laboratory experiment, the geometrical asymmetry is seeming to be finite, which is neither completely geometrically asymmetric nor geometrically symmetric[24]. Thus, to make the study reasonable to experiment, we have also studied the dual frequency CCRF plasma with incorporating a finite geometrical asymmetry (ratio between the surface areas of the electrodes) of 1.2.

II. THE MODEL AND THE EQUATIONS

Fig. 1. Shows the non-linear global model used to study the influences of harmonic ratios of the dual frequency CCRF plasma. It is a modification of the non-linear global model of asymmetric CCRF discharge [21-26]. The model have been also study the dual frequency geometrically symmetric CCRF plasma by considering the second sheath at the grounded electrode[9,22-24].

In plasma column, it is assumed that the rf current is carried by electron conduction and thus, can be model by Ohm's law by taking 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 as[9,13, 19,21],

$$\nu_{eff} = \nu_m + \nu_e / l_p \qquad (1)$$

where, $\nu_e = \left(8eT_e/\pi m\right)^{\frac{1}{2}}$ is the mean thermal speed of the electron[19,9,21,13] and l_p is the length of the plasma bulk, m and T_e is the electron mass and electron temperature respectively. Due to the inertia of the electron, the plasma bulk also behave like an inductance (L_P) and could be represented as[27-29]

$$L_p = \frac{1}{\omega_{pe}^2 C_0} = \frac{m l_p}{A_p n_e e^2} \qquad (2)$$

where, n_e is the plasma density, $\omega_{pe} = \sqrt{n_e e^2/\varepsilon_0 m}$ is the plasma frequency and $C_0 = \varepsilon_0 A_P / l_p$ is the capacitance of the parallel electrodes.

The electron current inside the sheath at powered and grounded electrode are taken as $I_{e,P} = A_P e n_e \nu_e \exp\left(-V_{S,P}/T_e\right)$ and $I_{e,G} = A_G e n_e \nu_e \exp\left(-V_{S,G}/T_e\right)$ respectively.

Similarly, the ion current inside the sheath at the powered and grounded electrode are taken as $I_{i,P} = A_P e n_e \nu_{Bohm}$ and $I_{i,G} = A_G e n_e \nu_{Bohm}$ respectively, with $\nu_{Bohm} = \left(eT_e/M\right)^{\frac{1}{2}}$ is the Bohm speed and M is the ion mass.

Applying Kirchhoff's law in the model, it can expressed the two sheath charges ($V_{S,P}$, $V_{S,G}$), rf plasma current (I(t))and dc self-bias (V_B) in the following form[9,21-23]

$$\frac{dV_{Sp}}{dt} = -\frac{1}{C_{SP}}\left[I_P + A_P e n_e \nu_{Bohm} - A_P e n_e \nu_e \exp\left(V_{S,P}/T_e\right)\right] \qquad (3)$$

$$\frac{dV_{SG}}{dt} = -\frac{1}{C_{SG}}\left[-I_P + A_G e n_e \nu_{Bohm} - A_G e n_e \nu_e \exp\left(V_{S,G}/T_e\right)\right] \qquad (4)$$

$$\frac{dI_P}{dt} = \frac{1}{L_p}\left[V_{RF1}\cos(\omega_1 t) + V_{RF2}\cos(\omega_2 t + \phi) + V_{SP} - V_{SG} + V_B\right] - \left(\nu_m + \nu_e/l_p\right) I_P \qquad (5)$$

$$\frac{dV_B}{dt} = -\frac{1}{C_B} I_P \qquad (6)$$

In several previous studies the ion density inside the sheath was assumed to be homogeneous [21-28] and equal to that in the plasma bulk, which lead to a quadratic relation between the sheath k(k =G, P) voltage and the sheath charge as given by,

$$C_{S,k}(t) = \left[2en_e\varepsilon_0 A_k^2 / V_{Sk}\right]^{\frac{1}{2}} \qquad (7)$$

In addition, recently it has been also reported that the sheath charge-voltage relation also have higher order term, basically a cubic term, and the relation is slightly deviates from quadratic nature[14]. It is worth to mention here that in CCRF plasma a dc-self bias is generated inside the plasma sheath, which accelerate the ions to the electrodes, which may reduce the ion density inside the sheath from the bulk of the plasma. To taking account theses phenomena into calculation and evaluate the sheath voltage-charge relations, the fluid equations for the ions are incorporated and couple to the Eqs. (3)-(6) as follows. The time varying sheath capacitance of the both the sheath can be expressed in terms of the electrode geometry and sheath thickness ($d_{S,k}$) as

$$C_{S,k}(t) = \frac{\varepsilon_0 A_k}{d_{S,k}(t)} \qquad (8)$$

In order to calculate sheath thickness ($d_{S,k}$) at any time the fluid equations for ions along with the Poisson equation have been considered. Considering

collision less sheath, the variation of the ion density $n_{i,k}(x,t)$, the ion drift velocity $u_{i,k}(x,t)$ and the potential $V_k(x,t)$ inside the sheath k (k =G, P) can be expressed as [29-31],

$$\frac{\partial n_{i,k}(x,t)}{\partial t}+\frac{\partial\left(n_{i,k}(x,t)u_{i,k}(x,t)\right)}{\partial x}=0 \quad (9)$$

$$\frac{\partial u_{i,k}(x,t)}{\partial t}+u_{i,k}(x,t)\frac{\partial u_{i,k}(x,t)}{\partial x}=-\frac{e}{M}\frac{\partial V_k(x,t)}{\partial x} \quad (10)$$

For typical CCRF plasma operated at 13.56 MHz or higher, the ion plasma frequency (ω_{pi}) is much smaller than the applied frequency (ω_1, ω_2) and hence the ions do not respond to the instantaneous sheath potential. In this case, the time dependent terms in Eqs. (9) and (10) can be neglected and the equations can be expressed as[29-31],

$$\frac{\partial\left(n_{i,k}(x)u_{i,k}(x)\right)}{\partial x}=0 \quad (11)$$

$$u_{i,k}(x)\frac{\partial u_{i,k}(x)}{\partial x}=-\frac{e}{M}\frac{\partial V_k(x,t)}{\partial x} \quad (12)$$

The Eqs. (11) and (12) represent the steady state fluid equations for ions. These equations are realized to be valid for describing the ions inside the both sheaths, since the applied frequency of the rf voltage is higher than the typical ion plasma frequency. The electric potential inside the both sheaths are governed by the distributions of net charges inside the sheaths and can be represent by the Poisson equation[29-31],

$$\frac{\partial^2 V_k}{\partial x^2}=-\frac{e}{\varepsilon_0}\left(n_{i,k}-n_{e,k}(x,t)\right) \quad (13)$$

Since the typical electron plasma frequency is higher than the applied rf frequency and the collision frequency, it can be assumed that the electrons are fast enough to respond the instantaneous potential inside the both sheaths. Hence it can be considering that the electron density inside the both sheaths ($n_{e,k}(x,t)$) changes continuously and is given by Boltzmann distribution[29-31],

$$n_{e,k}(x,t)=n_e\exp\left(\frac{e\left(V_k(x,t)-V_k(t)\right)}{k_B T_e}\right) \quad (14)$$

To calculate the sheath thickness from the Eqs. (11)-(14), the following boundary conditions are chosen. The value of the potential at the sheath-electrode interface $(x=0)$ and at the sheath-plasma boundary $(x=d_{S,k})$ are taken as $V_k(0)=-V_{S,k}$ and $V_k\left(d_{S,k}\right)=0$ respectively. It has been also assumed that the ion enter the sheath with a velocity equal to Bohm velocity (v_{Bohm}). At the plasma-sheath boundary the quasineutrality is assumed and hence the ion density set equal to the electron density,

$$n_{i,k}(d_{S,k})=n_e(d_{S,K})=n_e \quad (15)$$

The Eqs. (4) -(7) are solved coupling with equations (12)- (15) with a typical set of plasma parameters, n_e=5x10^{16} m^{-3}, T_e = 1.5ev, l_p=5.7 cm, l_b=0.0027 cm, and $\nu_m=K_m n_g$, where K_m = 10^{13} m^{3}s^{-1}is the rate coefficient, n_g (m^{-3}) =3.3x10^{22} p (Torr) is the neutral gas density, p=2mTorr is the pressure. Both the driving voltage have been varied from 150 V to 250 V for different values of the harmonic ratios of the applied frequency keeping the higher frequency at 27.12 MHz The computation is conducted for two different cases, one is the geometrically symmetric case (ratio of the electrode geometry A_G/A_P=1) and the other is geometrically not-symmetric case (A_G/A_P=1.2). The total dissipation (η_{total}), which is of course the sum of Ohmic and stochastic dissipations are calculated from the rf plasma currents as,

$$\eta_{total}=\left\langle\left(\nu_m+\frac{v_e}{l_p}\right)L_p I(t)^2\right\rangle \quad (16)$$

III. RESULTS AND DISCUSSION

Fig. 2 shows the variation of the time average dc self-bias with driving voltages in the case of geometrically symmetric case, with higher frequency of 27.12 MHz and different low frequency with harmonic ratios of 2,4, 8 and 12 respectively. It has been observed that the dc self-bias is increasing with increasing the lowfrequency voltage for lower ratio of the harmonics. Irrespective of the harmonic ratios, the dc self-bias is found almost constant with highfrequency voltage. However, the variation of the dc self -bias with low frequency voltage is prominent for harmonic ratio of 2. For higher values of the harmonic ratios, the dc self-bias is almost negligible for geometrically symmetric electrodes. The variations of the plasma heating with low and high frequency driving voltages in the geometrically symmetric case, for the harmonic ratios of 2,4,6 and 8. It has been observed that the plasma heating is increasing with increasing the high frequency voltage. Thus, it seems that the independent control of plasma heating, which determine the ion density, without effecting the dc self-bias could be possible by using two frequencies with higher harmonic ratios. On the other hand, for almost independent control of dc self-bias, which determine the ion energy, and plasma heating could be possible by adjusting the low and high frequency voltage respectively with lower harmonic ratio of 2.

Fig. 4 shows the variation of the time average dc self-bias with low and high frequency driving voltages in the case of finite geometrically asymmetry of 1.2for harmonic ratios of 2,4, 8 and 12 respectively.In contrast to the geometrically symmetric case, the dc self-bias is found to increase with increasing either the low and high frequency voltages irrespective of

the harmonic ratios. It is worth to mention here that the phase angle of the applied RF waveforms also plays a crucial role in determining the dc-self bias[32]. However, in the present study, we kept the phase angle constant. Fig. 5 shows the variation of the plasma heating with low and high frequency driving voltages in the case of finite geometrically asymmetry of 1.2 for harmonic ratios of 2,4, 8 and 12 respectively.Similar to the geometrically symmetric case, the plasma heating is found to increase with increase dominantly with high frequency voltage. However, a minor variation of plasma heating is found with low frequency voltage depending on the harmonic ratio. It has been observed that the plasma heating is increasing slightly with increasing low frequency voltage for harmonic ratios of 4,6 and 8, whereas no such increase is found for harmonic ration of 2. Thus, it could be conclude that for independent control of ion energy and ion density, only two frequencies is not sufficient, its required proper combination and phase lock between the applied RF waveforms.

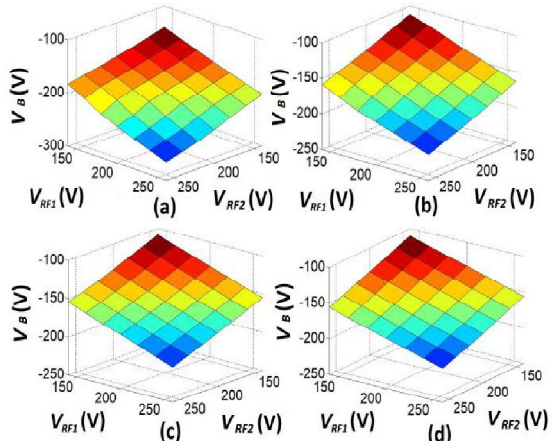


Figure 4. Variation time average dc self-bias with driving voltages in the case of geometrically asymmetric electrode configuration with finite geometrical asymmetry of 1.2 for different harmonic ratios of (a) 2, (b) 4, (c) 8 and (d) 12.

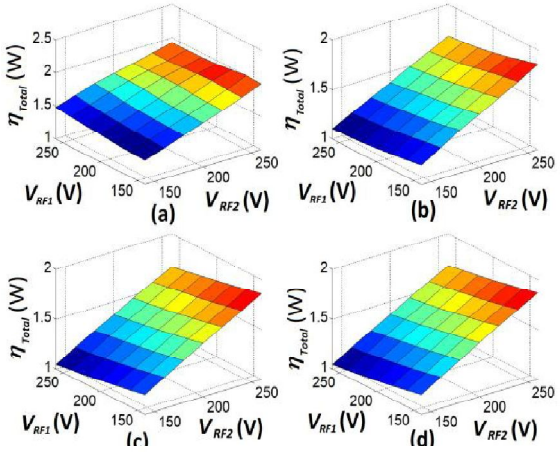


Figure 5. Variation of total plasma heating with driving voltages in the case of geometrically asymmetric electrode configuration with finite geometrical asymmetry of 1.2 fordifferent harmonic ratios of (a) 2, (b) 4, (c) 8 and (d) 12.

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