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Non-linear lumped model circuit of capacitively coupled plasmas at the intermediate radio-frequencies

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A B S T R A C T

The discharge dynamics in geometrically asymmetric capacitively coupled plasmas are investigated via a lumped model circuit. A realistic reactor configuration is assumed. A single and two separate RF voltage sources are considered. One of the driven frequencies (the higher frequency) has been adjusted to excite a plasma series resonance, while the second frequency (the lower frequency) is in the range of the ion plasma frequency. Increasing the plasma pressure in the low pressure regime (≤ 100 mTorr) is found to diminish the amplitude of the self-excited harmonics of the discharge current, however, the net result is enhancing the plasma heating. The modulation of the ion density with the lower driving frequency affect the plasma heating considerably. The net effect depends on the amplitude and the phase of the ion modulation.

1. Introduction

Capacitively coupled plasmas (CCPs) are used extensively in material processing of semiconductors. They have found widespread in many applications such as etching, sputtering, and deposition. Monitoring of the ion flux and the energy of bombarding ions at the substrate is mandatory for the process optimization and the control of the substrate microstructure [1–3]. In conventional single frequency capacitively coupled plasma (1f-CCP), the ion flux and the ion energy bombarding the substrate can't be controlled separately. This of course is a big challenge and gives the motivation to utilize a dual or multi frequency capacitively coupled plasmas [4–7]. Dual frequency capacitively coupled plasmas (2f-CCPs) are claimed to remedied the problem. In the linear regime, the voltage of the high frequency source drops across the bulk leading to electron heating, and, consequently, sustains the plasma via ionization; the high frequency determines the ion flux. The lower frequency voltage drops across the sheath and adjusts the incident ion energy. Moreover, the current through the plasma is simply the superposition of the two "single frequency" spectra. Therefore, the ion flux and the ion energy at the substrate can be separately optimized. In contrast, as in reality, due to the nonlinearity of the discharge, harmonics and sidebands appears in the current spectrum [8–12] and adjustment of the ion flux and the ion energy at the substrate is not always perfect [13].

In this contribution, we show results for the high radio frequency regime, where the driven RF frequency is larger than the ion plasma frequency and very small compared to the electron plasma frequency. In this regime we study the excitation of plasma series resonance at different low pressures. Then, we focus on the intermediate RF regime, where the driven frequencies modulate the ion density in the plasma sheath. Finally, we study the discharge dynamics of 2f-CCPs when the driven frequencies can excite plasma series resonance and modulate the ion density. The relation among characteristic frequencies reads as:

$$\omega_{\text{pi}} \approx \omega_{\text{LF}} \ll \omega_{\text{HF}} \approx \omega_{\text{PSR}} \ll \omega_{\text{pe}}, \tag{1}$$

where ω_{pi}, ω_{LF}, ω_{HF}, ω_{PSR}, and ω_{pe}, are the ion plasma frequency, the low RF frequency, the high RF frequency, the plasma series resonance frequency, and the electron plasma frequency, respectively. In this regime, the nonlinearity and its effect on the total energy budget need clarification. When one of the driven frequencies or an self-excited frequency is in the range of the ion plasma frequency, ions in the sheath oscillate. The modulation of the ion flux at the electrode and other hysteresis effects have been reported theoretically and experimentally [14–18]. For the first time, we will show that distinct RF frequencies from different RF regimes ($\omega_{\text{HF}}/\omega_{\text{LF}} \geq 20$) might also interface and affect the energy budget.

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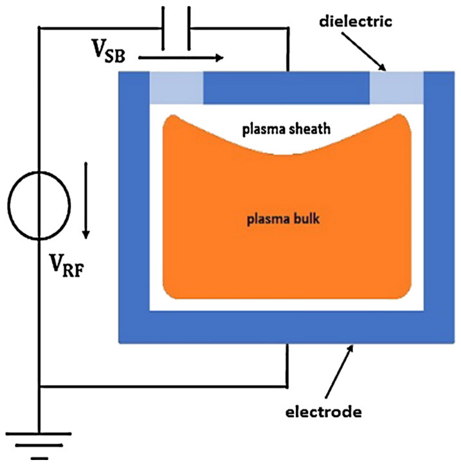

Fig. 1. A schematic set-up of geometrically asymmetric RF CCPs discharge. A self-bias is built in front of the powered electrode.

Because self-consistent kinetic simulations are computationally demanding, we will consider and evaluate a nonlinear global model for 2f-CCPs as displayed in Fig. 1. It is geometrically asymmetric reactor. The area of the powered electrode is much less than the ground electrode. The RF power is derived to the electrodes through a blocking capacitor. The blocking capacitor is charged by all particles leave the plasma and a self-bias is built up providing a thicker sheath in front of the powered electrode than that is formed in front of the ground electrode.

In the next section we introduce details of the lumped model circuit shown in Fig. 2. In section 3, we present results of 1f-CCP works at the plasma series resonance frequency to check our findings with respect to the published results, then we consider the effect of the ion modulation on the plasma series resonance and the energy budget. Finally, section 4 concludes our study.

2. The mathematical model

We revisit and modify the global model implemented by Ziegler et al. [12], where they studied the enhancement of the power dissipation in geometrically asymmetric 2f-CCPS due to the excitation of plasma series resonance beside non-resonant (Ohmic) heating. In a previous study they also derived an exact analytical solution of the nonlinear discharge current equation [9,10]. The exact solution demonstrates the effect of the amplitude of the driven frequencies, the driven frequencies, and the collision frequency on the power dissipation. However, they restrict their results to the high frequency regime, where ions are heavy enough to see only the time averaged fields and electrons obey Boltzmann distribution and follow the time varying fields instantaneously. Here, we would like to know what is going on when driven frequencies or self-excited frequencies are comparable to the ion plasma frequency.

As shown in Fig. 2, the discharge region – the gap between the two electrodes in Fig. 1 – is divided into three distinct regions: The electrode sheath (i.e., the sheath in front of the powered electrode), the plasma bulk, and the ground sheath (i.e., the sheath in front of the ground electrode). Therefore, the lumped element model consists of electrode sheath module, a plasma bulk module based on a fluid approach, and a ground sheath module. The modules are coupled together using Kirchoff's laws with the driven powers to calculate the self-bias on the blocking capacitor self-consistently.

The electrode sheath is RF modulated sheath characterized with three parallel currents, termed the ion, electron, and displacement current. The ion current ($I_i(t)$) is represented as a time dependent current source, where the modulation amplitude of the ion current depends on the ratios of the ion plasma frequency to the RF driven frequencies and to the excited frequencies. Assuming a sheath modulated ion density $n_s(t)$ and a modulated ion speed $u_s(t)$, the ion current reads as $(-en_s(t)u_s(t)A_s)$, where A_s is the area of the powered electrode. Bohm's criterion with $u_B = \sqrt{T_e/m_i}$ is Bohm's velocity at the bulk-sheath edge and n_B is the ion density in the plasma bulk. The electron current $(I_e(t))$ is represented by a reverse-biased diode, where electrons leave the plasma only when their energy is bigger than the sheath potential and/or the electrode is positively biased. Assuming Maxwell–Boltzmann distribution for electrons, the electron current can be expressed as Boltzmann exponential function of the sheath voltage. The displacement current is represented by a variable capacitor. Because the electrode sheath is depleted from electrons, the sheath is treated as a nonlinear capacitor. Its capacitance in a simple form is given as $C(t) = \epsilon(t)s(t)/A_s$, where, $\epsilon(t)$ is the permittivity of the plasma sheath which might be time-dependent due to the ion modulation, $s(t)$ is the sheath width; hence, the nonlinearity of modulated RF sheaths rises up due to the electrons modulation in the high frequency regime and due to the electrons and ions modulation in the intermediate radio-frequency regime.

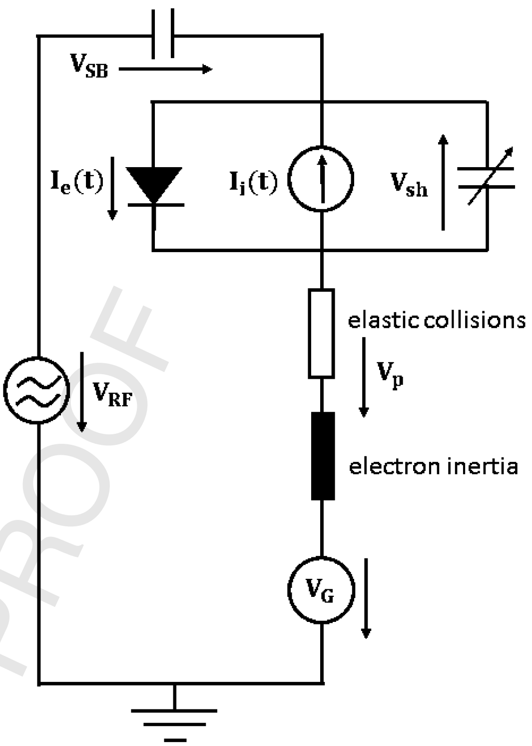

Fig. 2. Lumped element equivalent circuit of geometrically asymmetric 2f CCPs discharge.

Sarting with the current balance equation, the temporal variation of the sheath charge $Q(t)$ is determined by the current from the bulk $(-I)$ and the ion current and electron current to the powered electrode;

$$\frac{dQ(t)}{dt} = -I - en_s(t)A_s u_s(t) + en_B\sqrt{(T_e/2\pi m_e)}A_s \exp(-eV_s(t)/T_e). \quad (2)$$

Ions are assumed to form a time modulated matrix of space charge. Let the plasma/sheath boundary at $s(t)$ and the powered electrode is placed at the origin, then the electron density is vanished for $x < s(t)$ and the electron density equals the bulk density when $x > s(t)$. By the integration of Poisson's equation, one ob-

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