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11 Non-linear lumped model circuit of capacitively coupled plasmas $\frac{11}{12}$ Non-linear lumped model circuit of capacitively coupled plasmas $\frac{77}{78}$ ¹³ at the intermediate radio-frequencies **Alternative Contract Cont**

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20 ARTICLE INFO ABSTRACT 86

21 87 30 Radio-frequency capacitively coupled the set of the se $_{31}$ plasmas $_{97}$ $\frac{32}{2}$ by the limit of the defective regime. *Article history:* Received 27 January 2018 Received in revised form 26 March 2018 Accepted 4 April 2018 Available online xxxx Communicated by F. Porcelli *Keywords:* Global model of capacitively coupled plasmas Radio-frequency capacitively coupled plasmas The intermediate radio-frequency regime Ion modulation

33 99 Plasma heating (ohmic and stochastic heating)

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1. Introduction

40 Capacitively coupled plasmas (CCPs) are used extensively in In this contribution, we show results for the high radio fre- 106 41 material processing of semiconductors. They have found wide- quency regime, where the driven RF frequency is larger than the 107 42 spread in many applications such as etching, sputtering, and de-comparasmal frequency and very small compared to the electron the ¹⁰⁹ position. Monitoring of the ion flux and the energy of bombarding plasma frequency. In this regime we study the excitation of plasma ⁴⁴ ions at the substrate is mandatory for the process optimization series resonance at different low pressures. Then, we focus on the ¹¹⁰ 45 and the control of the substrate microstructure $[1-3]$. In conven-
intermediate RF regime where the driven frequencies modulate $\frac{111}{2}$ ⁴⁶ tional single frequency capacitively coupled plasma (1f-CCP), the the ion density in the plasma sheath Finally we study the dis-47 ion flux and the ion energy bombarding the substrate can't be charge dynamics of $2f$ CCPs when the driven frequencies can excite 113 48 controlled separately. This of course is a big challenge and gives also places accept to modulate the ion density. The relation 114 49 the motivation to utilize a dual or multi frequency capacitively and a propor characteristic frequencies reads as $\frac{1}{2}$ 50 116 coupled plasmas [\[4–7\]](#page--1-0). Dual frequency capacitively coupled plas-51 mas (2f-CCPs) are claimed to remedied the problem. In the linear $\omega \approx \omega r \approx \omega r \approx \omega \omega$ (1) ω (1) ω (1) 117 52 regime, the voltage of the high frequency source drops across the the content of the state of the state of the high frequency source drops across the 53 bulk leading to electron heating, and, consequently, sustains the where $\omega_{\rm pi}$, $\omega_{\rm LF}$, $\omega_{\rm HF}$, $\omega_{\rm PSR}$, and $\omega_{\rm pe}$, are the ion plasma frequency, 119 54 plasma via ionization; the high frequency determines the ion flux. If the low RF frequency, the high RF frequency, the plasma series res-
 55 The lower frequency voltage drops across the sheath and adjusts conance frequency, and the electron plasma frequency, respectively. The 56 122 the incident ion energy. Moreover, the current through the plasma 57 is simply the superposition of the two "single frequency" spectra. Dudget need clarification. When one of the driven frequencies or the tartion. 58 Therefore, the ion flux and the ion energy at the substrate can an self-excited frequency is in the range of the ion plasma fre-
 59 125 be separately optimized. In contrast, as in reality, due to the non-60 linearity of the discharge, harmonics and sidebands appears in the at the electrode and other hysteresis effects have been reported are 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

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25 Available online xxx
26 Communicated by F. Porcelli 25 Porcelli plasma frequency. Increasing the plasma pressure in the low pressure regime (≤ 100 mTorr) is found to 26 Communicated by F. Porcelli
diminish the amplitude of the self-excited harmonics of the discharge current, however, the net result $\frac{27}{\text{Kewords}}$ is enhancing the plasma heating. The modulation of the ion density with the lower driving frequency ²⁸ Global model of capacitively coupled **affect** the plasma heating considerably. The net effect depends on the amplitude and the phase of the ⁹⁴ 29 plasmas and the control of the control a plasma series resonance, while the second frequency (the lower frequency) is in the range of the ion ion modulation.

 37 38 **1. Introduction 1. Introduction 104 1** 39 105 ion energy at the substrate is not always perfect [\[13\]](#page--1-0).

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:

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

61 127 theoretically and experimentally [\[14–18\]](#page--1-0). For the first time, we 62 128 will show that distinct RF frequencies from different RF regimes 63 E-mail address: shihab.plasma@gmail.com.

(*ω*HF/*ω*LF ≥ 20) might also interface and affect the energy budget. 129 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

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charge.

2 *M. Shihab / Physics Letters A* ••• *(*••••*)* •••*–*•••

18 84 **Fig. 1.** A schematic set-up of geometrically asymmetric RF CCPs discharge. A self-bias $_{19}$ is built in front of the powered electrode. $_{85}$

21 Because self-consistent kinetic simulations are computationally de- $\{V\}$ 22 manding, we will consider and evaluate a nonlinear global model \mathbb{C}^d and \mathbb{C}^d and \mathbb{C}^d 23 for 2f-CCPs as displayed in Fig. 1. It is geometrically asymmet-**The contract of the contr** 24 increactor. The area of the powered electrode is much less than the control of the control of the state of the powered electrode is much less than the control of the control of the control of the control of the control 25 91 the ground electrode. The RF power is derived to the electrodes 26 92 through a blocking capacitor. The blocking capacitor is charged by 27 all particles leave the plasma and a self-bias is built up provid- \sim $-$ 28 ing a thicker sheath in front of the powered electrode than that is $\frac{1}{1}$ $\frac{1}{1}$ 29 **formed in front of the ground electrode.** The set of the ground electrode. The set of the ground electrode.

30 96 In the next section we introduce details of the lumped model 31 circuit shown in Fig. 2. In section [3,](#page--1-0) we present results of 1f-CCP current depends on the price of the ion plasma frequency to the 32 works at the plasma series resonance frequency to check our find-
 $\frac{DE}{DE}$ driven frequencies and to the excited frequencies assuming a set $\frac{33}{2}$ ings with respect to the published results, then we consider the $\frac{1}{2}$ these modulated ion density $\frac{1}{2}$ (t) and a modulated ion speed as 34 effect of the ion modulation on the plasma series resonance and $\frac{1}{100}$ (t) the ion current reads as $\left(\frac{1}{100}(t) \frac{1}{100}(t) \frac{1}{100}(t) \frac{1}{100}(t) \frac{1}{100}(t) \frac{1}{100}(t) \frac{1}{100}(t) \frac{1}{100}(t) \frac{1}{100}(t) \frac{1}{100}(t)$ 35 the energy budget. Finally, section [4](#page--1-0) concludes our study.

2. The mathematical model

39 We revisit and modify the global model implemented by Ziegler $\frac{1}{2}$ when their energy is bigger than the sheath potential and/or the ⁴⁰ et al. [\[12\]](#page--1-0), where they studied the enhancement of the power dis-
¹⁰⁶ et al. [12], where they studied the enhancement of the power dis-⁴¹ sipation in geometrically asymmetric 2f-CCPS due to the excitation **the explore of the excitation** surface the excitation of the excitation of the excitation of the expressed as ¹⁰⁷ ⁴² of plasma series resonance beside non-resonant (Ohmic) heating. Boltzmann exponential function of the sheath voltage. The discussion ¹⁰⁹ 109 In a previous study they also derived an exact analytical solution of **the process of current is represented** by a variable capacitor. Because ⁴⁴ the nonlinear discharge current equation [\[9,10\]](#page--1-0). The exact solution $\frac{1}{h}$ the electrode sharth is depleted from electrons the sharth is ¹¹⁰ ⁴⁵ demonstrates the effect of the amplitude of the driven frequencies, tracted as a poplinear capacitor. Its capacitance in a simple form ¹¹¹ 46 the driven frequencies, and the collision frequency on the power $\frac{1}{16}$ ration as $C(t) = C(t)c(t)/4$ where $C(t)$ is the permittivity of 112 47 dissipation. However, they restrict their results to the high fre-
the plasma sharth which might be time dependent due to the ion 48 quency regime, where ions are heavy enough to see only the time $\frac{1}{2}$ modulation $\frac{f(t)}{g(t)}$ is the sharth width: hence the poplinearity of 114 49 averaged fields and electrons obey Boltzmann distribution and fol-
All the closing states in the electrons modulation in the closing of the closing the closing modulation in the ⁵⁰ low the time varying fields instantaneously. Here, we would like the high frequency regime and due to the electrons and instants on the section and instants of the section of the section of the section of the section ⁵¹ to know what is going on when driven frequencies or self-excited $\frac{1}{11}$ is the intermediate redio frequency regime. 52 118 frequencies are comparable to the ion plasma frequency.

 $\frac{53}{15}$ As shown in Fig. 2, the discharge region – the gap between the $\frac{53}{15}$ and $\frac{1}{15}$ the shown in Fig. 2, the discharge region – the gap between the starting factor of the starting of the starting of the 54 two electrodes in Fig. 1 – is divided into three distinct regions: $\frac{120}{120}$ is determined by the carrent from $\frac{120}{120}$ 55 The electrode sheath (i.e., the sheath in front of the powered elec-
 55 The electrode sheath (i.e., the sheath in front of the powered elec-56 trode), the plasma bulk, and the ground sheath (i.e., the sheath clear electrone, the shear of the sheath that the shear of the sheath ⁵⁷ in front of the ground electrode). Therefore, the lumped element $A\Omega(t)$ 58 model consists of electrode sheath module, a plasma bulk mod- $\frac{d^2C(t)}{dt^2} = -I - en_S(t)A_S u_S(t)$ ⁵⁹ ule based on a fluid approach, and a ground sheath module. The μ and μ and ⁶⁰ modules are coupled together using Kirchoff's laws with the driven $+en_{\rm B}\sqrt{(T_{\rm e}/2\pi m_{\rm e})A_{\rm s}}$ exp $(-eV_{\rm s}(t)/T_{\rm e})$. (2) ¹²⁶ ⁶¹ powers to calculate the self-bias on the blocking capacitor self-**comparison of the self-bias of the self-bias** 62 consistently. The same state of the set of the set of the set of space the set of space assumed to form a time modulated matrix of space 128 consistently.

⁶³ The electrode sheath is RF modulated sheath characterized with charge. Let the piasma/sheath boundary at s(t) and the powered 129 ⁶⁴ three parallel currents, termed the ion, electron, and displacement electrode is placed at the origin, then the electron density is van- 130 65 current. The ion current $(I_i(t))$ is represented as a time depen-
ished for $x < s(t)$ and the electron density equals the bulk density equals the bulk density 131 ⁶⁶ dent current source, where the modulation amplitude of the ion when $x > s(t)$. By the integration of Poisson's equation, one ob-
⁶⁶ current. The ion current $(I_i(t))$ is represented as a time depen-

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

36 102 is Bohm's velocity at the bulk-sheath edge and *n*^B is the ion den-37 **2. The mathematical model** sity in the plasma bulk. The electron current $(I_e(t))$ is represented ¹⁰⁴ ¹⁰⁴
by a reverse-biased diode, where electrons leave the plasma only 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 $u_B = \sqrt{T_e/m_i}$ 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.

> 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;

$$
\frac{dQ(t)}{dt} = -I - ens(t)Asus(t) + enB\sqrt{(Te/2\pi me)}As exp(-eVs(t)/Te).
$$
 (2)

charge. Let the plasma/sheath boundary at *s(t)* and the powered electrode is placed at the origin, then the electron density is vanwhen $x > s(t)$. By the integration of Poisson's equation, one ob-

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