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Effects of Phase Difference between Voltage Waves Applied to Primary and Secondary Electrodes in Dual Radio Frequency Plasma Chamber

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ABSTRACT

In plasma processing reactors, it is common practice to control plasma density and ion bombardment energy by manipulating excitation voltage and frequency. In this paper, a dually excited capacitively coupled rf plasma reactor is self-consistently simulated with a three moment model. Effects of phase differences between primary and secondary voltage waves, simultaneously modulated at various combinations of commensurate frequencies, on plasma properties are investigated. The simulation results show that plasma potential and density as well as primary self-dc bias are nearly unaffected by the phase lag between the primary and the secondary voltage waves. The results also show that, with the secondary frequency substantially lower than the primary frequency, secondary self-dc bias remains constant regardless of the phase lag. As the secondary frequency approaches to the primary frequency, however, the secondary self-dc bias becomes greatly altered by the phase lag, and so does the ion bombardment energy at the secondary electrode. These results demonstrate that ion bombardment energy can be more carefully controlled through plasma simulation.

Key Words : Capacitively Coupled Plasma, Dual Radio Frequency, Phase Difference, Self-DC Bias

1. INTRODUCTION

In capacitively coupled rf plasma reactors, plasma density and ion bombardment energy are often independently controlled by separate external power sources simultaneously exciting primary and secondary electrodes. With chamber walls grounded, plasma density is mainly controlled by modulating the primary electrode at a high frequency. At the same time, ion bombardment energy is manipulated by driving the secondary electrode, where a substrate resides, at a relatively lower frequency. In such systems, it has been already proved experimentally that an appropriate combination of excitation frequency and rf power is important for the accurate control of ion flux and ion bombardment energy at the substrate surface[1]. Effects of secondary rf power and frequency on the ion bombardment energy have been also investigated numerically[2], identifying their scaling relations through self-consistent simulations with a three moment model. Nonlinear dynamics of plasma reactors powered by multi-frequency sources have been theoretically studied[3], pointing out that nonlinear interaction effects need to be considered in the design of such discharges when the secondary frequency is commensurable to the primary frequency. Although having further investigated on the nature of dual frequency plasma, mostly by either analytical models or particle-in-cell simulations[4-5], suggesting the existence of the regime where the independent control of the ion bombardment flux and energy can be achieved, other researchers have not explicitly studied the phasing effects of voltage waves, imposed on primary and secondary electrodes, resulting from the nonlinear coupling of two different power sources.

This paper extends the previous scaling relations[2] by further numerically investigating the effects of phase differences between primary and secondary voltage waves driven at various combinations of commensurate frequencies

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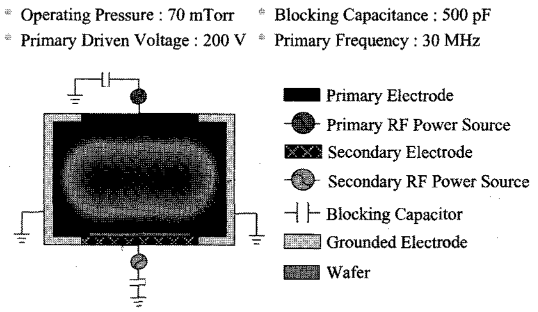


Fig. 1. Schematic of a dually excited capacitively coupled rf plasma chamber with fixed operating conditions.

2. PLASMA SIMULATION MODEL

The plasma model employed in this study consists of continuity, momentum and energy equations, for each charged species, derived from the first three moments of the Boltzmann equation. Since this three moment model has been previously described in detail[2, 6], only a brief description is provided. Governing equations in this three moment model are analogous to the Euler equations of gas dynamics except additional terms quantifying elastic and inelastic collisions, electric field forces and thermal conductivity. In the present model the following assumptions have been employed. The neutral gas density is constant, neutral fluid motion is not considered, neutral and ions are in thermal equilibrium with a spatiotemporally uniform temperature, and coulomb collisions among charged species are neglected. Furthermore only ground state electron impact ionization and excitation are considered. The electric field is self-consistently determined from Poisson's equation with boundary conditions specified in a manner that Gauss's law is satisfied for all discontinuous surfaces between different materials. Use of such boundary conditions at the surfaces of powered and grounded electrodes enables evaluation of self-dc biases, in turn determination of ion bombardment energies. The plasma model utilized in this study has been implemented in a virtual integrated prototyping simulation environment for plasma chamber analysis and design (VIP-SEPCAD)[7] with an efficient numerical algorithm developed for the rapid evaluation of time-periodic steady state solution[8].

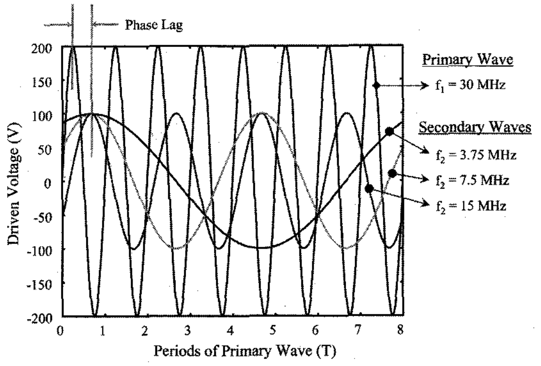


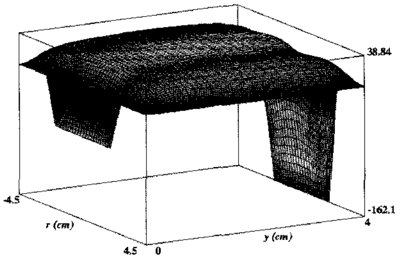
Fig. 2. Commensurate voltage waves applied to primary and secondary electrodes.

3. RESULTS AND DISCUSSION

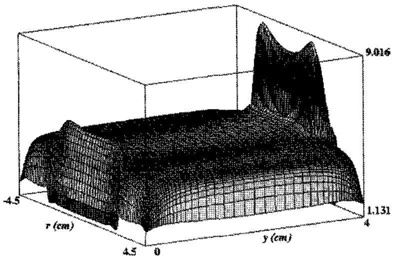
The reactor geometry of a dually excited capacitively coupled rf plasma is schematically shown in Fig. 1. Two-dimensional simulations of a dually excited capacitively coupled rf plasma were performed in cylindrical coordinates with Ar at 70 mTorr and 323 K. Primary and secondary electrodes were simultaneously powered with sinusoidal voltage wave forms, as shown in Fig. 2. The primary voltage and frequency were fixed at 200 V and 30 MHz, respectively. The secondary electrode was driven at 100 V with various frequencies commensurable to the primary frequency. The phase of the secondary wave with respect to the primary was also varied. Other detailed simulation parameters can be found elsewhere[2].

Fig. 3 shows time-averaged plasma properties when the secondary electrode is rf biased at 15 MHz without phase lag. The electron temperature inside the sheath region next to the primary electrode is shown to be much higher than that in the bulk plasma due to the acceleration of the secondary electrons emitted from the momentary cathode through the sheath, where a large axial electric field develops. Although these sheath electrons are highly energetic, they are so few, however, that ionization inside the sheath is relatively negligible. It is worth noting that most ionization occurs near the primary electrode, which implies that the plasma is dominantly generated by the primary power source. The peak plasma

(a) Plasma Potential (V)



(b) Electron Temperature (eV)



(c) Plasma Density (#/ cm^3)

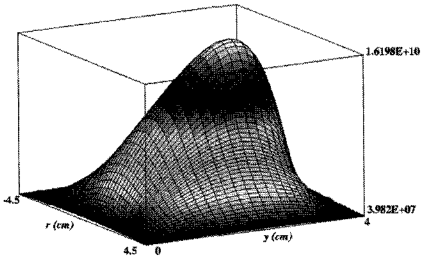


Fig. 3. Time-averaged plasma properties when the secondary electrode is powered at 15 MHz without phase lag.

density inclined toward the primary electrode, resulting in highly asymmetric plasma density profile. Such high asymmetricity is the result of much higher self-dc bias on the powered electrodes than on the secondary electrode. Spatial profiles of the time-averaged plasma properties for other secondary frequencies resemble those of 15 MHz qualitatively, except in the sheath region next to the secondary electrode.

Fig. 4 and Fig. 5 show phasing effects of the primary and secondary voltage waves on plasma properties. When the secondary frequency is substantially lower than the primary frequency, both primary and secondary rf powers as well as the plasma density stay almost constant as shown in Fig. 4. At the secondary frequency sufficiently close to the primary frequency, incremental changes in the phase lag result in a little perturbation in these properties due to interactions through nonlinear plasma medium[3]. However the plasma density remains reasonably constant. Furthermore the primary rf power is still substantially higher than the secondary rf power, clearly indicating that the plasma density is still predominantly determined by the primary rf source. In Fig. 5, however, it can be seen that the phasing effects on plasma potential and self-dc bias on the primary electrode are almost negligible for all cases. The secondary self-dc bias acquired at the secondary frequency of 3.75 MHz also stays constant. Meanwhile the secondary self-dc biases acquired at higher secondary frequen-

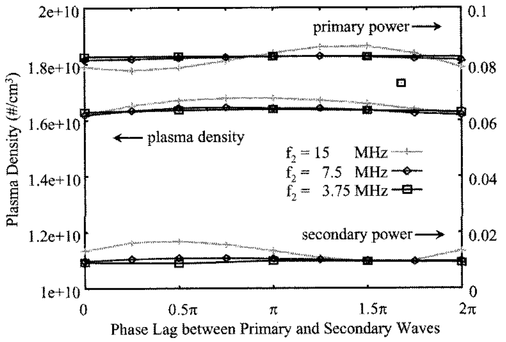


Fig. 4. Phasing effects of voltage waves between primary and secondary electrodes on plasma density and power.

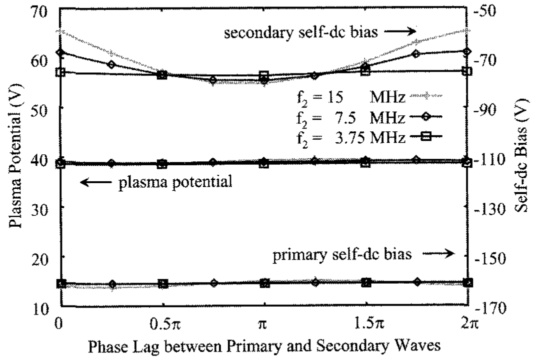


Fig. 5. Phasing effects of voltage waves between primary and secondary electrodes on plasma potential and self-dc bias.

cies are noticeably altered with the phase lag between the primary and secondary waves again due to nonlinear interactions. It implies that the energy of ions bombarding the secondary electrode vary in the same manner since ion bombardment energy approximately corresponds to the difference of plasma potential and self-dc bias, i.e. a sheath potential drop.

4. CONCLUSIONS

Through two-dimensional, cylindrical coordinate simulations of the dually excited capacitively coupled rf plasma, phasing effects of rf voltage waves applied to primary and secondary electrodes on the ion bombardment energy at the substrate surface have been investigated. The simulation results indicate that plasma potential as well as the primary self-dc bias is nearly affected by the phase lag between the primary and secondary voltage waves for all commensurate frequencies considered in this study. However the phasing effect on the secondary self-dc bias becomes more pronounced as the secondary frequency approaches more closely to the primary frequency. Consequently modulation of the secondary electrode at the commensurate frequency close to the primary frequency expands the controllable range of the sheath potential drop, in turn ion bombardment energy, near the secondary electrode. These results demonstrate that scaling relations among important process variables can be identified, for more accurate control of plasma characteristics, through a first principle based modeling and simulation approach.

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