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# Nonlinear Voltage-Current Characteristic of RF Capacitive Discharges

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**Abstract**

Nonlinear increase in a current ($I_{rf}$) of RF capacitive discharges with an RF voltage ($V_{rf}$) at medium pressure range is studied by means of particle-in-cell Monte Carlo simulations and an equivalent circuit analysis. The results show that the nonlinear increase of $I_{rf}$ may be caused by the increase of a sheath capacitance, or the contraction of a sheath width. The nonlinearity of the increase in $I_{rf}$ may be induced from the nonlinear relations among a sheath width, plasma density and $V_{rf}$. The change of the phase angle difference between $I_{rf}$ and $V_{rf}$ mainly due to the increase in the conductivity of a bulk plasma is also shown.

**Keywords:**

$\alpha$ to $\gamma$ transition, RF current, capacitively coupled RF discharge, sheath contraction, PIC simulation

## 1. Introduction

One of the specific features of RF capacitive discharges is the $\alpha$ to $\gamma$ transition that has been experimentally found by S.M. Levitskii [1] and studied by many scientists [2-10]. The transition accompanies a nonlinear increase in a plasma density and RF current ($I_{rf}$) and a decrease in an electron temperature with an RF voltage ($V_{rf}$). The fluid model simulations [7,9] and the convected scheme simulation [8] for the $\alpha$ to $\gamma$ transition have been carried out and succeeded in reproducing the phenomena qualitatively. It has been proposed that the abrupt increase of a plasma density due to an avalanche ionization induced by secondary electrons in a sheath sets up a sheath contraction that causes the increase in $I_{rf}$. However, the quantitative relations among $I_{rf}$, a sheath width ($S_m$) and plasma density have not been discussed in detail. We have studied the phenomena with particle-in-cell Monte Carlo simulations and a simple equivalent circuit consisting of a capacitance and a resistance. In addition to that, the phase angle difference between $I_{rf}$ and $V_{rf}$ has been studied, which has not been discussed before.

## 2. Simulation Model and Equivalent Circuit

The 1D electrostatic particle-in-cell Monte-Carlo simulation code, which has been developed by the Plasma Theory and Simulation Grope, the University of Calfornia-Berkeley [11] is used. The parameters of the simulation model are shown in Table I. In the simulations, the electrodes are assumed to be perfect conductor, and the boundary conditions for charged particles are adjusted so that electrons are absorbed, on the other hand ions emit secondary electrons with a certain probability after absorbed at electrodes. The interactions considered here are electron-neutral (elastic, excitation and ionization) and ion-neutral (charge exchange) collisions. The time step size $\Delta t$, the numerical grid size $\Delta x$ and the number of super particles N per a cell are determined to satisfied the conditions

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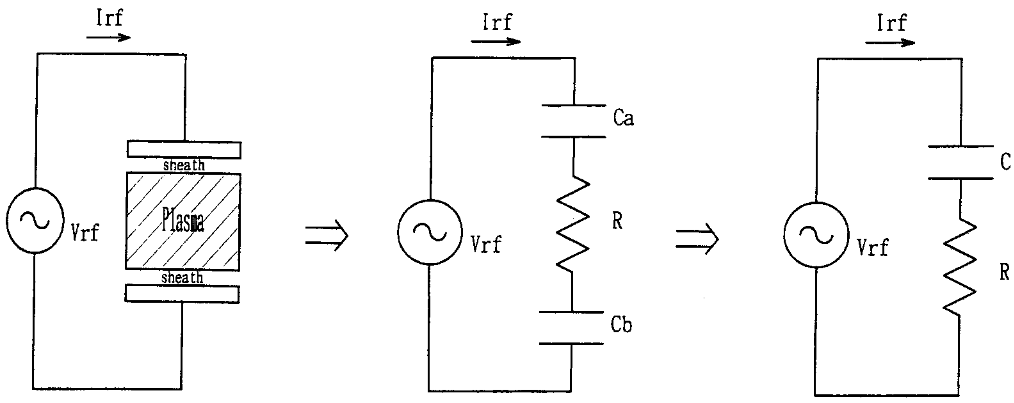


Fig. 1 Equivalent circuit

($V_e\Delta t/\Delta x < 1$, $\omega_{pe}\Delta t < 0.2$, $V_e$; electron thermal velocity, $\omega_{pe}$; electron plasma frequency) given by Ref. 11. The experimental results and the simulation results approximately agree each other. The dependence of electron temperature on $V_{rf}$ is quantitatively in good agreement with the experimental one, on the other hand that of electron density qualitatively agrees with experimental one [13]. Both show clearly the $\alpha-\gamma$ transition [14]. The equivalent circuit of capacitively coupled RF discharges consisting of a capacitance of sheaths (C) and a resistance of a bulk plasma (R) is shown in Fig. 1. Then $I_{rf}$ is expressed as follows, $I_{rf} \fallingdotseq \omega C(\omega CR + j)V_{rf}$, $\theta = \tan^{-1}(1/\omega CR)$ ($\theta$; the phase angle difference, $\omega CR \ll 1$). These equations suggest that $I_{rf}$ increases with $V_{rf}$ and $C$ ($|I_{rf}| \sim \omega C|V_{rf}|$, $\omega CR \ll 1$), while $\theta$ increases with $1/C$ and $1/R$.

## 3. Results and Discussion

A time averaged E-field at $V_{rf} = 150$V near the electrode is shown in Fig. 2. The definition of the sheath width ($S_m$) is indicated in Fig. 2. The dependence of $S_m$ and the electron density ($N_e$) at the center of a plasma on $V_{rf}$ is given in Fig. 3 and 4 respectively. We can calculate a capacitance of sheaths ($C$) and a resistance of a bulk plasma ($R$) from the sheath width and plasma density such as $C = 0.5kS/(\varepsilon_0 S_m)$ ($k = 4/3$; the correction coefficient due to E-field in a sheath, here we assume $E(x) = E_0(S_m - x)/S_m$, $S$; cross section of an electrode (= 0.01 m$^2$), $\varepsilon_0$; permittivity), $R = L/(\sigma S)$ ($L$; plasma length, $\sigma$; plasma conductivity, $\sigma \fallingdotseq \sigma_{dc}(= e^2N_e/m_e\nu_m)$ because of $\omega(\fallingdotseq 8.5 \times 10^7 s^{-1}) \ll \nu_m(\fallingdotseq 1.7 \times 10^9 s^{-1}$, the collision frequency between neutral atom and electron), $\omega_{pe}(\fallingdotseq 1.8 \times 10^9 \sim 1.1 \times 10^{10} s^{-1})$. Figures 5 and 6 show the dependence of $I_{rf}$ and $\theta$ on $V_{rf}$ respectively as well as the calculated ones from the equivalent circuit. There

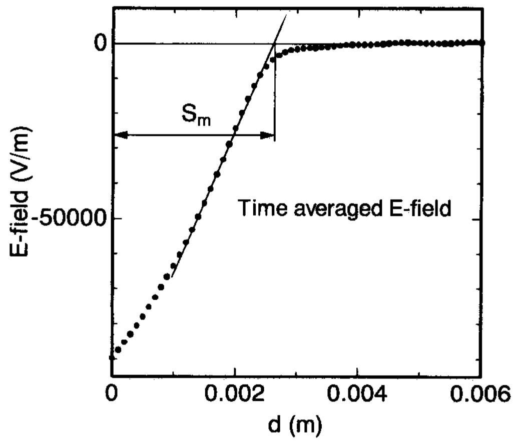


Fig. 2 Time averaged electric field in a sheath ($V_{rf}$ = 150 V, $P$ = 66.5Pa, $L$ = 0.05m and other parameters are given in Table I).

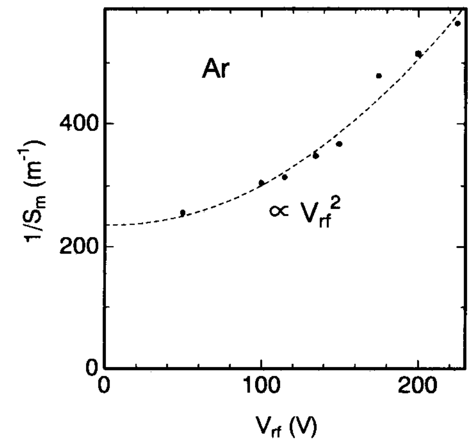


Fig. 3 The dependence of the sheath width on the RF voltage ($P$ = 66.5Pa, $L$ = 0.05m and other parameters are given in Table I).

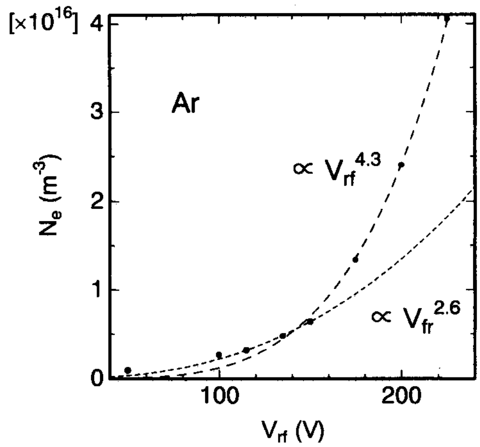


Fig. 4 The dependence of the electron density on the RF voltage (parameters are the same as Fig. 3).

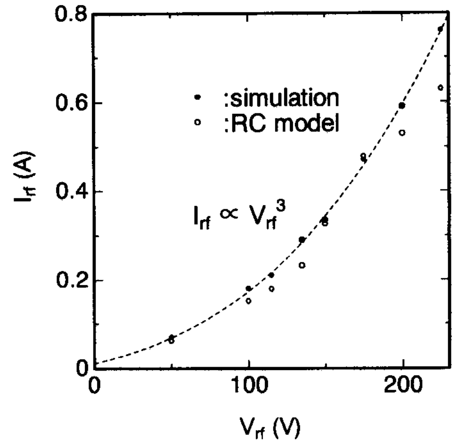


Fig. 5 The dependence of the RF current on the RF voltage (parameters are the same as Fig. 3).

are good agreement between the simulation and the equivalent circuit calculation, which suggests that the nonlinear increase of $I_{rf}$ with $V_{rf}$ ($|I_{rf}| \propto |V_{rf}|^3$) may be caused by the increase in the sheath capacitance, or the contraction of a sheath width. For DC sheaths, a sheath width is approximately proportional to $\sqrt{V_{dc}/N_e}$ [12]. The sheath width $S_m$ is plotted as a function of $\sqrt{V_{rf}/N_e}$ in Fig. 7, which shows that $S_m$ is nearly proportional to $\sqrt{V_{rf}/N_e}$. Therefore we think that the abrupt increase in $N_e$ with $V_{rf}$ induces the contraction of a sheath width. The increase in $\theta$ may be also caused by the R reduction due to the increase in $N_e$ that exceeds the reverse effect of the $C$ increase. One can see the inflection point in Fig. 5 and 6 around $V_{rf} = 100 \sim 120$V, where the $\alpha$ to $\gamma$ transition starts, as a result an electron density drastically increases with $V_{rf}$.

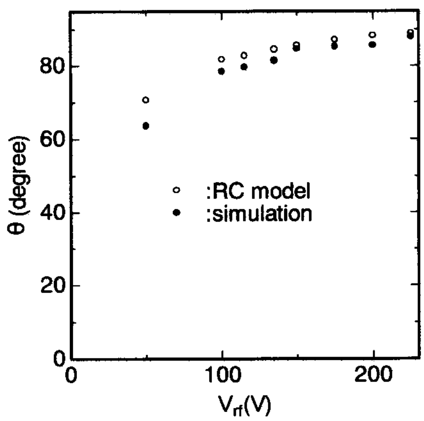


Fig. 6 The dependence of the phase angle difference on the RF voltage (parameters are the same as Fig. 3).

## 4. Conclusions

The simulation results indicate that the nonlinear increase in the RF current with the RF voltage ($|I_{rf}| \propto |V_{rf}|^3$) may be caused mainly from the increase of a sheath capacitance, or the contraction of a sheath width, while the increase in $\theta$ may be caused by the reduction of the resistivity of the bulk plasma due to the density increase that may exceed the effect of the increase in the sheath capacitance. The measurement of the phase angle during the $\alpha$ to $\gamma$ transition, which has not been done so far, is under way to confirm the simulation results.

We appreciate the kind policy of the Plasma Theory and Simulation Group, the University of California-Berkeley to open the PIC code (xpdp1) to the public.

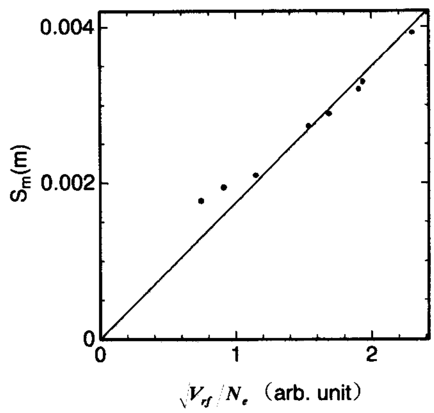


Fig. 7 The variation of the sheath width as function of $\sqrt{V_{rf}/N_e}$ (parameters are the same as Fig. 3).

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