Step Response of RF Plasma in Carbon Tetrafluoride(CF_4)

Soon-Youl So, Akinori Oda, Hirotake Sugawara, and Yosuke Sakai

Abstract

To understand the behavior of electron, ions and radicals on radio-frequency non-equilibrium plasma, it is necessary to know the basic information about its fundamental properties and reactions. Especially, the transient response of radio-frequency plasma has an important means of controlling selective etch rates and investigating the stability of a plasma chemical process. In this paper, we present the results of periodic steady-state behavior and transient behavior carbon Tetrafluoride(CF_4) discharge at 0.2 Torr in a 2 cm gap parallel-plate. After the number densities of charged particles became steady-state, the applied voltage was increased or decreased in an instant and the transient behavior of charged particles and radicals was investigated from one steady-state to the next steady state.

Key word : plasma discharge, CF_4, transient behavior, step response

1. Introduction

Plasma etching is a key process for removing material from surfaces. These gases of CF_4, CCl_4, CF_3Cl, COF_2, SF_6, etc. are used for plasma etching. Among these gases, carbon Tetrafluoride(CF4) including halogen compounds is used extensively in the technical fields which are plasma etching in the semiconductor industry, gas insulation materials, and so on.

It is a common etchant and one of useful components of feed gas in the etching process of microelectronic industry. To understand the behavior of CF_4 plasma, it is important to know the basic information about its fundamental properties and reactions.

So far, the steady-state behaviors of this gas have been reported: the cross-section and the rate coefficients for collisional interactions with electrons, development of gas-phase plasma simulator for the physics and chemistry, the effect of electrons, ions and neutral gases and dependence of driving frequency[1][2].

It is important to characterize the transient behaviors, because, in the actual system, the applied voltage is re-iterately changed during the pulsed modulation. Also, induced transients are an important means of process identification for diagnostics and of investigating the stability of plasma chemical processes[3].

In this paper, we investigate influence of transient charged species when the external RF voltage is changed using a one-dimensional model and capacitively coupled plasma(CCP) source at 0.2 Torr.

2. Modeling and Numerical Method

The configuration of discharge system is a conventional RF parallel plate reactor operation at 13.56 MHz. The electrode distance is d=2 cm, a gap capacitance(C_g) is 10 pF and a blocking

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capacitance(C_b) is 8.0 pF as shown Figure 1. The drift velocity and diffusion coefficient of the electron are calculated from Boltzmann equation.

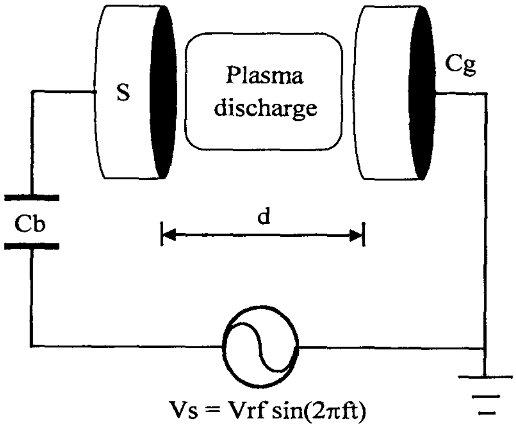


Fig. 1. The electrode configuration used in the CCP model.

The numerical method to resolve the behavior of electrons and ions can be described in several models: fluid model, particle-in-cell Monte Carlo (PIC-MCC) model, solution of Boltzmann equation, hybrid model and etc.. The used numerical model for plasma sources is a fluid model consisted of continuity equation, energy equation and Poisson's equation. Under the continuity equation induced from solution of the moments of Boltzmann equation along with an energy equation and Poisson's equation, we investigated the plasma properities of charged species.

$$\frac{\partial n_j}{\partial t} = -\frac{\partial \Gamma_j}{\partial x} + S_j \qquad (1)$$

$$\Gamma_j = W_j \cdot n_j - D_j \frac{\partial n_j}{\partial x} \qquad (2)$$

where n_j, Γ_j, W_j, D_j, S_j denote the particle concentration, flux, drift velocity, diffusion coefficient and source term for the j kind of charged species, respectively. The subscript j represents an electron, five positive ions of CF_3^+, CF_2^+, CF^+, C^+, F^+ and two negative ions of F^-, CF_3^-.

To solve the energy equation, we assumed that the electron energy distribution function is Maxwellian and that the electron thermal energy is much greater than the electron kinetic energy.

The first-order contribution calculation of charged particles and radicals was handled using a donor cell algorithm with simple Eulerian time integration. The donor cell fluxes are

$$\Gamma_j = W_{j-\frac{1}{2}} \cdot n_{j-\frac{1}{2}} - D_{j-\frac{1}{2}} \cdot \frac{n_j - n_{j-1}}{\Delta x_{j-\frac{1}{2}}} (W_{j-\frac{1}{2}} > 0)$$

$$= W_{j-\frac{1}{2}} \cdot n_j - D_{j-\frac{1}{2}} \cdot \frac{n_j - n_{j-1}}{\Delta x_{j-\frac{1}{2}}} (W_{j-\frac{1}{2}} < 0)$$

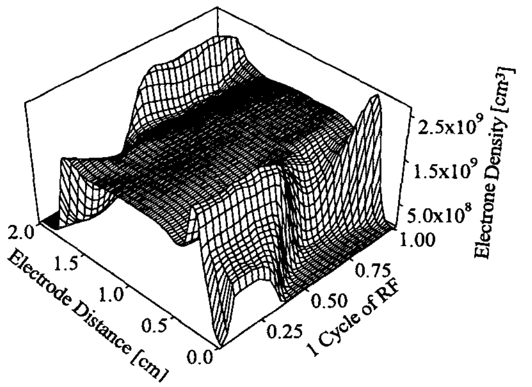
$$\Gamma_j = X_{j-1} \cdot n_j - Y_{j-1} \cdot n_{j-1} \qquad (3)$$

Figures 2 show the cross-section set for CF_4 as a function of the electron energy.

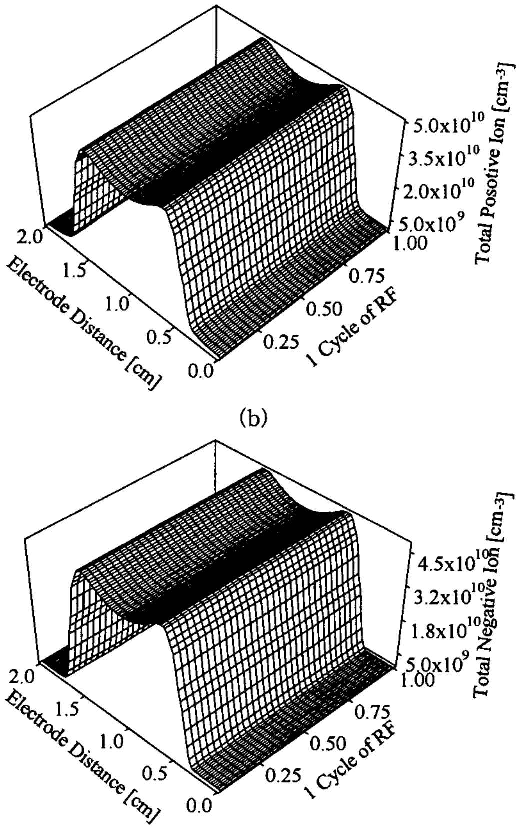
3. Result and Discussion

3. 1 Periodic Steady-State Result

The following figures are the results when the electrode distance is 2 cm, neutral gas pressure is 0.2 Torr, V_{rf} = 0~2300 V and coupling condenser is 8 pF in the RF plasma. The powered electrode is at x=0 cm and the grounded electrode is at x=2 cm. Figure 3 shows the periodic steady-state results for electron number density, ion number density for the case of 2000 V_{rf} in the gap of a RF period. These results show the typical electron-negative structure.



(a)



(b)

(c)

Fig. 3. The periodic steady state as a function of a RF period: (a) electron density; (b) total positive ion; (c) total negative ion.

The ion density profiles are relatively independent of the phase of the applied voltage. However, the electrons oscillate by responding to the time varying electric field in an RF period. The positive ion sheath is always kept in near of the electrodes (sheath region) during a period, followed by the double layer.

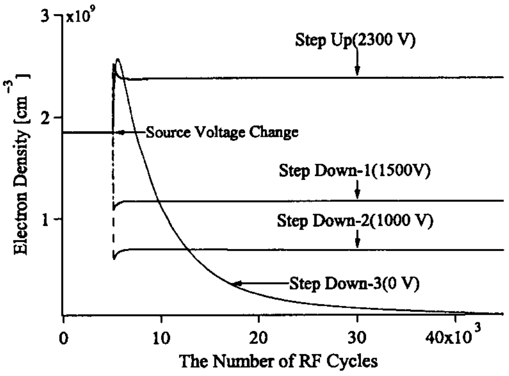
3.2 Step Responses in CF$_4$

Why it is important something to understand the transient behavior of plasma discharge is to develop sources that operate in a pulsed mode or in which the power may be modulated and to be a tool for process identification into complex systems. In this paper, we consider two classes of transient behavior: step increase and step decrease of the amplitude of external RF voltage from 2000 V to 0 V. Figure 4 displays the maximum densities variation of electron and ion densities as a function of time for transient. For every step change, the plasma will proceed from one steady-state to another. In case of the bulk plasma on step up, the time-averaged plasma potential is increased and the number density of electron increases by ionization reaction. While collision frequencies of ionization increase as the mean electron energy is higher, collision frequencies of attachment decreases. Therefore, the more the mean electron energy increases, the more the number density of electron increase. The number density of total positive ion has an effect of recombination reaction. Therefore, number density of total positive ion is up to steady state with oscillation. While, the number density of total negative ion decreases without oscillation because collision frequencies of ionization increase as the mean electron energy is higher and collision frequencies of attachment decrease. In the case of step down, the mean electron energy clearly decreases as a function of time and the variance decreases after the step change. The number density of electron decreases by diffusion to the electrode surface and attachment reaction. As the mean electron energy increase again, the number density of electron is up to steady state. According to the voltage drop of step decrease is higher, the mean electron energy is closed to the zero eV which it has no effect of collision frequencies of ionization, attachment, dissociation and has only the chemical reactions of detachment and recombination. Therefore, the number density of electron increases instantly and decreases. When a step change occurs, the movement of electron by alteration of electrical field is faster than that of ions. In the sheath region on step down to 0 V, total positive ion and total negative ion come into being greater density distribution than the other step response.

4. Conclusion

In this paper, we have described the transient behaviors of plasma properties when the external RF voltage changes to up and down. The present simulation results using CF_4 plasma shows typical electro-negative structure.

The transient response is controlled by plsama chemistry effects such as negative ion dynamics and the relationship between the overall attachment and ionization coefficients in contrast to the transport controlled behavior of the electro-positive discharges like Ar. An implication of this work is that RF voltage amplitude modulation instead of pure pulsing may be used to obtain the same effect as a pulsed capacitively coupled RF source.



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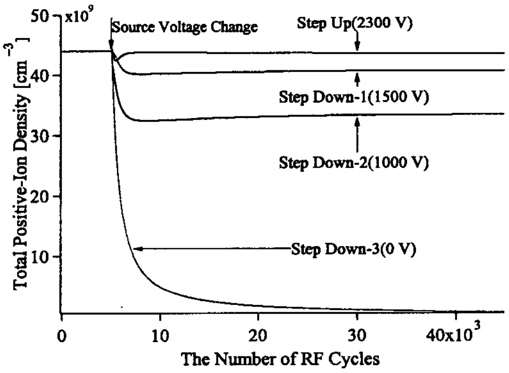

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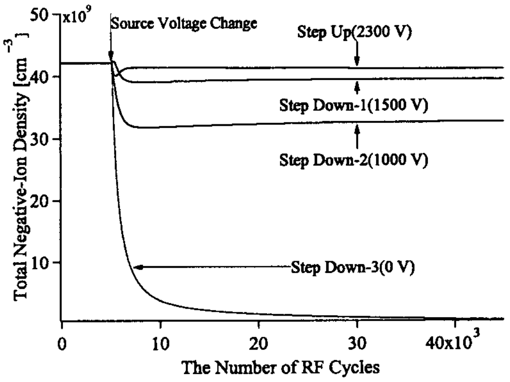

(c)

Fig. 4. The step responses the bulk plasma: (a) electron density, (b) total positive ion, (c) total negative ion.

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