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Role of Secondary Electrons in the α to γ Transition of RF Capacitive Discharges

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Abstract

The role of secondary electrons in the α-γ transition of RF capacitive discharges are studied numerically by means of Particle-in-Cell Monte Carlo Collision (PIC-MCC) simulations with and without ion-induced secondary electron emission. As a result, the simulations only with a secondary electron emission show clearly the α-γ transition. It suggests that secondary electrons would induce the transition. Furthermore, the phenomena which occur in the sheath regions are discussed in detail based on the simulation results.

Keywords:

α-γ transition, Particle-in-Cell Monte Carlo Collision (PIC-MCC) simulation, secondary electron emission

1. Introduction

In RF capacitive discharges at a medium pressure range, a transition is found, which accompanies not only the nonlinear increase in an RF current and a plasma density but also the drop in an electron temperature with an RF voltage [1,2]. It is difficult to explain the phenomena by the fundamental principles of plasmas, such as the particle and energy balance. For instance, it is predicted by the particle balance that an electron temperature is kept constant with an RF [3]. Therefore, it has been considered that the two distinct discharge regimes (α, γ regime) differed in their governing discharge mechanisms exist. And the transition between these discharge regimes has been named as the α to γ (α-γ) transition.

According to Levitskii, bulk plasma ionization and the avalanche ionization due to secondary electron ("secondary breakdown") are given as their governing discharge mechanisms respectively [1]. But to confirm experimentally his hypothesis is difficult, because to control the emission rate of secondary electrons is difficult. On the other hand, to control the emission rate in numerical simulations, especially in Particle-in-Cell Monte Carlo Collision (PIC-MCC) simulations, is easy. So we tried to clarify the mechanism of the phenomena by means of PIC-MCC simulations with and without secondary electron emission.

2. Simulation Model

In this study, we used the simulation code which has been developed by the Plasma Theory and Simulation Group, the University of California - Berkeley [4]. This code is a 1D electrostatic simulation code. And the collision processes, such as electron-neutral collision (elasticity, excitation and ionization) and ion-neutral collision (charge exchange), are considered in the code.

The simulation model used in this study is as follows. The electrode separation is 0.05m, the cross

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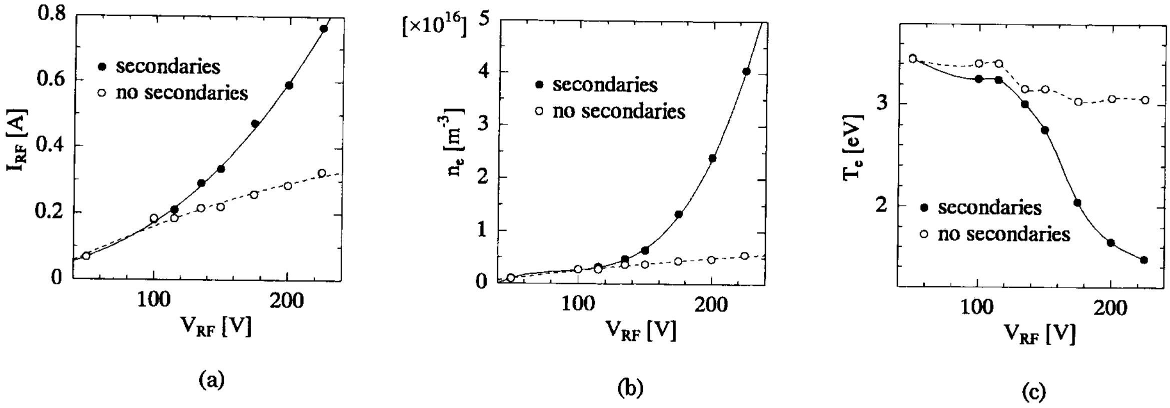

Fig. 1 Dependence of the RF current (a), plasma density (b) and electron temperature (c) on the RF voltage.

section of electrode is 0.001m^2, the RF voltage (f = 13.56MHz) is changed from 50 to 225V, gas species is Ar, gas pressure is 0.5Torr. The secondary electron emission coefficient is fixed at 0.2 or 0.0, for ion which collides with electrodes.

3. Results and Discussion

The dependence of the RF current, plasma density and electron temperature on the RF voltage is shown in Figs. 1(a-c), respectively. The RF current and plasma density with secondary electron emission show nonlinear increase, while those without the secondary electron emission show nearly linear increase. The electron temperatures with and without the secondary electron emission suddenly start to drop around the RF voltage 120V, although the former drops more drastically. Thus, the experimentally observed phenomena which accompany the α-γ transition is confirmed also in the PIC-MCC simulations with the secondary electron emission. Without secondary electron emission, the clear phenomena are not observed except for the weak drop in the dependence of the electron temperature on the RF voltage (Fig. 1(c)). These simulation results indicate that secondary electrons emitted from electrodes would induce the transition.

To investigate in detail the contribution of secondary electrons emitted from RF electrodes, we focused our attention on the sheath region. As a result, the appearance of peaks in the profile of the ionization rate near the electrodes (Fig. 2) and the contraction of sheath width defined as the distance between an electrode and a point that time-averaged E-field is zero as the RF voltage increases (Fig. 3) are found. Fig. 2 also shows that the ionization in a bulk plasma is not the

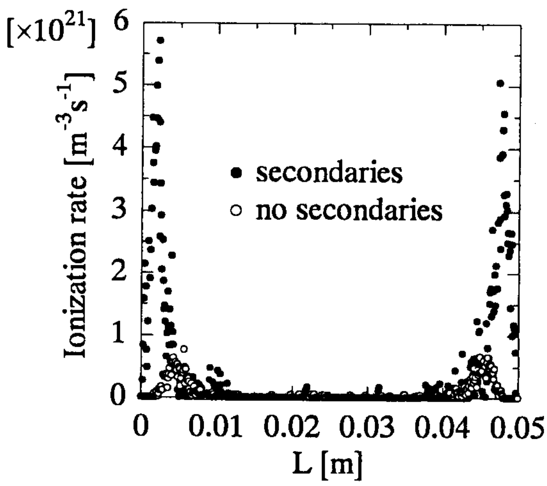

Fig. 2 Profile of the ionization rate on the RF voltage 200V.

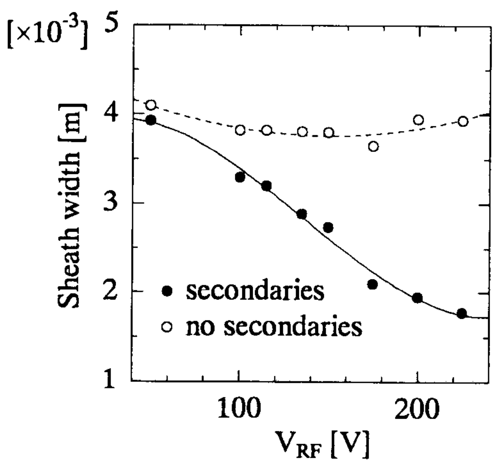

Fig. 3 Dependence of the sheath width on the RF voltage.

governing mechanisms in the γ regime. These results lead us a hypothesis for a role of secondary electrons in the α-γ transition.

When an RF voltage is low, secondary electrons do not play the dominant role in maintenance of a plasma (α regime). As an RF voltage increases, secondary electrons emitted from electrodes gain enough energy to ionize neutral particles from electric field in sheath regions. Then, in sheath regions, such ionization is repeated and results in an avalanche ionization (γ regime). But if an RF voltage increase further, a plasma density increased by an avalanche ionization would induce the contraction of a sheath width, and the avalanche ionization would be suppressed because the number of an ionization by a secondary electron in a sheath would be reduced.

The additional condition for the occurrence of the α-γ transition on the hypothesis is that a mean free path should be shorter enough than the sheath width, which is a necessary condition for an avalanche ionization. The additional condition explains that the occurrence of the α-γ transition is restricted in more than medium pressure ($p > 0.1$Torr).

The difference between with and without a secondary electron emission can be understood by the following way. The electric field in a sheath region has the strongest intensity on the electrode. And it is shielded gradually to zero at a bulk plasma edge. Secondary electrons gain energy from intense electric field, while other electrons in a sheath region gain from shielded electric field. For this reason, secondary electrons can induce an avalanche ionization, and other electrons can not induce it so strongly.

In consequence of this, our hypothesis can explain the experiments and simulations for the α-γ transition.

4. Conclusions

The α-γ transition of RF capacitive discharges is reproduced numerically by the PIC-MCC simulations for the first time. The simulations show the clear α-γ transition only with a secondary electron emission. However, the weak drop in the electron temperature is predicted in the simulations without secondary electron emission. It would be caused from other electrons in the sheath. The mechanism of the α-γ transition is also discussed, which explains that the occurrence of the α-γ transition is restricted in more than medium pressure ($p > 0.1$Torr).

Acknowledgement

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