INFLUENCE OF DUST PARTICLES ON RF-DISCHARGE PLASMA AFTERGLOW

O.Yu. Kravchenko, I.S. Maruschak, Yu.V. Yushchyshena

Taras Shevchenko Kyiv University, Kyiv, Ukraine

E-mail: kay@univ.kiev.ua

In this paper we report about results of computer simulation by PIC/MCC method of the discharging of dust particles in the plasma afterglow and time dependence of plasma parameters in discharge gap after switching off the voltage. It is shown that discharging of dust particles in the afterglow plasma after switching off voltage of radiofrequency discharge occurs faster in the central part of the electrode gap due to the ion cloud forming and intense recombination of electrons in collisions with dust particles in this area. Moreover, the discharging rate is increasing with increasing of the dust particles density. In the initial stage after the switching off the voltage plasma has a positive potential relative to the electrodes. Eventually, when the electron and ion densities are significantly reduced, the charge of the plasma is determined by the amount of negative dust particles. In this case, the plasma potential is negative relative to the electrodes, which contributes to the effective diffusion of dust particles on the walls of the discharge chamber.

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INTRODUCTION

Dusty or complex plasmas are partially ionized gas composed of neutral species, ions, electrons, and charged dust particles. Radio-frequency discharge is often used to create dusty plasma. Dust particles are charged in plasma and can significantly affect the plasma parameters. Dust-particle charge is a key parameter in complex plasma. It determines the interaction between a dust particle and electrons, ion, its neighbouring dust particles, and electric field. Knowledge of dust charge will allow us to understand the basic properties of dusty plasma, particle dynamics in dust clouds, and methods to manipulate the particles. Thus one of the main dusty plasma challenges is to understand the dust charging in a wide range of experimental conditions, which simulates industrial and space plasmas.

There are many publications reporting on the investigation of dust charging in discharge plasma. However there are only a few papers devoted to dust charging, or discharging to be more specific, in the discharge afterglow. These papers report that dust particles retained residual electric charges when the power of the discharge was switched off. Nevertheless, the discharging phenomenon was not totally understood. In [1], the nanoparticles' spatial distribution in a dusty plasma afterglow was studied and it was found that most of the dust particles were neutral. The variation of charge of dust particles in the afterglow of a complex rf plasma in microgravity conditions was investigated experimentally and theoretically in [2-4], and the existence of negative residual charges on the dust particles was shown.

Properties of plasma afterglows with large dust density were studied in [5, 6]. In the afterglow experiments, the electron density showed an unexpected increase at the very beginning of the plasma decay.

In this paper, we study the time dependencies for the plasma parameters and the dust charge in the afterglow of a radio-frequency discharge with dust particles, using PIC/MCC simulation.

MODEL AND SIMULATION METHOD

A one-dimensional RF discharge is considered between two plane electrodes separated by a gap of $d = 0.08\,m$ which is filled with Ar at pressure p=0.1 Torr. At initial time dust particles of a given radius $r_d = 100\,\mu m$ are distributed uniformly in the region $\delta \le x \le d-\delta$ and there are no dust particles near electrodes $x < \delta$ and $d-\delta \le x \le d$ $(\delta = 0.001\,m)$. The dust particles collect and scatter electrons and ions distributed in the discharge with density n_e and n_i, respectively.

The PIC/MCC method was described in detail in [7] for discharges without dust particles. It was developed for computer simulations of the RF discharge with dust particles [8]. The Monte Carlo technique is used to describe electrons and ions collisions. The collision types include elastic collisions of electrons and ions with atoms, an ionization and excitation of atoms by electrons, the charge exchange between ions and atoms, Coulomb collisions of electrons and ions with dust particles, as well as the electron and ion collection and scattering by dust particles [9].

The model took into account the secondary electron emission from the surface of the dust particles in collisions of ions with dust particles. Simulations have been carried out at several different dust densities (n_d=0…5·10^{13} m^{-3}) and secondary emission yields (γ_i=0…0.8). A harmonic external voltage $V_e(t) = V_0 \sin(2\pi f t)$ at a frequency $f = 10$ MHz and amplitude $V_0 = 150\,V$ sustains the RF discharge. Simulation of radio-frequency discharge lasted for 100 periods. During this time, a quasi-steady mode of discharge is established, when the average for the period parameters of plasma do not change. After that, the voltage between the electrodes is switched off and the plasma begins to decay. According to our model, the plasma particles can disappear due to recombination on the walls and dust particles.

RESULTS AND DISCUSSION

Simulations of a plasma afterglow after switching off radio-frequency discharge were carried out at different values of the dust particles density and yields of secondary electron emission from the surface of the dust particles.

Fig. 1 shows the charge density of dust particles at different times after switching off the voltage. Curves in Fig. 1, a correspond to the case $n_d = 10^{13}\ m^{-3}$ and curves in Fig. 1, b correspond to the case $n_d = 5 \cdot 10^{13}\ m^{-3}$. In both cases, it was assumed that the secondary emission coefficient is $\gamma_i = 0.4$. As can be seen from the figure, the charge of dust particles is decreased with time in magnitude in the central part of the inter-electrode gap. Moreover, discharging of dust particles is faster in case of dust density increasing. To understand the cause of this phenomenon, we analyze the temporal variation in densities of electrons and ions in the plasma afterglow both with and without dust particles.

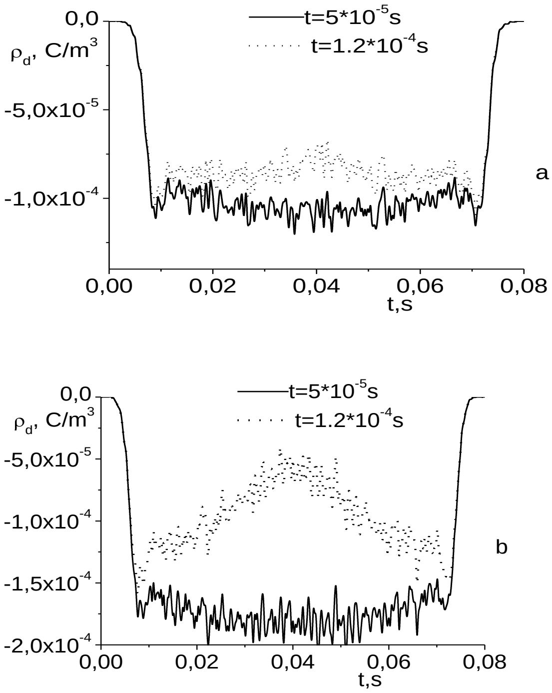

Fig. 1. Spatial distributions of charge density of dust particles ($a - r_d = 100\,nm,\ n_d = 10^{13}\ m^{-3}$; $b - r_d = 100\ nm,\ \ n_d = 5 \cdot 10^{13}\ m^{-3}$)

In Fig. 2 are represented spatial distributions of electron density (a) and ion density (b) for case without dust particles in the discharge ($n_d = 0$). In this calculation, the voltage was turned off at time $t = 5 \cdot 10^{-5}\ s$. Dependences above show that sheaths arise near the electrodes and peaks of ion and electron densities are formed at their boundaries. It is seen from Fig. 2 that electron and ion densities are changing slightly at the next time interval $\Delta t = 2 \cdot 10^{-5}\ s$. Distributions of electrons and ions in plasma afterglow with dust particles are shown in Fig. 3. In the central part of the inter-electrode gap the ion and electron densities are being reduced over time, however electron density is being decreased faster.

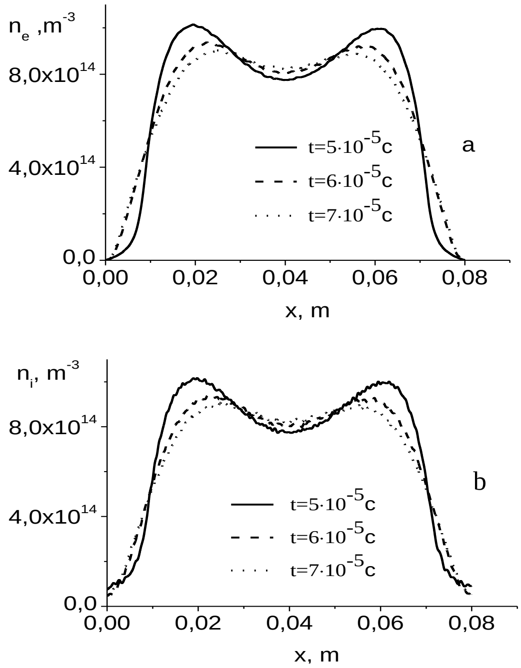

Fig. 2. Spatial distributions of electron (a) and ion (b) densities at different times after the switching off rf-discharge without dust particles

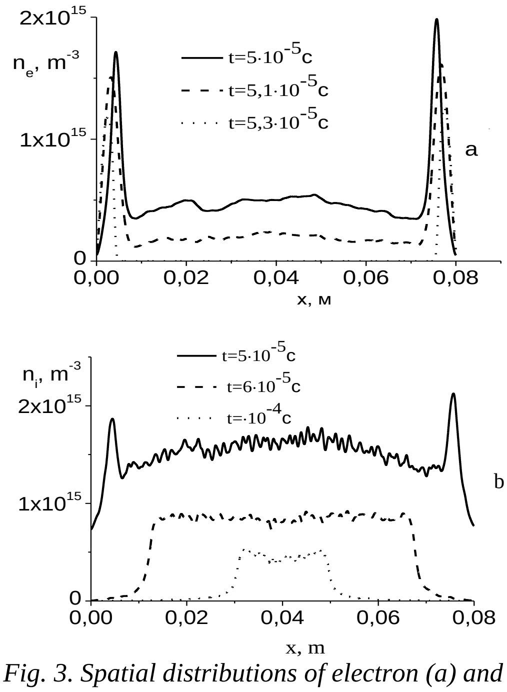

Fig. 3. Spatial distributions of electron (a) and ion (b) densities at different times after the switching off rf-discharge for $r_d = 100\ nm,\ \ n_d = 5 \cdot 10^{13}\ m^{-3}$

Thus, at time $t = 7 \cdot 10^{-5} s$ electrons in the central part of the inter-electrode gap is practically absent. At these times only ion current flows on dust particles, which leads to decreasing of dust particle charge in magnitude. On the contrary, electron clouds are formed in the sheaths, which are stored for a long time. This leads to that the electron current on the dust particles is considerably long time and as a result, the charge of the dust particles near the electrode is changed slowly.

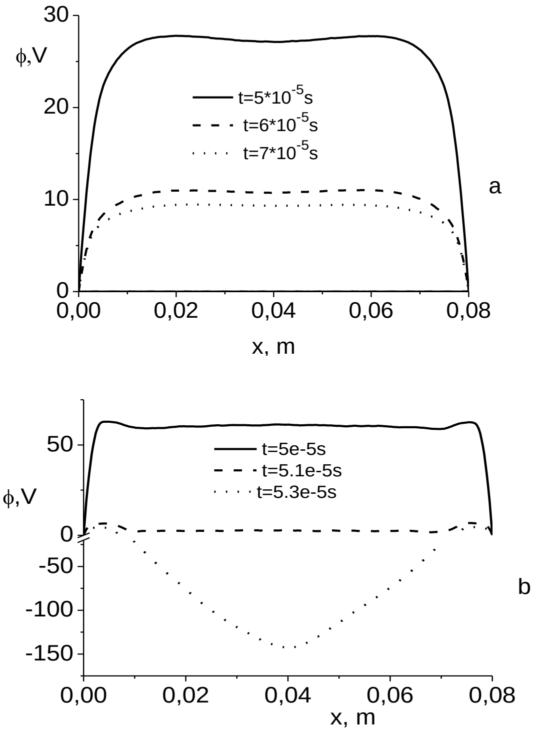

Fig. 4. Averaged over the period of rf-discharge spatial distributions of electric potential in the plasma afterglow for the case $n_d = 0$ *(a) and* $n_d = 10^{13}\, m^{-3}$, $r_d = 100\, nm$ *(b)*

Fig. 4 shows spatial distributions of electric potential at different times, indicated in the figure, for the cases $n_d = 0$ (a) and $n_d = 10^{-13}\, m^{-3}$ (b). In the case of absence of dust particles in the discharge, region of constant positive potential with respect to the electrodes is observed in the central part of the inter-electrode gap. Near the electrodes are formed sheaths in which there is an abrupt change of the potential. Over time after switching-off the voltage, the value of potential jumps in the sheaths, as well as the positive potential in the center of the electrode gap are decreased.

With the presence of dust particles in the discharge chamber other potential distribution are observed. Immediately after switching off the voltage the potential plasma is positive toward the electrodes. Near the electrodes are formed potential jumps (about 60 V), and its maxima at the sheaths edges. This is due to the fact that the charge of the plasma in the inter-electrode gap is positive. Over time, the plasma potential is decreasing due to decreasing of the ion density. As a result, at the time $t = 10^{-4}\ s$ the charge of the plasma is negative, since the negative charge of the dust particles exceeds the charge of the ions. This causes a negative plasma potential relative to the electrodes.

Fig. 5 shows phase portraits of ions for the case $n_d = 10^{13}\, m^{-3}$, $r_d = 100\, nm$ at different times. It is seen that ions are accelerated towards electrodes in sheaths when the discharge is supported by the applied voltage (see Fig. 5,a). At the stage afterglow plasma ions reflect from the walls and oscillate in the central region of the discharge chamber (see Fig. 5,b). In this case, the ion velocity distribution function is broadened significantly, indicating an increase in their average thermal energy.

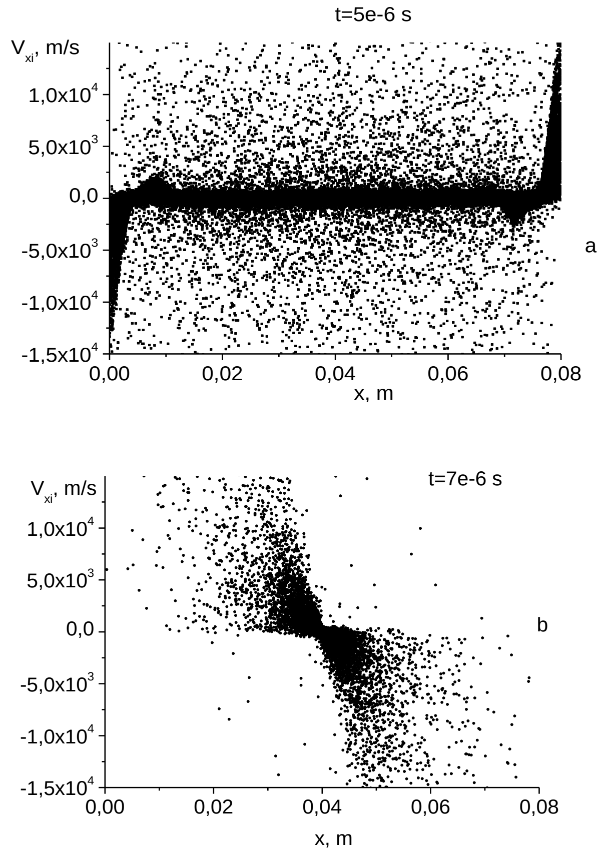

Fig. 5. The phase portrait of ions for the case $n_d = 10^{13}\, m^{-3}$, $r_d = 100\, nm$ *at time* $t = 5 \cdot 10^{-5}\, s$ *(a) and* $t = 7 \cdot 10^{-5}\, s$ *(b)*

CONCLUSIONS

Discharging of dust particles in the plasma afterglow after switching off the voltage of radio-frequency discharge occurs faster in the central part of the electrode gap. Moreover, the discharge rate increases with increasing of the dust particles density. Since negatively charged dust particles are remained in the volume, the plasma potential is negative relative to the electrodes. Remaining in the discharge ions are trapped in the potential well, and for negatively charged dust particles there are conditions for the diffusion to the walls.

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ВЛИЯНИЕ ПЫЛЕВЫХ ЧАСТИЦ НА ПОСЛЕСВЕЧЕНИЕ РАДИОЧАСТОТНОГО РАЗРЯДА

О.Ю. Кравченко, И.С. Марущак, Ю.В. Ющишена

Представлены результаты компьютерного моделирования методом PIC/MCC разрядки пылевых частиц в послесвечении плазмы радиочастотного разряда и временные зависимости параметров плазмы в разрядном промежутке после выключения напряжения. Показано, что разрядка пылевых частиц в послесвечении плазмы после выключения напряжения радиочастотного разряда происходит быстрее в центральной части межэлектродного промежутка, что обусловлено образованием ионного сгустка и интенсивной рекомбинацией электронов при столкновении с пылинками в этой области. Кроме того, скорость разрядки увеличивается с увеличением плотности частиц пыли. В начальной стадии после выключения напряжения плазма имеет положительный потенциал относительно электродов. В конце концов, когда концентрации электронов и ионов значительно снижаются, заряд плазмы определяется количеством отрицательных частиц пыли. В этом случае потенциал плазмы является отрицательным по отношению к электродам.

ВПЛИВ ПИЛОВИХ ЧАСТИНОК НА ПІСЛЯСВІТІННЯ РАДІОЧАСТОТНОГО РОЗРЯДУ

О.Ю. Кравченко, І.С. Марущак, Ю.В. Ющишена

Представлено результати комп'ютерного моделювання методом PIC/MCC розрядки пилових частинок у післясвітінні плазми радіочастотного розряду та часові розподіли параметрів плазми в розрядному проміжку після вимкнення напруги. Показано, що розрядка пилових частинок у післясвітінні плазми після вимкнення напруги радіочастотного розряду відбувається швидше в центральній частині міжелектродного проміжку, що пов’язано з утворенням іонного згустка та інтенсивною рекомбінацією електронів при зіткненні з пилинками в цій області. Крім того, швидкість розрядки збільшується зі збільшенням концентрації частинок пилу в розряді. На початковій стадії після вимкнення напруги плазма має позитивний потенціал щодо електродів. Зрештою, коли концентрації електронів та іонів значно знижуються, заряд плазми визначається кількістю негативних частинок пилу. У цьому випадку потенціал плазми є негативним по відношенню до електродів.