EFFECT OF SECONDARY EMISSION ON THE AFTERGLOW OF ARGON WITH NEGATIVELY CHARGED DUST PARTICLES

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A theoretical model for an argon/dusty plasma afterglow in presence of nano-sized dust particles with large density is developed. According to the model, in the plasma afterglow the electrons are generated in metastable collisions and in the secondary emission by collisions of ions with electrodes. By using the model and experimental time-dependencies for metastable density and electrode bias, the time-dependencies for electron density in argon/dusty plasma afterglow are calculated. The effect of secondary emission on electron generation in argon/dusty plasma afterglow is analyzed.

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INTRODUCTION

In the last two decades plasmas with nano- and micrometre-sized (dust) particles have been extensively studied. However, most of the studies are focused on the steady-state plasma regime [1-3]. In contrast, the properties of dusty plasmas in the afterglow regime are still not well studied, especially of the plasmas with large dust density where negative charge on dust particles is larger than free electron density $|n_d Z_d| \geq n_e$. n_e, n_d and Z_d are the electron density, dust density and dust charge, respectively.

In [4, 5], experimental results on plasma afterglow with large dust density are presented. It was found that at the very beginning of the plasma decay the electron density increased unexpectedly. First, the increase of n_e was attributed to the releasing of electrons from dust particles by secondary emission in collisions of reactive species with dusts [4, 5]. Later on, it was shown that the Ar metastable-metastable collisions (metastable pooling) can be the source of the observed electron density increase [6, 7]. Recent experiments on plasma afterglow with large dust density revealed the negative electrode voltage in the afterglow sufficiently large to produce secondary electrons by collisions of positive ions with electrodes. This also can increase n_e at the very beginning of the plasma decay [8, 9].

In this paper, we study the effect of the secondary electron emission from electrodes on the properties of argon/dusty plasma afterglow with large dust density. The study is carried out for 0.1 mbar argon plasma generated by a capacitively coupled symmetrically driven RF discharge between two 30 cm diameter electrodes with 7 cm gap, the same as that used in experiments of Refs. [4, 5]. We will compare: i) the time-dependencies for density of electrons calculated by taking into account the secondary emission from electrodes ii) the time-dependencies of electron density without secondary emission and iii) electron density measured in the experiment.

THEORETICAL MODEL AND ASSUMPTIONS

Let us consider the plasma of radius R=15 cm and height L= 7 cm, consisting of singly charged positive ions (Ar^+) with density n_i, negatively charged dust particles with density n_d, radius a_d and mean (averaged over all particles) charge Z_d (in units of electron charge e), ground-state argon atoms (Ar^0) with density n_a and metastable argon atoms (Ar^m) with density n_m. It is assumed that there are three groups of electrons in the plasma afterglow: i) thermal electrons with Maxwellian distribution and characterized by electron temperature T_e and density n_e, ii) "energetic" electrons generated by metastable pooling with density n_{ef} and energies about 7.3 eV [6], and iii) secondary electrons generated on electrodes with density n_h and energies about the electrode voltage.

We assume that soon after switching of the RF power the electron temperature decays exponentialy according to $T_e(t) = T_{e0}\exp(-t/\tau_T)$, where t is the time, T_{e0} is the electron temperature in power-on phase and $\tau_T = 50\mu s$ is the T_e's decay time [5,6]. We assume that T_e can not be smaller than a certain temperature T_{aft} = 0.1 eV [10], i. e. the electron temperature stays constant after it reaches T_{aft}. The potentials of a cylindrical metal wall and the electrode potential with respect to bulk plasma are $\Phi_w = -4.7T_e$ and $U_{el} \approx V_f + \Phi_w$, respectively [11]. V_f is the electrode potential with respect to the cylindrical wall [11]. The electrode potentials as a function of time were measured for dust-free and dusty plasma afterglows (Fig. 1) [8, 9].

The density of thermal electrons in the plasma afterglow is governed by the following equation:

$$\partial n_e / \partial t = K_a^i n_a n_e + (K_{mh}^i n_m + K_{ah}^i n_a) n_h + n_h \nu_h^* + n_{ef} \nu_f^* + K_{me}^i n_e n_m - n_e / \tau_{ew} - K_d^e n_e n_d . \quad (1)$$

Here, K_a^i is the rate for ionization of ground-state atoms by Maxwellian electrons, K_{mh}^i and K_{ah}^i are the rates for ionization of metastable atoms and ground-state atoms by secondary electrons, respectively. ν_h^* and ν_f^* are the frequencies determining the termalization of electrons due to inelastic collisions of secondary and energetic electrons, respectively. K_{me}^i is the rate for ionization of Ar metastable atoms by thermal electrons. τ_{ew} is the electron diffusion time constant. K_d^e is the rate for collection of thermal electrons by dust particles, which is calculated by orbital motion limited (OML) theory.

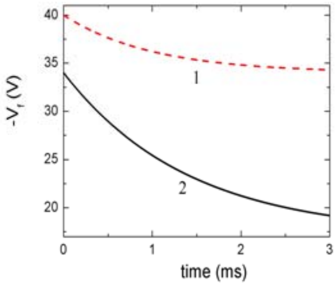

Fig. 1. The time-dependence of electrode voltages V_f in the dust-free (curve 1) and dusty (curve 2) plasma afterglows

The balance equation for energetic electrons is [7]:

$$\partial n_{ef}/\partial t = k_m n_m^2 - \nu_f^* n_{ef} - K_d^{ef} n_{ef} n_d - n_{ef}/\tau_{fw}, \quad (2)$$

where k_m is the rate for electron production in metastable pooling. K_d^{ef} is the rate for collection of energetic electrons by dust particles, and τ_{fw} is the time characterizing the escape of energetic electrons to the walls.

The balance equation for secondary electrons is:

$$\partial n_h/\partial t = \gamma_i n_i/\tau_{iw} - n_h \nu_h^* - K_d^h n_h n_d - n_h/\tau_{hw}. \quad (3)$$

The first term on the right-hand side in (3) describes generation of secondary electrons on the electrodes. Here, γ_i is the effective secondary emission yield, and τ_{iw} is the ion diffusion time constant. The second term accounts for the thermalization of secondary electrons in inelastic collisions. The third term on the right-hand side in (3) describes the collection of secondary electrons by dust particles with the rate K_d^h.

To calculate the rates K_d^e, K_d^{ef} and K_d^h in (1)-(3), one has to know the dust particle charge. Z_d is found from the balance equation for dust charging:

$$\partial|Z_d|/\partial t = K_d^e n_e + K_d^{ef} n_{ef} + K_d^h n_h - K_d^i n_i, \quad (4)$$

where K_d^i is the rate for collection of ions by dust particles.

The time-dependence for ion density in the afterglow is described by the ion balance equation:

$$\partial n_i/\partial t = K_a^i n_a n_e + (K_{mh}^i n_m + K_{ah}^i n_a) n_h + K_{me}^i n_e n_m + k_m n_m^2 - n_i/\tau_{iw} - K_d^i n_i n_d. \quad (5)$$

The plasma is assumed to be quasi-neutral, or

$$n_i = n_e + n_{ef} + n_h + |Z_d| n_d. \quad (6)$$

Equations (1) - (6) are solved numerically. The time dependencies for metastable density and electrode voltage in the afterglow are taken from the experiment [7-9], while the dust radius and ion density for the power-on phase are assumed to be known. In particular, the time-dependence for the spatially-averaged Ar metastable density can be approximated as $n_m(t) = n_m(0)\times\exp(-t/\tau_m)$, where $n_m(0)$ is the metastable density in the power-on phase and τ_m is the decay time for metastable density [7]. The procedure of calculation is similar to that used in [6].

RESULTS

Using the analytical expressions (1)-(6), we have calculated plasma parameters (the densities of thermal, energetic and secondary electrons, ion density and dust charge) as a function of time in the dusty plasma afterglow.

The calculated decay of spatially averaged thermal electron density and the experimental results of electron decay are compared in Fig. 2. The time-dependence for n_e is calculated for a_d = 50 nm, $n_d = 3.5\times10^7$ cm^{-3}, p = 0.1 mbar, T_g= 366 K and $\gamma_i = 0.1$.

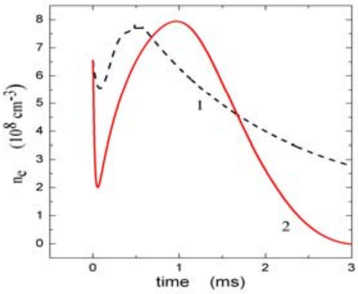

Fig. 2. The time-dependence for n_e in dusty plasma afterglow, measured in the experiment (curve 1) and calculated using the model (curve 2)

One can see from Fig. 2 that the calculated electron density follows well the experimental value. However, the calculated $n_e(t)$ dependence has a peak at $t \approx 1$ ms, while the peak for experimental electron density is at $t \approx 0.5$ ms. Moreover, for $t > 1$ ms, the decrease of the calculated electron density with time is faster than that in the experiment. We belive that our model underestimates the electron temperature at the begining of the afterglow (for $t < 1$ ms) and overestimates the electron loss in the late afterglow (for $t > 1$ ms).

Next, we analysed how metastable pooling and secondary electron emission from the electrodes affect the electron density in the afterglow. To understand the role of the electron production processes, we made calculations with different simplifications. First, we considered the case when the secondary emission is absent, while the metastable pooling takes place. In Fig. 3, the $n_e(t)$ dependence calculated for $\gamma_i = 0$ (curve 2) is compared with that for $\gamma_i = 0.1$ (curve 1).

One can see that the secondary emission increases the electron density. The peak density at $\gamma_i = 0.1$ is about 15 % larger than that at $\gamma_i = 0$. In the case when the metastable pooling is absent (k_m=0) and the secondary emission takes place ($\gamma_i = 0.1$), it was found that the thermal electron density decreases rapidly with time (see curve 3 in Fig. 3). Thus, the effect of secondary electron emission is less important than metastable pooling in argon/dusty plasma afterglow.

Note that nearly the same time-dependence for $n_e(t)$ can be obtained by excluding the secondary electron emission ($\gamma_i = 0$) but decreasing the dust density down to $n_d = 3.25 \times 10^7$ cm^{-3}.

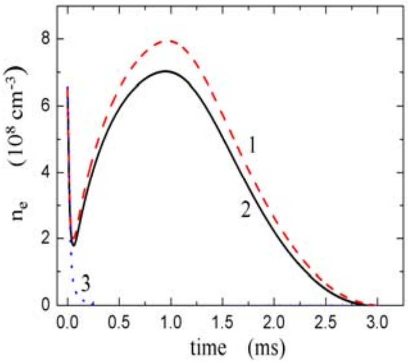

Fig. 3. The time-dependences for n_e calculated using different assumptions in the model

In conclusion, we have calculated the time-dependencies for electron density in argon/dusty plasma afterglow by using the model and experimental time-dependencies for metastable density and electrode voltage. The effect of secondary electron emission from the electrodes on the electron behaviour in argon/dusty plasma afterglow has been estimated by varying secondary emission yields. It has been found that the secondary electron emission is less important than argon metastable pooling.

REFERENCES

1. A. Bouchoule. *Dusty Plasmas: Physics, Chemistry, and Technological Impacts in Plasma Processing / E*d by. New York. "Wiley", 1999, p. 418.
2. I. Denysenko, K. Ostrikov, M.Y. Yu, N.A. Azarenkov // *Phys. Rev. E.* 2006, v. 74, p. 036402.
3. I. Denysenko, M.Y. Yu, L. Stenflo, S. Xu // *Phys. Rev. E.* 2005, v. 72, p. 016405.
4. J. Berndt et. al. Anomalous behaviour of the electron density in a pulsed complex plasma // *Plasma Sources Sci. Technol. (15).* 2006, p. 18.
5. I. Stefanović et al. Secondary electron emission of carbonaceous dust particles // *Phys. Rev. E.* 2006, v. 74, p. 026406.
6. I. Denysenko et al. // *J. Phys. D: Appl. Phys.* 2011, v. 44, p. 205204.
7. I.B. Denysenko et al. Discharging of dust particles in the afterglow of plasma with large dust density // *Phys. Rev. E.* 2013, v. 88, p. 023104.
8. B. Sikimić, I. Stefanović, I.B. Denysenko, J. Winter. A non-invasive technique to determine ion fluxes and ion densities in reactive and non-reactive pulsed plasmas // *Plasma Sources Sci. Technol.* 2013, v. 22, p. 045009.
9. B. Sikimić et al. Dynamics of pulsed reactive RF discharges in response to thin film deposition // *Plasma Sources Sci. Technol.* 2014, v. 23, p. 025010.
10. V.I. Demidov, C.A. DeJoseph, A.A. Kudryavtsev. Anomalously high near-wall sheath potential drop in a plasma with nonlocal fast electrons // *Phys. Rev. Lett.* 2005, v. 95, p. 215002.
11. M. Lieberman, A. Lichtenberg. *Principles of Plasma Discharges and Material Processing.* New York: "Wiley", 2005, p. 757.

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ВЛИЯНИЕ ВТОРИЧНОЙ ЭМИССИИ НА РАСПАД АРГОНОВОЙ ПЛАЗМЫ, КОТОРАЯ СОДЕРЖИТ НЕГАТИВНО ЗАРЯЖЕННЫЕ ПЫЛЕВЫЕ ЧАСТИЦЫ

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Разработана теоретическая модель распадающейся пылевой аргоновой плазмы, которая имеет высокую плотность наноразмерных пылинок. Данная модель учитывает генерацию электронов при столкновениях метастабильных атомов между собой и благодаря вторичной эмиссии при столкновениях ионов с электродами. Используя эту модель и экспериментальные временные зависимости для плотности метастабильных атомов и потенциала электродов, рассчитаны временные зависимости для плотности электронов в пылевой распадающейся аргоновой плазме. Проанализировано влияние вторичной эмиссии на генерацию электронов в этой среде.

ВПЛИВ ВТОРИННОЇ ЕМІСІЇ НА РОЗПАД АРГОНОВОЇ ПЛАЗМИ, ЩО МІСТИТЬ НЕГАТИВНО ЗАРЯДЖЕНІ ПИЛЬОВІ ЧАСТИНКИ

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Розроблено теоретичну модель пилової аргонової плазми, що розпадається, та має високу густину порошинок нанорозміру. Дана модель враховує генерацію електронів при зіткнені метастабільних атомів між собою та завдяки вторинній емісії при зіткнені іонів з електродами. Використовуючи цю модель та експериментальні часові залежності для густини метастабільних атомів та потенціалу електродів, розраховано часові залежності для густини електронів у запорошеній аргоновій плазмі, що розпадається. Проаналізовано вплив вторинної емісії на генерацію електронів у цьому середовищі.