Afterglow of rf discharge with nanoparticles

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The influence of nanoparticles on discharge plasma afterglow in argon is studied in PIC-MCC simulations. The anomalous electron density increase observed in experiment [1] is analyzed on the basis of the electron and ion distribution functions. It is shown that the departure of fast electrons to the electrodes in early afterglow is responsible for rapid increase of the electron density. The additional production of electrons due to metastable - metastable ionization enhances the effect of dust discharging.

The interesting phenomena in the pulsed complex plasma was observed in the experiment [1]. The electron density in gas discharge exhibited the anomalous behavior in early afterglow. In Ref. [1], the release of electrons from dust surface was discussed as a possible explanation of this phenomena. In later publication [2] the authors considered the different mechanisms possibly responsible for this anomalous increase of electron density in afterglow. In conclusion of Ref. [2] the following three mechanisms have been put forward. These mechanisms were the secondary electron emission caused by ion-dust interaction and metastable - dust interaction and metastable - metastable ionization. In this work we try to simulate the anomalous density behavior by release of electrons from dust. We study the rf discharge afterglow with nanoparticles for typical conditions of plasma technologies when the negative charge of nanoparticles is larger than the electron density. The simulations of 13.56 MHz capacitive discharge with nanoparticles were performed using the one-dimensional for space and three-dimensional for velocities particle-in-cell Monte Carlo collisions (PIC-MCC) method. We perform self-consistent simulation of electron and ion dynamics and movable dust, which transport is described with the fluid model. The balance equation describes the distribution of argon atoms in metastable state. The charge of nanoparticles is calculated using local time-dependent values of electron and ion distribution functions.

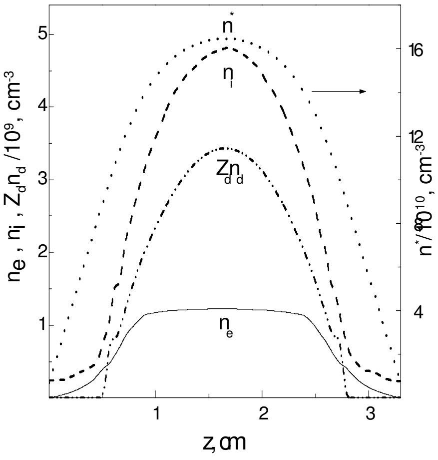

Fig. 1: Distributions of densities of electrons n_e, dust charge Zn_d, ions ni and metastables n^* in rf capacitive discharge with nanoparticles with r_d=50nm.

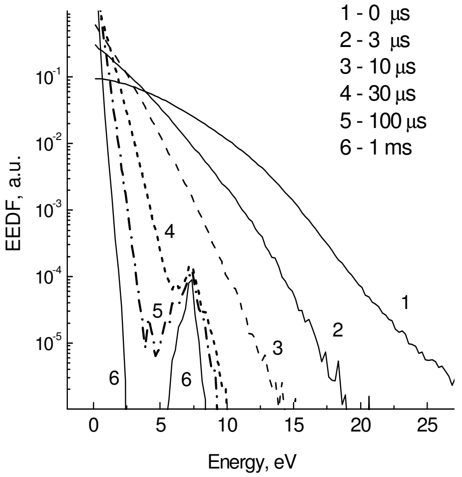

Fig. 2: Electron energy distribution function in the center of discharge gap for different time moments of afterglow with nanoparticles with r_d = 50nm.

The electrons released from the dust surface when the floating dust potential magnitude decreases are taken again in PIC-MCC simulations. Our model of rf discharge interaction with dust [3] is similar to the models from Refs. [4-6]. The electrons and ions scattering by dust particles together with electron and ion elastic and inelastic scattering on argon atoms determine the charged species transport. The distributions of charged species and metastables in operating discharge with dust are shown in Fig. 1. In Fig. 2, one can see the depletion of high energy tail of the electron energy distribution function (EEDF) during first 30 μs of afterglow. For larger time, t > 30 μs, the EEDF consists of two groups of electrons. The higher energy group includes electrons released from the dust surface and electrons produced by the metastable-metastable (M-M) ionization. The lower energy electrons confined by the potential well in the center of discharge and their dynamics is defined by ambipolar diffusion. For better understanding of influence of the dust on the plasma decay let us first consider the case without dust. Fig. 3 shows the evolution of electron density and temperature with/without M-M ionization.

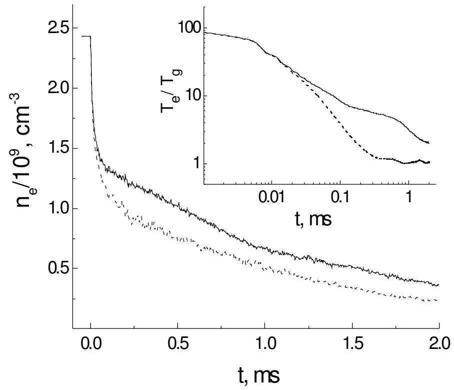

Fig. 3: Decay of electron density and temperature (insert) in pure argon in the center of discharge gap with metastable - metastable ionization (solid curve) and without it (dashed curve).

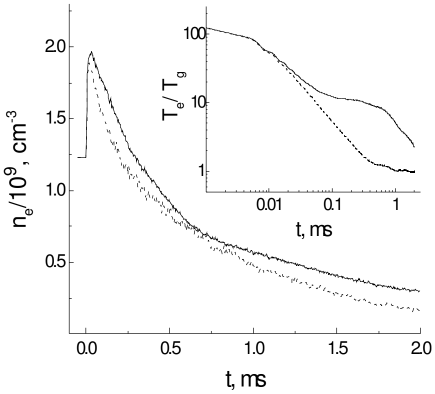

Fig. 4: The same as in Fig. 3, but with nanoparticles with r_d=50nm.

In contrast, the presence of dust alters qualitatively the evolution of the electron density. As seen in Fig. 4, just after switching off the voltage the electron density rapidly increases, similar to results of the experiment [1]. As mentioned above, during the first 30 μs the fast electrons leave the discharge volume (see EEDF in Fig. 2) and electron current to the dust surface drops.

References

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