Transition in discharge plasma of Hall thruster type in presence of secondary electron emissive surface

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Abstract. Modification of the sheath structure near the emissive plate placed in magnetized DC discharge plasma of Hall thruster type was studied in the experiment and in kinetic simulations. The plate is made from Al$_2$O$_3$ which has enhanced secondary electron emission yield. The energetic electrons emitted by heated cathode provide the volume ionization and the secondary electron emission from the plate. An increase of the electron beam energy leads to an increase of the secondary electron generation, which initiates the transition in sheath structure over the emissive plate.

1. Introduction

Plasma properties are strongly dependent on the processes of plasma-wall interaction. The secondary electron emission (SEE) from the chamber wall strongly affects the properties of Debye sheath on the wall, which screens plasma from the surface. Using materials with enhanced SEE for chamber walls and electrodes can change the classical structure of wall Debye sheath (see, for example, [1-4]). Rearrangement of Debye sheath for the materials with large SEE depends on plasma electrons temperature $T_e$ and energy of emitted electrons in the collisionless plasma [5,6]. The variations of Debye sheath structure leads to change of plasma parameters. For example, in experiments investigating Hall thruster plasma, the wall material with enhanced SEE yield led to saturation of the $T_e$ growth with increasing of applied voltage, but for material with small SEE yield the $T_e$ demonstrated linear growth with voltage [7].

In this work, in the experiment and kinetic simulations we study the DC discharge plasma of Hall thruster type, controlled by electron beam from heated cathode. The aim of work was to investigate the effect of variation of the electron beam energy $\epsilon_e$, on the structure of wall sheath near a Al$_2$O$_3$ plate, having enhanced SEE yield, for the conditions similar to the plasma of Hall thruster.

2. The experimental setup

In the experiment, the direct current discharge glows in a cylindrical chamber with radius of 8 cm and H=15 cm at low gas pressure, $P=4\times10^{-4}$ Torr. The walls of the chamber are grounded. The external magnetic field ($B=24$ G) is generated by coils of wire (solenoid) and directed along the axis of symmetry. The cathode is the system of tungsten wires which are heated and emit electrons. This cathode biased with the voltage of 0 - 300 V. The floating plate made from Al$_2$O$_3$ is placed 9 cm apart from the cathode. An additional mesh electrode is placed 0.5 cm apart from the plate surface. This electrode can be used to measure the plasma potential and to control the secondary electron emission current from the surface.
3. Theoretical model

The magnetized plasma is described with the system of equations including the Boltzmann equations for electrons and ions and fast neutral atoms. The distribution functions for electrons \( f_e(t,x,v) \) and ions \( f_i(t,x,v) \) are calculated by solving the Boltzmann equations

\[
\frac{\partial f_e}{\partial t} + v_e \frac{\partial f_e}{\partial r} + \frac{e(E + v_e \times B)}{m_e} \frac{\partial f_e}{\partial v_e} = J_e, \quad n_e = \int f_e \, dv_e, \\
\frac{\partial f_i}{\partial t} + v_i \frac{\partial f_i}{\partial r} + \frac{e(E + v_i \times B)}{m_i} \frac{\partial f_i}{\partial v_i} = J_i, \quad n_i = \int f_i \, dv_i.
\]

and the Poisson equation for the electric potential \( \phi \) is also solved:

\[
\Delta \phi = 4 \pi (n_e - n_i), \quad E = -\frac{\partial \phi}{\partial r}.
\]

where \( v_e, v_i, n_e, n_i, m_e, m_i \) are the velocity vectors, densities and masses of electrons and ions respectively, \( E, B \) are the electrical and magnetic field vectors, \( J_e, J_i \) are the collisional integrals for electrons and ions. The Particle in Cell Monte Carlo Collision (PIC MCC) method [8] was applied to solve the Boltzmann equations, which are two-dimensional in space and three-dimensional in velocity space. The system of equations are solved self-consistently with PlasmaNOV code [9]. For the electrons, the model includes elastic scattering, excitation and ionization collisions are accounted; for ions, the resonant charge exchange collisions with background argon gas are included.

In simulations, the applied voltage \( U_c \) is ranged from 0 to 300 V. For these plasma parameters the electron Larmor radius \( r_L \) is comparable to the Debye length \( \lambda_D \), \( r_L < \lambda_D \approx 0.1-0.5 \) cm. The plasma frequency \( \omega_p < \Omega_e \approx (5-50) \times 10^8 \) s\(^{-1}\), where \( \Omega_e \) is the electron gyrofrequency.

In calculations, the electron time step is \( (2-5) \times 10^{-12} \) s. The grid is uniform in \( z \)-direction and nonuniform over radius condensing with decreasing \( r \). The total number of pseudoparticles for PCC MCC algorythm is chosen so that there is an average of approximately 100 positive and negative particles per Debye sphere.

In Figure 1 (left), the calculation domain is shown. The plasma is embedded in a cylindrical chamber with the radius of 8 cm and the height of 10 cm. The cathode radius is 2 cm.
In the experiment, the heating of tungsten wires of the cathode with 12 A current gives us the maximum of the emissive electron current of 100-140 μA. The emissive electrons crossing the cathode sheath gain the energy of $e\phi_c$, where $\phi_c$ is the potential drop over the cathode sheath. Thus the energy of beam electrons rises with increase of applied voltage $U_c$. In Figure 1 (right), the measured current to the anode plate as function of $U_c$ is shown for the grounded anode and wall of the chamber. It is seen that for smaller $U_c < 50$ V, only a minor part of electrons reaches the anode. The computed electron current distribution is shown in Figure 2 for $U_c = 30$ V and 150 V.

To study the sheath modification with an increase of the electron beam energy, in the experiment, the measurements of floating potential on the Al$_2$O$_3$ plate surface and 0.5 cm apart from the surface were done for different applied voltages. The results are given in Figure 3 (left). Note that the difference in the potentials is essential for $U_c < 100$ V. For $U_c > 100$ V, the potentials on the plate surface and 0.5 cm apart for the surface practically coincide.

It is seen that the floating potential of the plate surface does not change with $U_c$. In contrary, the plasma potential at $z=0.5$ cm apart from the surface varies essentially. It manifests the collapse of sheath near the emissive surface for the case when secondary emission becomes pronounced.

As simulations show, for $U < 100$ V, the potential drop near the floating plate surface $\Delta \phi$ is set by currents of the beam electrons $j_{be}$ and secondary electrons, $j_{be} = j_{se}$. The ion current is negligible. The transition happens at $U \approx 100$ V. It is clearly indicated in Figure 3 (right) by a decrease of difference in potentials of plate surface and 0.5 cm apart.

The mean temperature of the plasma electrons also decreases at the point of the transition. In this new regime (collapsed sheath), the cold plasma electrons start to contribute to the current balance on the plate. Now the currents of the cold plasma electrons $j_{pe}$, beam electrons $j_{be}$ and secondary electrons, $j_{be} + j_{pe} = j_{se}$ set the potential drop near the floating plate. Since the density of the slow plasma electrons is much larger than that of the beam electrons, a small decrease of $\Delta \phi$ leads to considerable increase of the plasma electron current. With increasing $U_c$, the potential drop $\Delta \phi$ tends to value of $T_e$.

In conclusion, we have studied the sheath formation in DC discharge plasma in front of floating emissive plate made of Al$_2$O$_3$ with enhanced secondary emission coefficient. The discharge operation is maintained by beam of energetic electrons from the heated cathode. The voltage is applied to the cathode, and the energy of electron beam is set by this applied voltage. We have found the collapse of sheath near the floating plate with increasing applied voltage.
Figure 3. Left: the floating potential, measured in the experiment, on the plate surface (solid line) and 0.5 cm apart from the surface (dashed line) for different applied voltages. Right: calculated potential distribution over axis of symmetry for \( U_c = 60 \text{ V} \) (dashed line) and 110 V (solid line).

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