SIMULATION AND EXPERIMENTAL RESEARCH OF LANGMUIR PROBE OPERATION IN ELECTRO-NEGATIVE PLASMA

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The mathematical model of single cylindrical Langmuir probe describing dependence of positive ion current gathered by the probe on the basic parameters of electronegative plasma, such as probe potential, densities of electrons, positive and negative ions, relation between ion and electron temperatures is built. The model is based on the theory of the radial motion of charged particles. The model covers wide parameters domain of the electronegative plasma, particularly the whole range typical for technological systems. The experimental measurements, confirming the high reliability of the model are reported. The model can be used in probe measurements of electronegative plasma parameters in laboratory and technological systems, as well as for further theories perfection of surface layers in gas-discharge plasma.

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INTRODUCTION

Electronegative plasma can offer useful advantages in a variety of applications, for example charge-free etching in the semiconductor industry [1, 2], neutral beam injections for fusion [3, 4] or electric propulsion in space applications [5]. One of the most attractive methods for measuring of the electro-negative plasma parameters is the Langmuir probe method providing local measurement of main plasma parameters in wide range of their change. However, the probe measurements in electro-negative plasma have specific peculiarities appearing due to complex composition of the plasma. The influence of negative ions on the positive ion branch of the current-voltage characteristics in the case of spherical and cylindrical Langmuir probe was considered in the Amemiya and Annaratone's paper [6]. However, in this paper the current-voltage characteristics of a cylindrical probe in electronegative plasma are presented only for one value of plasma electronegativity parameter α = 0.9, that limits the possibility of practical application of the simulation results. The purpose of this paper is the development and experimental verification of a mathematical model of the single cylindrical Langmuir probe in electronegative plasmas, describing dependence of the ion current collected by the probe on the main parameters of the plasma, such as the potential of the probe, the density of positive and negative ions, the ratio of the ion and electron temperatures. The model should cover wide range of plasma parameters, particularly, the full range characteristic for technological systems.

1. THEORETICAL MODEL

The present paper investigates current of positive ions to a single Langmuir probe in the form of an infinitely extended cylinder with no edge effects. The probe is immersed in a highly non-isothermal plasma, where the temperature of the positive ions is much lower than the temperatures of both the electrons and negative ions: $T_i/T_e<<1$ и $T_i/T_n<<1$. The distribution of electrons and negative ions in the plasma is assumed to be Maxwellian. Probe sheath is considered as collisionless, so that all the collisions between particles are neglected. The model is based on the solution of the Poisson's equation for electronegative plasma written in cylindrical coordinates.

In order to simplify the problem solving we have introduced the following dimensionless variables:
dimensionless potential $\psi = e\varphi/kT_e$,
dimensionless coordinate $x = r/\lambda_{Di}$,
and dimensionless parameters:
dimensionless probe radius $x_p = r_p/\lambda_{Di}$,
dimensionless probe potential $\psi_p = e\varphi_p/kT_e$,
negative ions and electrons temperature ratio $\gamma = T_n/T_e$,
Debye radius for positive ions $\lambda_{Di} = (kT_e/4\pi e^2 n_{i0})^{1/2}$,
dimensionless positive ion current to the probe
$i = I_i/(2\pi r_p L e n_{i0}(2kT_e/m_i)^{1/2})$.

In addition, we have introduced another dimensionless parameter characterizing the number of negative ions in the plasma. It is determined by the ratio of the negative ion density n_n and positive ion density n_i: $\alpha = n_n/n_i$. In the case of large values of α it is also convenient to use a different parameter $\alpha_e = n_e/n_i$, where n_e is electron density. The values of the parameter α vary from 0 (the case of classical plasma), to 1 (the case of ion-ion plasma).

Poisson's equation in dimensionless variables can thus be written as follows:

$$\frac{d^2\psi}{dx^2}+\frac{1}{x}\frac{d\psi}{dx}=-\left(i\frac{x_p}{x}\frac{1}{\sqrt{-\psi}}\right)+(1-\alpha)\exp(\psi)+\alpha\exp(-\frac{1}{\gamma}\psi).$$

The boundary conditions are defined in the presheath, where the motion of positive ions is mainly directed to the probe, as opposed to undisturbed plasma, where it is mostly chaotic. The boundary radius x_0 was chosen to satisfy the conditions of quasineutrality and $kT_e >> |e\varphi| >> kT_i$, $kT_n >> |e\varphi| >> kT_i$. Thus, we used the following boundary conditions:

$$x_0 = ix_p/\sqrt{\tau}, \qquad \psi_0 = -\tau, \qquad (d\psi/dx)_0 = 2\tau/x_0,$$

where $\tau = e\varphi_0/kT_e$ is the ratio of positive ions energy at the boundary surface to the electron temperature. Note that such choice of the dimensionless variables has made it possible to reduce the problem solution downto

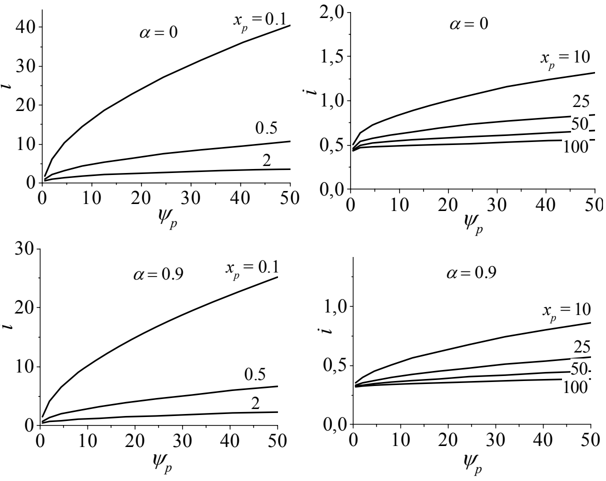

Fig. 1. Dimensionless current-voltage characteristics of Langmuir probe for different values of dimensionless radius x_p in electropositive (α = 0) and electronegative (α = 0.9) plasma

finding the dependence of the current on six parameters instead of eight in the dimensional form.

The numerical results are presented in Fig. 1 as a set of curves representing dependency of the dimensionless current function of the dimensionless probe potential. One can see from these dependencies that the value of dimensionless current drops with the rise of dimensionless radius, that is associated with decrease of the probe sheath thickness. It is seen that the current of positive ions to the probe falls also with the plasma electronegativity increase.

In Fig. 2 the comparison of radial distributions of charged particle densities in the vicinity of the probe in electropositive and electronegative plasmas is shown. The plasma electronegativity increase means the negative charge redistribution between the electrons and negative ions, while the negative ion density decreases faster when approaching the probe due to lower temperature. Fig. 2 shows that such a change in the structure of the probe sheath also has a strong influence on the distribution of the density of positive ions.

2. EXPERIMENTAL RESULTS AND DISCUSSION

In order to create a strongly electronegative plasma a system was used based on electrostatic grid-type electron filter described in [7]. In this system a vacuum chamber with 250 mm diameter is divided by the filter grid into two regions: the region with the dense ICP plasma, produced by 2 turn shielded inductive coil with 13,56 MHz RF power 200 W, and the region with strongly electronegative plasma. On the opposite side the electronegative plasma region is restricted by the grounded extraction electrode with 250 mm diameter, placed at 100 mm distance from the grid. The experiments were carried out at pressure of 10^{-3} … 10^{-2} Torr with the following operating gases: Ar, O_2, SF_6, mixture of Ar and SF_6. The residual pressure in the chamber did not exceed $5 \cdot 10^{-6}$ Torr. In all the described experiments single cylindrical Langmuir probes with length of 5 mm and a diameter of 70 microns was used.

The comparison of the experimentally measured probe current-voltage characteristics are shown in Fig. 3 for the gas mixtures of Ar and SF_6 with different ratio of the gas partial pressures. As can be seen, with the SF_6 partial pressure increase the electron saturation current of the probe trace decreases with almost constant positive ion current. This look natural taking in to account that SF_6 is an electronegative gas, so its concentration increase causes the growth of the negative ion density in the plasma and subsequent decrease electron density.

In Fig. 4 a typical experimentally measured current-voltage characteristics of the probe are shown in comparison to the calculation results converted to dimensional form. Comparison of all the experimental and theoretical data shows that the results of measurements and calculations are in good agreement in wide range of parameters: for different gases at different pressures and with different degrees of the plasma electronegativity.

The simulation results show that the probe current can depend not only on the parameter *α*, but also on the temperature of the negative ions. Fig. 5 shows the dependence of the dimensionless saturation current of

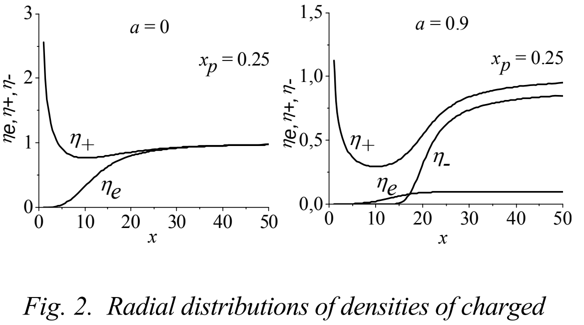

Fig. 2. Radial distributions of densities of charged particles for different values of parameter α with x_p = 0.25. $\eta_e = n_e/n_{e0}$ is dimensionless electron density, $\eta_+ = n_i/n_{e0}$ is dimensionless positive ions density, $\eta_- = n_n/n_{e0}$ is dimensionless negative ions density

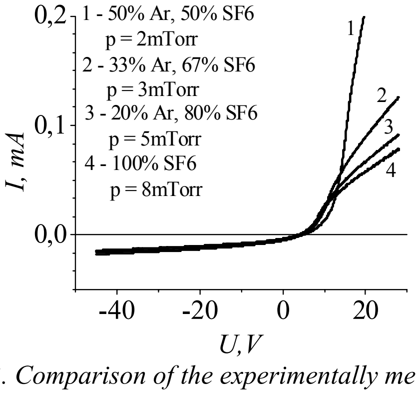

Fig. 3. Comparison of the experimentally measured probe current-voltage characteristics for the gas mixture of Ar and SF_6, with different concentrations of the gases

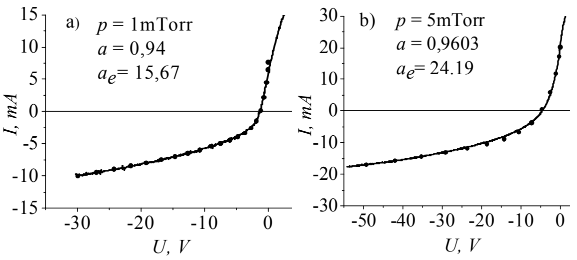

Fig. 4. a) Probe trace for O_2. $\alpha = 0,94$, $\alpha_e = 15,67$; b) probe trace for gas mixture of 20% Ar and 80% SF_6. $\alpha = 0,9603$, $\alpha_e = 24,19$. Solid curve: experimentally measured. Points: calculation results

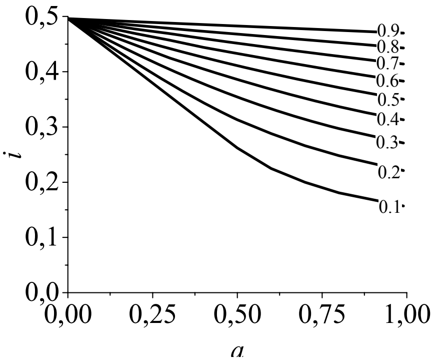

Fig. 5. Dependencies of the dimensionless probe current i on the parameter α for different γ in the large probe limit ($x_p = 100$)

positive ions to the large probe ($x_p = 100$) on the parameter α for different values of γ (0.1…0.9) characterizing the negative ion temperature. A conclusion may be derived from these dependencies that the Bohm current density of the positive ions is reduced with the plasma electronegativity increase and negative ion temperature decrease.

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МОДЕЛИРОВАНИЕ И ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ РАБОТЫ ЗОНДА ЛЕНГМЮРА В ЭЛЕКТРООТРИЦАТЕЛЬНОЙ ПЛАЗМЕ

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Построена математическая модель работы одиночного цилиндрического зонда Ленгмюра, описывающая взаимосвязь собираемого зондом тока положительных ионов с основными параметрами электроотрицательной плазмы, такими как: потенциал зонда, плотности электронов, положительных и отрицательных ионов, отношение температур электронов и ионов. Модель основывается на теории радиального движения заряженных частиц. Она перекрывает широкую область параметров электроотрицательной плазмы, в частности, весь диапазон, характерный для технологических систем. Проведены экспериментальные измерения, подтверждающие высокую достоверность модели. Модель может быть использована при проведении зондовых исследований в электроотрицательной плазме в лабораторных и технологических системах, а также для дальнейшего совершенствования теорий приповерхностных слоев в газоразрядной плазме.

МОДЕЛЮВАННЯ ТА ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ РОБОТЫ ЗОНДА ЛЕНГМЮРА В ЕЛЕКТРОНЕГАТИВНІЙ ПЛАЗМІ

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Побудовано математичну модель роботи одиночного циліндричного зонда Ленгмюра, яка описує взаємозв'язок струму позитивних іонів, що збирається зондом, з основними параметрами електронегативної плазми, такими як: потенціал зонда, густина електронів, позитивних та негативних іонів, співвідношення температур електронів та іонів. Модель грунтується на теорії радіального руху заряджених частинок. Вона перекриває широку область параметрів електронегативної плазми, зокрема, весь діапазон, характерний для технологічних систем. Проведено експериментальні вимірювання, які підтверджують високу достовірність моделі. Модель може бути використана під час проведення зондових досліджень електронегативної плазми в лабораторних і технологічних системах, а також для подальшого вдосконалення теорій приповерхневих шарів в газорозрядній плазмі.