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Investigation of the conditions for the formation of the second point of electric field reversal of the sign in the glow discharge

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An experimental study of the longitudinal distribution of glow discharge parameters in argon in the pressure range 0.1−0.7 Torr at a discharge current of 10 mA has been carried out. The longitudinal distributions of electron concentration and temperature and space potential are obtained by the method of the second derivative of the probe current. The glow of the discharge was studied using a photomultiplier. Analysis of the measured data shows that at low pressures there is one point of reversal of the field in the middle of the luminous region corresponding to the maximum plasma density. At the same time, the surface of the anode is dark, the anode drop is negative (repels electrons). With increasing pressure, a luminous film appears on the anode and a second field reversal point is formed. The anode drop is positive (attracts electrons).

Keywords: Inverse electron distribution function, points field reversal, glow discharge.

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In recent times, more and more attention is being paid to the conditions of manifestation of a nontrivial and debatable phenomenon: sign reversal of the electric field (field reversal, FR) in a DC glow discharge [1–3]. Thus far, the positioning of the first (counting in the direction from the cathode to the anode) FR point, which is located at the point of maximum density of negative glow (NG) plasma, has been studied in most detail both theoretically and experimentally. At the same time, no experiments on identifying the second FR point have been performed.

It was established that the emergence of the first FR point is associated with specific features of ionization and transport processes in the near-cathode discharge region. Electrons produce more than 99% of the current in positive column (PC) plasma, and the ratio of electron to ion currents directly at the cathode is low: $j_e(0)/j_i(0) = \gamma \ll 1$. Since the variation of partial current in a given region is equal to the ionization rate in it, ionization (and, consequently, the electric field) in the near-cathode discharge region should be more intense than in the PC. Thus, electrons acquire a considerable energy in a strong field of the cathode layer and multiply rapidly. Fast electrons accelerated in the cathode layer with a thickness of d then enter the region of NG plasma and induce substantial nonlocal ionization there. With the ionization rate in this region comparable to the one in the cathode layer, spatial removal of electrons from NG plasma with a weak field is inhibited. This is the reason why a significant plasma density peak forms here; as a matter of fact, the brightest region with the maximum charge density is the feature that gave a glow discharge its name. Under these conditions, the diffusion current of electrons toward the anode starts exceeding the total discharge current

$$eD_e \nabla n_e > j, \qquad (1)$$

where e is the electron charge, D_e is the electron diffusion coefficient, ∇n_e is the electron density gradient, and j is the total discharge current density.

However, the current in a steady discharge remains constant along its length and is equal to the discharge current. Therefore, a reverse polarization (ambipolar) charge separation field, which decelerates electrons and ensures invariability of current over the cross section, forms beyond the plasma density maximum in order to balance out the „excess" diffusion current:

$$j(z) = eD_e \nabla n_e - e\mu_e E n_e = \text{const}, \qquad (2)$$

where $j(z)$ is the density of current along axis z, μ_e is the electron mobility coefficient, n_e is the electron concentration, and E is the strength of electric field in the discharge.

Condition (1) is the criterion of formation of the first FR point x_m at the maximum of the NG plasma density. The positioning of this point is important for conditions of maintaining the discharge, since ions produced through to this point ($x < x_m$) return to the cathode and contribute (often significantly) to the emission of electrons from its surface. At the same time, ions produced in region $x > x_m$ move to the anode in the reverse field that decelerates electrons and accelerates ions toward the anode instead of the cathode.

In a short (without a PC) discharge, the anode field cannot change sign (with a positive anode fall (AF), these ions would have no site to recombine). Therefore, the AF sign in a short discharge is negative (electron-decelerating). The AF value here is $e\varphi_A \approx T_e \ln(M/m)$ (φ_A is the anode potential, T_e is the electron temperature, and $\ln(M/m)$ is the natural logarithm of the ratio of ion and electron masses) and is on the order of the electron temperature [4,5]. Thus, the majority of electrons are trapped in a potential well, and the anode is dark. The overall potential variation in this well is insignificant ($< 1-2$ eV), since it is specified by a relatively low (< 1 eV) temperature of trapped electrons T_e [4,5]. The existence of the first FR point near the plasma density maximum x_m has been verified numerous times both theoretically and experimentally [1–3].

In a long discharge with a longitudinally uniform PC, the second term with an external (forward) field is dominant in current (2). Under these conditions, a second FR point should necessarily form in the region of transition to a PC at certain position x_2. Beyond it (in the direction of the anode), the field is forward: accelerates electrons toward the anode and decelerates ions. A positive AF of potential (on the order of the gas ionization potential) thus emerges near the anode, inducing the formation of a glowing film at the anode [4–6].

As for the second FR point, its positioning has not been examined experimentally. This is largely attributable to the fact that the transition to the second FR point occurs under a small (several millivolts) variation of the space potential. Therefore, this change is hard to detect in an experiment. The physical and practical irrelevance of the positioning of this point is another probable reason why data on it are lacking.

A surge in interest in the second field sign reversal point is largely attributable to the prediction made in [7] regarding the possibility of inversion of the electron distribution function (EDF) around this point. An inverse EDF should allow one to make headway in solving the crucial problem of obtaining an absolute negative conductivity of electron gas in gases with a Ramsauer minimum of the elastic scattering cross section (argon, krypton, xenon). It bears reminding that the prediction and implementation of inverse population of excited states of atoms and molecules provided and opportunity to design a broad spectrum of lasers that are used widely in various engineering applications. In a manner similar to the inverse population of excited states in lasers, a medium with an inverse EDF should amplify electromagnetic waves.

It was demonstrated in [7] that the criterion for implementation of an inverse EDF f_0 takes the form

$$(\partial f_0/\partial w)|_{w=0} = (\partial f_0/\partial x)|_{w=0}/E_x, \qquad (3)$$

where f_0 is the energy distribution function of electrons, w is the electron energy, and E_x is the longitudinal electric field strength.

It follows from formula (3) that if an electric field changes sign at certain point x_0, $(\partial f_0/\partial w)|_{w=0}$ changes sign when and only when the sign of $(\partial f_0/\partial x)|_{w=0}$ does not change. If $(\partial f_0/\partial x)|_{w=0} < 0$ and $E_x < 0$ (this corresponds to an increase in potential), $(\partial f_0/\partial w)|_{w=0} > 0$; i.e., f_0 features inversion. It is evident that the inversion conditions are not satisfied in the vicinity of the first point. At the same time, the field may start intensifying to a PC directly beyond the second FR point where $(\partial f_0/\partial x)|_{w=0} < 0$ still holds; i.e., condition $E_x < 0$ may be satisfied. Formula (3) then yields $(\partial f_0/\partial w)|_{w=0} > 0$; i.e., the EDF will feature inversion at zero energy [7].

In the present study, a complex experimental examination of the longitudinal distribution of glow discharge parameters in argon was performed within the $0.1-0.7$ Torr pressure range at a discharge current of 10 mA. Experiments were carried out in a glass discharge tube 65 mm in diameter with an interelectrode distance of 160 mm. A traveling electric probe was used to determine the electron parameters. Longitudinal distributions of the electron concentration and temperature and the space potential were determined from the second derivative of the probe current. A photomultiplier tube was used to study the discharge glow.

A radiotechnical method with a high-frequency amplitude-modulated signal introduced into the probe circuit was used to find the second derivative [8]. The anode was the reference electrode in probe measurements.

It follows from the results of analysis of experimental data that a single FR point is present in the middle of the glowing region, which corresponds to the plasma density maximum, under low pressures (the studied discharge is then composed only of cathode and anode layers and the bright NG plasma region). The anode surface is dark under these conditions, and the AF is negative (electrons are repelled). The temperature of thermal electrons in the potential well between the cathode and anode layers is low (< 1 eV), and their energy EDF is close to the Maxwellian one. The temperature of electrons was determined by examining the slope of the logarithm of the second derivative of the probe current with respect to the probe potential.

In step with a subsequent pressure increase, a dark region of FDS (Faraday dark space) plasma starts forming. This region grows in length from the anode toward the cathode, while the NG region shrinks in size accordingly. A glowing film is then produced on the anode, and the second FR point, which is of interest to us, emerges. As the pressure grows further, a glowing positive discharge column with a high (on the order of 3 eV) electron temperature starts forming near the anode. Although both FR points are preserved, the distances between them and to the cathode shorten, making them much harder to detect under higher pressures. The temperature of electrons trapped in the plasma region between the first and the second FR points is fittingly low (below 1 eV), and their EDF is near-Maxwellian.

Experimental data for two most distinctive regimes (pressures of 0.1 and 0.4 Torr) are shown in Fig. 1 for illustrative purposes. Figure 1, *a* presents the longitudinal distribution of the discharge glow intensity. As is known, the glow maximum corresponds to the position of the cathode layer boundary (d). As could be expected, the layer becomes thinner as the pressure rises and the voltage decreases.

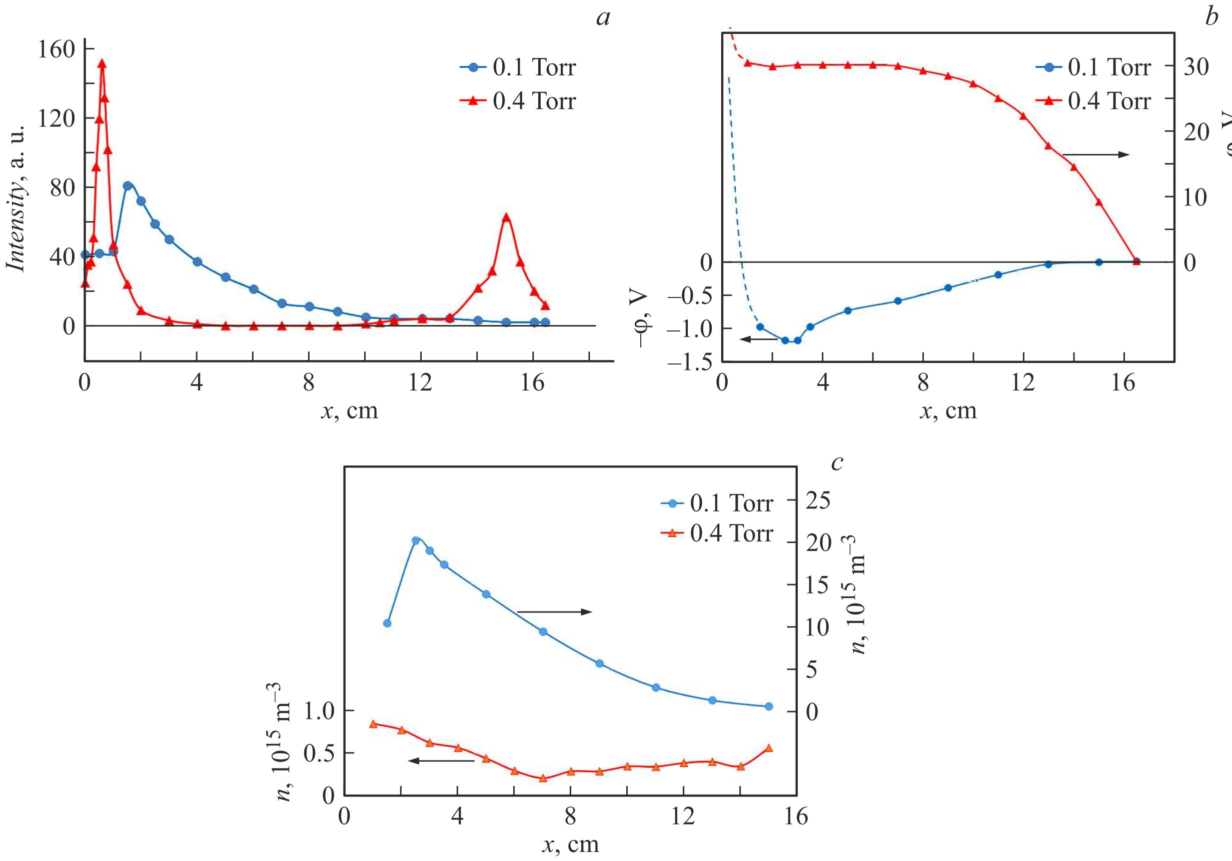

Figure 1. Axial distribution of the discharge glow intensity (*a*), the space potential (cathode is on the left, and anode is on the right) (*b*), and the electron concentration (*c*).

Under a pressure of 0.1 Torr, thickness $d \approx 1.8$ cm; at 0.4 Torr, $d \approx 0.8$ cm. At 0.1 Torr, NG plasma occupies almost the entire discharge volume, and the anode is dark. Under a pressure of 0.4 Torr, the Faraday dark space, which merges into a glowing PC, occupies a considerable fraction of the discharge. A bright anode glow film is observed near the anode.

Figure 1, *b* presents the results of axial measurements of the plasma potential. Probe measurements were carried out up to the boundary of the cathode layer; to the left of it (i.e., in the layer itself), the potential starts increasing rapidly. The temperature of electrons in NG plasma falls within the 0.3−0.4 eV range (0.36 eV at $x = 7$ cm). It can be seen that the potential under low pressures has a minimum around $x_m \approx 2.8-3$ cm. This point corresponds approximately to the plasma density maximum (Fig. 1, *c*). The plasma region is a potential well for electrons with a slight (~ 1 V) variation of potential relative to the reference electrode (grounded anode).

This pattern changes dramatically under a pressure of 0.4 Torr. First, a positive anode fall of approximately 30 V is observed. Second, the first FR point is poorly resolved and is positioned approximately at $x_m \approx 1.5-2$ cm. The potential varies weakly further up to the second FR point ($\sim 6-7$ cm). Beyond it, the potential (and, consequently, the electric field strength) rises in the region of transition to a PC. The temperature of electrons in NG plasma falls within the 0.3−0.4 eV range and starts growing in the transition region (0.57 eV at $x = 7$ cm). Following the transition to a forward field, a reduction in plasma density in the NG and FDS region gives way to its growth at $x > 7$ cm.

The concentration and the mean energy of electrons were determined by integrating the EDF, which was derived from the results of measurements of the second derivative of the probe current, over energy.

In order to determine the second derivative of the probe current in absolute units, the setup was calibrated by feeding an audio-frequency (modulation frequency) signal to the probe and calculating the probe current. The typical shape of measured second derivatives is shown in Figs. 2, *a* and *b*.

Thus, it was demonstrated that the second point of sign reversal of the electric field in a glow discharge in argon emerges necessarily when the gas pressure (parameter $pL > 3\,\text{cm} \cdot \text{Torr}$, where p is the gas pressure and L is the distance between the anode and the cathode of the discharge) increases as a region of transition from a Faraday dark space to a positive column forms. The obtained experimental data verify the results of theoretical analysis [4,5] and modeling [7] that suggested the emergence of the second field reversal point in the region of transition to a positive column in a glow discharge.

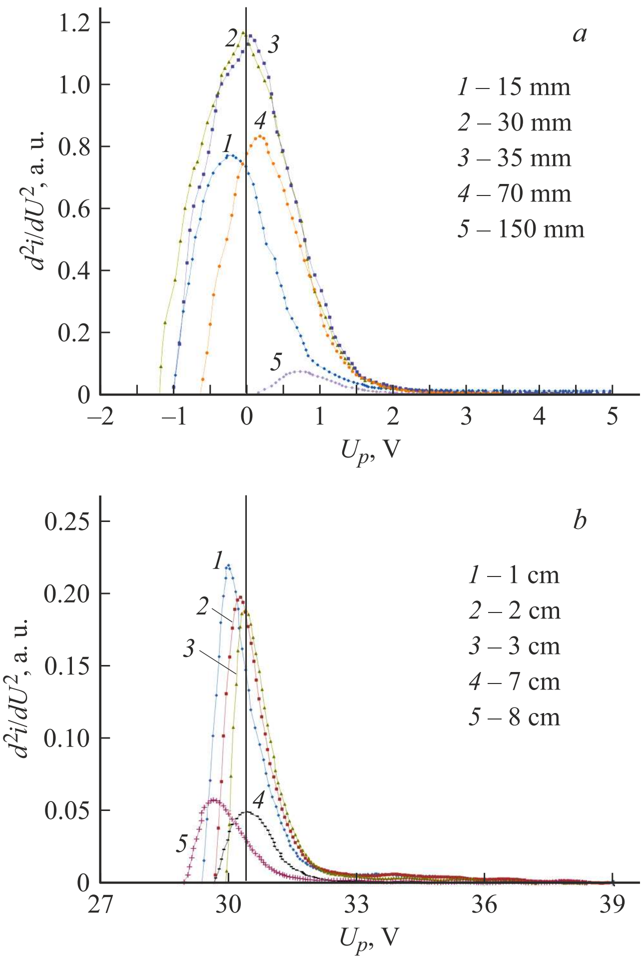

Figure 2. Second derivatives of the probe current on the discharge axis in argon for different distances to the cathode (indicated). *a* — $p = 0.1$ Torr, $I = 10$ mA; *b* — $p = 0.4$ Torr, $I = 10$ mA. U_p — probe voltage.

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Conflict of interest

The authors declare that they have no conflict of interest.

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