SECONDARY STREAMERS IN THE PRIMARY STREAMER CHANNEL

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The propagation of the process with ionization and attachment in the remainder of the streamer channel is studied. From the simplified model consideration it is shown that in the conditions of the attachment instability development the spatially inhomogeneous perturbations move to anode. The conditions, in which the perturbations move to cathode, as it is usually observed for the secondary streamers, are discussed.

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INTRODUCTION

The discharge between the needle anode and the plane cathode is used in plasma chemistry for a long time. In the form of cathode directed streamers [1] the discharge is effective for the non-equilibrium plasma production. The study of the processes, which accompany the streamer propagation, is continued up to now [2, 3]. In the paper [4], the numerical simulations of the cathode directed streamer propagation in the electronegative gases with strong attachment are carried out for the quasi-stationary stage, far from electrodes, and for the stage of going out to cathode. In the present paper, the phenomenon of the secondary streamer is studied. It is observed at the final stage of streamer propagation in some electronegative gases, when the streamer goes out to cathode. The secondary streamer is the domain with intensive glow in the channel of the primary streamer. Sufficiently convinced explanation of the secondary streamers nature is presented in the paper [5]. It is shown that the attachment instability leads to monotonous increase of electron and ion density perturbations and to appearing of the channel domains with strong and weak field. But in the approximation considered in [5], the boundaries of the domains are motionless. In the present paper, it is carried out the study of the model near to one studied in [5], with estimation of the displacement velocity for the charge density perturbations. It is shown that in the conditions of the attachment instability the perturbations move to anode, whereas the secondary streamers usually move to cathode. So, the attachment instability may be considered as the cause of appearing of the channel domains with strong and weak field, but movement of these domains to cathode may take place in the conditions of the attachment instability absence, when spatially inhomogeneous perturbations fade away.

1. SIMPLIFIED MODEL

In the model considered in [5], the ratio of attachment and relaxation frequency is small parameter, the relationships are deduced in the assumption about such degree of plasma quasi-neutrality, which does not prohibit the electric field strength distribution to be inhomogeneous, and the displacement current is neglected. Also, in fact, the assumption is made that the emission current from cathode, I_e, is near to the ratio I_0 of the applied voltage and the discharge gap resistance. In reality, the emission current is determined by a lot of factors, and the difference between the entrance current and the exit current leads to change of the total charge value inside the gap. If $I_\mathrm{e} < I_0$ then it is formed the comparatively thin near-cathode layer with large non-compensated positive charge density and not very small part of the total potential drop, and the ratio of the other parts of the potential drop and the discharge gap resistance should be near to I_e. To consider the next approximations in the expansion with respect to the mentioned small parameter, it is necessary to impose the clear condition on the entrance current. To keep the main results of [5], it is necessary to keep quasi-neutrality. To ensure the absence of the non-compensated charge in the whole discharge gap, the entrance and exit currents should be equal. The results obtained in consideration of such model may be applied for more real situation of non-equal entrance and exit currents with aid of decrease of the potential drop over the gap on the value of the potential drop over the mentioned near-cathode layer.

So, it is considered the plasma in the gap between cathode ($x = 0$) and anode ($x = b > 0$). Ion motion is neglected. The plasma is described by the equations

$$\partial_t n_\mathrm{e} + \partial_x (n_\mathrm{e} \mu_\mathrm{e} E) = -\nu_\mathrm{a} n_\mathrm{e} = \partial_t n_\mathrm{i} , \qquad (1)$$

$$\varepsilon_0 \partial_x E = e_0 (n_\mathrm{e} - n_\mathrm{i}) , \qquad (2)$$

where ∂ with index means derivative with respect to the variable indicated in index, μ_e and n_e are mobility and density of electrons, n_i is the difference of the densities of positive and negative ions, E is the quantity opposite to the x-component of the electric field strength ($E = -E_x$, $E > 0$), ε_0 is electric constant, e_0 is elementary charge ($e_0 > 0$), ν_a is difference between the attachment and ionization frequencies. It is assumed that $\nu_\mathrm{a} = \nu_\mathrm{a}(E)$ and $\mu_\mathrm{e} = \mathrm{const}$. It is imposed the condition $\int_0^b dxE = U$, where U is voltage applied to the gap, and the condition

$$\int_0^b dx(n_\mathrm{i} - n_\mathrm{e}) = 0 . \qquad (3)$$

Integration of the equation (2) and the equality $\partial_t (n_\mathrm{i} - n_\mathrm{e}) = \partial_x (n_\mathrm{e} \mu_\mathrm{e} E)$ (following from (1)) with use of (3) gives the equalities $E|_{x=0} = E|_{x=b}$ and

$$(n_\mathrm{e} E)_{x=0} = (n_\mathrm{e} E)_{x=b} , \qquad (4)$$

and then the quantities n_e, $\partial_t n_e$, $\partial_t n_i$, and $\partial_x(n_e E)$ at the different boundaries ($x = 0$ and $x = b$) also should have equal values. The condition (4) may be imposed instead of (3).

2. APPROXIMATE SOLUTION

For the homogeneous distribution, indicating the quantities with the index 0, one gets $\partial_t n_{e0} = -\nu_{a0} n_{e0}$, $n_{e0}(t) = n_{e0}(0)\exp(-\nu_{a0}t)$, $n_{i0} = n_{e0}$, and $E_0 = U/b$.

To ensure (4), the linear perturbations of the homogeneous distribution are searched in the form of the real parts of the products of the amplitudes (dependent on time and indicated with the index 1) and the factor $\exp(ikx)$ with $k = 2\pi n/b$ and nonzero integer n. For the amplitudes one gets the equations

$$\partial_t n_{e1}(t) + ik\mu_e[n_{e1}(t)E_0 + n_{e0}(t)E_1(t)] = = -\nu_{a0} n_{e1}(t) - \nu_{aE0} E_1(t) n_{e0}(t) = \partial_t n_{i1}(t), \qquad (5)$$

$$ik\varepsilon_0 E_1(t) = e_0[n_{e1}(t) - n_{i1}(t)], \qquad (6)$$

where ν_{aE0} is the value of the derivative $\partial_E \nu_a(E)$ at $E = E_0$. Denoting $Q(t) = n_{i1}(t) - n_{e1}(t)$, $v_{e0} = \mu_e E_0$, $\nu_{r0} = \varepsilon_0^{-1} e_0 \mu_e n_{e0}(0)$, and $\nu_r(t) = \nu_{r0}\exp(-\nu_{a0}t)$, with use of the equations (5) and (6) one gets the equations

$$E_1(t) = -(ik\varepsilon_0)^{-1} e_0 Q(t),\ n_{e1}(t) = n_{i1}(t) - Q(t),$$

$$ikv_{e0} n_{i1}(t) = \partial_t Q(t) + [ikv_{e0} + \nu_r(t)]Q(t),$$

$$\partial_t^2 Q(t) + [ikv_{e0} + \nu_{a0} + \nu_r(t)]\partial_t Q(t) = = \nu_{aE0} E_0 \nu_r(t) Q(t) .$$

The function $P(t) = \nu_{r0}^{-1}\ln Q(t)$ obeys to the equation

$$\nu_{r0}^{-1}\partial_t^2 P(t) + [\partial_t P(t)]^2 + +[(ikv_{e0} + \nu_{a0})\nu_{r0}^{-1} + \exp(-\nu_{a0}t)]\partial_t P(t) = = \nu_{aE0} E_0 \nu_{r0}^{-1}\exp(-\nu_{a0}t) . \qquad (7)$$

Under the assumption $\nu_r(t) \gg \nu_{a0} \sim \nu_{aE0} E_0$, the function $P(t)$ may be given with the asymptotic expansion $P(t) = \sum_{m\ge 0}[\nu_{r0}^{-m} p_m(t)]$. Its substitution into (7) gives the equation $\sum_{m\ge 0}[\nu_{r0}^{-m} Z_m(t)] = 0$, with

$$Z_0(t) = \partial_t p_0(t)[\partial_t p_0(t) + \exp(-\nu_{a0}t)],$$

$$Z_1(t) = \partial_t^2 p_0(t) + \exp(-\nu_{a0}t)[\partial_t p_1(t) - \nu_{aE0}E_0] + +[2\partial_t p_1(t) + ikv_{e0} + \nu_{a0}]\partial_t p_0(t) ,$$

$$Z_2(t) = \partial_t^2 p_1(t) + [ikv_{e0} + \nu_{a0} + \partial_t p_1(t)]\partial_t p_1(t) + +[2\partial_t p_0(t) + \exp(-\nu_{a0}t)]\partial_t p_2(t) .$$

It is imposed the requirement $Z_m(t) = 0$, for each m. For $m = 0$ one gets two different solutions: $p_0^-(t) = p_0^-(0) - \nu_{a0}^{-1}[1 - \exp(-\nu_{a0}t)]$, $p_0^+(t) = p_0^+(0)$. The next terms for these two solutions are the following: $p_1^-(t) = p_1^-(0) - (ikv_{e0} + \nu_{aE0}E_0)t$,

$$p_1^+(t) = p_1^+(0) + \nu_{aE0}E_0 t,$$

$$p_2^+(t) = p_2^+(0) - f^+(t)(ikv_{e0} + \nu_{a0} + \nu_{aE0}E_0),$$

with $f^+(t) = \nu_{a0}^{-1}[\exp(\nu_{a0}t) - 1]\nu_{aE0}E_0$. It is worthy to note that $\exp(ikx)Q(t) = \exp[ikx + \nu_{r0}P(t)]$, the sum $ikx + \nu_{r0}P^{\pm}(t)$ contains the parameter k in the term $ik[x - x_0^{\pm}(t)]$, with $x_0^+(t) = \nu_{r0}^{-1} v_{e0} f^+(t)$, $x_0^-(t) = v_{e0}t$, and for $\nu_{aE0} \ne 0$ one gets the relationship $\nu_{aE0}\partial_t x_0^+(t) > 0$, which connects the direction of the perturbation movement with the sign of ν_{aE0}.

The solution $P^-(t)$ is characterized by the fast decay, and the perturbations move to anode with the electron velocity. The time evolution of the spatial perturbations determined by the solution $P^+(t)$ is described by the factor $\exp(\nu_{aE0}E_0 t)$. So, the stability of the solution $P^+(t)$ depends on the sign of ν_{aE0}. For $\nu_{aE0} > 0$, the solution $P^+(t)$ is unstable, the perturbations move to anode with the velocities much less than electron velocity. Such motion direction is typical for the attachment instability [6]. For $\nu_{aE0} < 0$, the solution $P^+(t)$ is stable, and the perturbations move to cathode. The evolution of the homogeneous electron density is described by the factor $\exp(-\nu_{a0}t)$. The cases $\nu_{a0} > 0$ and $\nu_{a0} < 0$ correspond to attachment decay and ionization growth, respectively.

3. DISCUSSION

So, in the conditions of attachment instability, the perturbations move to anode, whereas the secondary streamers usually move to cathode. In the paper [5], the motion of the leading edge of the glow domain to cathode is obtained in assumption of gas density decrease with time (due to streamer channel heating) and relevant increase of the ratio of electric field strength and the gas density, which determines the rates of electron processes. The same effect may be obtained with relevant increase of the potential drop on the gap.

As it is mentioned above, the electric field strength distribution in the gap essentially depends on the entrance current. In particular, in the limit case when the entrance current becomes zero, the channel soon gets the additional positive charge through the electron going out to anode, and then the quasi-stationary field distribution is set (if the ion motion is neglected), in which almost all potential drop is related to the comparatively thin near-cathode layer, and in the plasma channel the field is very weak. When the streamer goes out to cathode the situation is near to the opposite one. Namely, before the streamer approach to cathode the considerable part of the potential drop falls on the small domain in front of streamer. During the streamer going out to cathode, the domain dimension decreases, and also, the electron emission from cathode considerably increases, leading to the field strength decrease near the cathode. As a result, the field strength in the other part of channel increases, leading to propagation of glow in the channel in both directions. The velocity of the intensive glow domain boundary propagation is very small for the boundary, near which the spatial variation of the field strength is very sharp. So, such field strength increase can give the secondary streamer with propagating forward boundary and practically motionless backward boundary situated near the space with the comparatively large difference between the positive and negative ion densities in the channel remainder.

The propagation of the secondary streamer backward boundary to cathode (Fig. 2 in [5]) may be the ionization wave propagation, which starts near the mentioned channel non-uniformity in consequence of the field strength increase up to the level, at which the tendency to decrease of the difference between the positive and negative ion densities is replaced with the tendency to its increase and the following space charge field strengthening. And the field strength increase, which gives the start to the ionization wave propagation, may be the result of the increase of the potential drop on the relevant part of streamer channel during the streamer going out to cathode. On the other hand, the ionization wave propagation is accompanied with recovery of high conductivity behind the wave front, and so, with the potential redistribution and the field strength increase between the front and cathode, leading to the additional propagation of the secondary streamer forward boundary to cathode.

CONCLUSIONS

The secondary streamer is the moving glowing domain with comparatively large field strength, in the streamer channel. In the paper [5], it is substantiated that the contrast in glow increases due to the attachment instability. In the present paper, from the simplified model consideration, it is estimated the velocity of the spatially inhomogeneous perturbation movement in the conditions of the attachment instability and it is attracted the attention to the movement direction, which is opposite to one usually observed for the secondary streamers. Besides the gas density decrease through the channel heating, the propagation of the forward boundary of the large field strength domain to cathode may be resulted from the potential redistribution during going out of the ionization waves to cathode, which leads to the field strength increase in the considerable part of the discharge gap not very near to cathode. When field strength increases near the domain with the enlarged difference between the positive and negative ion densities in the channel remainder, the ionization wave may start from there, so that the wave front becomes the backward boundary of the secondary streamer, and the wave front propagation to cathode leads to further field strength increase between the front and cathode, that is, to further propagation of the forward boundary of the large field strength domain to cathode.

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ВТОРИЧНЫЕ СТРИМЕРЫ В КАНАЛЕ ПЕРВИЧНОГО СТРИМЕРА

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Изучается распространение процесса с ионизацией и прилипанием в остатке канала стримера. Из рассмотрения упрощенной модели видно, что в условиях развития прилипательной неустойчивости пространственно неоднородные возмущения движутся к аноду. Обсуждаются условия, при которых эти возмущения движутся к катоду, как это обычно наблюдается для вторичных стримеров.

ВТОРИННІ СТРИМЕРИ В КАНАЛІ ПЕРВИННОГО СТРИМЕРА

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Вивчається поширення процесу з іонізацією та налипанням у залишку каналу стримера. З розгляду спрощеної моделі видно, що в умовах розвитку налипальної нестійкості просторово неоднорідні збурення рухаються до анода. Обговорюються умови, за яких ті збурення рухаються до катода, як це зазвичай спостерігається для вторинних стримерів.