https://doi.org/10.46813/2025-158-097

INITIAL EVOLUTION OF THE CATHODE DIRECTED STREAMER CHANNEL AFTER BRIDGING THE DISCHARGE GAP

B.B. Kadolin, V.M. Ostroushko, G.V. Taran
National Science Center "Kharkiv Institute of Physics and Technology", Kharkiv, Ukraine
E-mail: ostroushko-v@kipt.kharkov.ua

To describe the beginning of the evolution of the cathode-directed streamer channel after it has bridged the discharge gap, a simplified model is considered, which considers ionization, heating, and heat removal through thermal conductivity. The spatial picture obtained from it and the estimates of the values of the process characteristics correspond to those observed in secondary streamers. Factors are indicated that practically make it impossible to stop the propagation of the secondary streamer in the part of the channel nearer to the cathode.

PACS: 52.80.Hc

INTRODUCTION

A secondary streamer is a process observed in the channel of a cathode directed streamer (hereinafter referred to as the primary streamer) after it has bridged the discharge gap. In [1], the similarity of the secondary streamer to the positive column of a low-pressure glow discharge is indicated and the statement that the luminescence intensity is relatively higher from those parts of the channel in which the electron density is relatively lower is substantiated. The paper [2] contains a detailed review of research on secondary streamers, examining in detail the processes that occur in them, and also, in [2], it is indicated the connection of secondary streamers with the instability associated with electron attachment and analyzed in [3]. The mentioned instability is because the attachment reduces the "average mobility" of negatively charged particles, leading to an amplification of small variations in the spatial distribution of the charge density and its electric field. In the positive column of a glow discharge, such instability leads to the formation of luminescence layers and to the movement of the layers towards the anode, and it develops in the range of the reduced (divided by pressure) electric field strengths that is typical for the channel. But the luminescence from the secondary streamer has the appearance of an indivisible one, one of its edges moves towards the cathode, and the other remains almost motionless [4]. Research into the processes that occur in streamer discharge continues [5, 6]. The paper [7] contains a review of streamer diagnostics and modeling. In the present work, based on the consideration of a simplified model of the evolution of the primary streamer channel after it bridges the discharge gap, a spatial picture and estimates of the process characteristics values are obtained, which are consistent with those observed in secondary streamers. Also, estimates of the characteristics when the process transitions to a spark are obtained. For some completeness, at the beginning, estimates of the characteristics of the primary streamer during its propagation in the discharge gap are given.

1. CHARACTERISTICS OF CATHODE DIRECTED STREAMER PROPAGATING IN DISCHARGE GAP

When a streamer propagates in the discharge gap, the main part of the potential difference between the anode and cathode occurs in the gap between the streamer head and the cathode. The electric field strength E_i in the intense ionization zone in front of the streamer head is estimated by the relationship

$$E_i \sim (f_E r_s)^{-1} U_0, \quad (1)$$

in which U_0 is applied voltage, r_s may be considered as the characteristic radius of curvature of the streamer head or as half of the characteristic transverse size of the head, and the coefficient f_E decreases logarithmically with increasing ratio of streamer length to its diameter. Such relationship can be obtained for the field induced near the apex of a long prolate spheroid under the action of a uniform external field parallel to axis of symmetry. And for centimeter-long streamers in air under normal conditions, it may be taken $f_E \sim 3$.

The process of propagation of the primary streamer is realized through the formation of a space with high conductivity further from the current position of the streamer head due to photoionization, electron impact ionization and charge displacement, which weakens the field in the formed space (and thereby moves the head towards the cathode through it), but enhances the field on the cathode side of that space. An electron avalanche stops development when a relaxation movement of a significant number of electrons occurs within the time of the order of the characteristic time between successive ionizations carried out by an electron at such field level. And then the field strength decreases to such values, at which ionization is practically absent. The characteristic time of such a movement (which is called viscoelastic relaxation, Maxwell relaxation) is determined by the equality $t_M = \varepsilon_0 (e_0 n_e \mu_e)^{-1}$, in which ε_0 is electric constant, e_0 is the elementary charge, μ_e is the electron mobility, n_e is the electron number per volume. The characteristic time between the successive ionizations mentioned satisfies the relationship $t_i \sim (\alpha_i \mu_e E_i)^{-1}$, in which α_i is the ionization coefficient value typical for the zone of intense ionization in front of the streamer head. The condition $t_i \sim t_M$ gives the relation

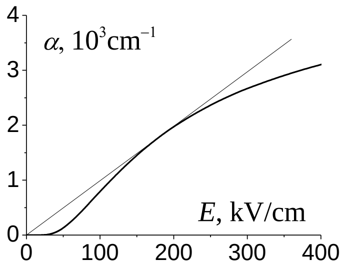
$$n_e \sim e_0^{-1} \varepsilon_0 \alpha_i E_i, \quad (2)$$

which relates the electron density behind the head (in the streamer channel) to the field strength in front of the head. Substitution of the values, $\mu_e = 400$ cm$^2\cdot$ V$^{-1}\cdot$ s^{-1}, $\alpha_i = 2000$ cm^{-1}, $E_i = 200$ kV/cm, which may be obtained with aid of Bolsigplus [8], gives, $t_i \sim 6\cdot10^{-12}$ s, $n_e \sim 2\cdot10^{14}$ cm^{-3}.

The velocity υ_s of the streamer as an ionization wave is determined by the time of development of the ionization process in front of the streamer head at a distance of the order of r_s from the head, $\upsilon_s \sim (\Lambda_i\, t_i)^{-1} r_s$, where Λ_i is the number of consecutive ionization acts that increase the electron density from the initial value (far from the streamer) to the maximum one (in the streamer channel). When the streamer propagates in atmospheric air, the initial electron density is 6…8 orders of magnitude less than the final one [7], therefore, $\Lambda_i \sim 20…30$. The relevant level of initial electron density is provided mainly by photons emitted from the state of the N_2 molecule with an energy of 12.25 eV, which is greater than the ionization energy of the O_2 molecule (12.06 eV). The distance over which the electron avalanche moves when Λ_i ionization acts are performed is determined by the equality $l_a = \alpha_i^{-1} \Lambda_i \ln 2$, and to maintain the field strength at the appropriate level, the relation $r_s \sim l_a$, should be held, which, in combination with relationship (1), gives the relationship

$$\alpha_i \sim U_0^{-1} \Lambda_i\, E_i. \qquad (3)$$

Estimates of the values of α_i, E_i, and r_s can be obtained using the graph of the dependence of $\alpha(E)$, the ionization coefficient α on the field strength E. Figure shows the curve of such dependence for atmospheric air [8] and the line, $\alpha = U_0^{-1} \Lambda_i\, E$, which is tangent to the curve, due to the corresponding value of U_0.



Dependence of the ionization coefficient on the field strength for atmospheric air

If estimate (3), in order of magnitude, is considered as an exact condition, then for values of U_0, corresponding to the lines, which do not have common points with the curve, quasi-stationary streamer propagation is impossible (because at any value of the streamer head radius, the field in front of the head is so weak that the product of the electron drift length between successive ionizations with the required number of ionization acts exceeds this value of the streamer head radius), and for values of U_0, corresponding to the lines which intersect the curve at two points, the process selects the point for which the streamer velocity is greater. The relations, $\upsilon_s \sim (\Lambda_i\, t_i)^{-1} r_s$, $t_i \sim (\alpha_i\, \mu_e\, E_i)^{-1}$, and $r_s \sim \Lambda_i / \alpha_i$, give the relation $\upsilon_s \sim \mu_e\, E_i$, so for the values of U_0, corresponding to the lines with two intersections of the curve, a streamer is realized corresponding to the intersection point with the larger value of E_i. The value of the applied voltage, U_{0min}, for which the corresponding line is tangent to the curve, is the smallest of those for which the propagation of the streamer is possible. For the corresponding value of the field strength, E_{imin}, denoting a derivative with respect to an argument with a prime in the function, we have the equalities,

$$E_{imin}\, \alpha'(E_{imin}) = \alpha(E_{imin}) = U_{0min}^{-1} \Lambda_i\, E_{imin}, \qquad (4)$$

and using the relation (1), for the corresponding value, r_{smin}, of characteristic radius of curvature of the streamer head, we obtain the relation $r_{smin} \sim (f_E\, E_{imin})^{-1} U_{0min}$. And for the lines close to one tangent to the curve, the relations hold,

$$E_i \sim E_{imin},\; r_s / U_0 \approx r_{smin} / U_{0min} \sim (f_E\, E_{imin})^{-1},$$

in which the values of r_s and E_i, for different U_0, should be taken at points equally spaced within the gap. Also, using the relations for points on the lines near to one tangent to the curve, and relation (2), for the corresponding characteristic values of the ionization coefficient, α_i, and the electron densities, per volume, n_e, and linear one, N (number of particles per unit length of the channel), we have the relations,

$$\alpha_i / \alpha_{imin} \approx E_i / E_{imin} \sim 1,\; n_e / n_{emin} \approx (E_i / E_{imin})^2 \sim 1,$$
$$N / N_{min} \approx (r_s / r_{smin})^2 \approx (U_0 / U_{0min})^2. \qquad (5)$$

Substitution $\alpha_{imin} = 2 \cdot 10^3$ cm^{-1}, $E_{imin} = 200$ kV / cm, gives $r_{smin} \sim 10^{-2}$ cm, $\upsilon_{smin} \sim 8 \cdot 10^7$ cm/s, $U_{0min} \sim 6$ kV.

As the primary streamer approaches the cathode, the field strength in front of the streamer head increases due to the addition of the field from the "mirror reflection" of the streamer in the cathode. The field enhancement is somewhat diminished by such an increase in the transverse size, which, in combination with that enhancement, gives the maximum speed of streamer propagation. But in any case, a higher propagation speed requires a higher ionization intensity, which leads to an increase in the linear density of electrons and positive ions at the head of the primary streamer as it approaches the cathode. In the part of the gap far from the needle-anode, but not very close to the cathode, the change in the field strength, according to relation (1), is mainly determined by the logarithmic decrease in the coefficient f_E, with an increase in the ratio of the streamer length to its diameter, and therefore the non-uniformity of the distribution of the linear density of electrons and positive ions in a given part of the formed channel is relatively small.

2. IONIZATION IN THE STREAMER CHANNEL AFTER ITS BRIDGING THE DISCHARGE GAP

After the primary streamer bridges the discharge gap, all the applied voltage falls on the streamer channel, and the field strength in the channel becomes significantly higher than one before the bridging. The speed of field redistribution inside the channel is limited by the speed of propagation of the electromagnetic signal and the speed of relaxation of possible local inhomogeneity in the distribution of the uncompensated charge. During the mentioned relaxation time, $t_M \sim 6 \cdot 10^{-12}$ s, the light propagates over the distance of the order of 2 mm.

To describe the stage during which a quasi-steady current flows in the streamer channel, we use the equality $e_0 \mu_e E(z,t) N(z,t) = I(t)$, in which I is a current value that depends on time t but is common to the entire channel, and which relates the local value of the electric field strength in the channel to the local value of the linear electron density. Since the channel plasma is quasi-neutral and the density of negative ions in the channel is much lower than the density of positive ions, the density of positive ions is close to the electron density. Denoting by b the width of the discharge gap and assigning the values 0 and b to the coordinates of the anode and cathode, respectively, we have the equality $\int_0^b dz\, E(z,t) = U_0$.

The dependence of the ionization frequency carried out by a single electron on the field strength, $\nu(E)$, is assumed connected with the dependence of the ionization coefficient on the field strength, $\alpha(E)$, by the equality $\nu(E) = \alpha(E)\,\mu_e E$. The values of the field strength in the channel are much smaller than the one corresponding to the point of contact of the line with the curve in Fig. 1. For them we have the relation

$$E\,\nu'(E) >> \nu(E), \qquad (6)$$

due to which ionization at a given time instant occurs practically only where the linear density of the plasma is the lowest (and the field strength is the highest), and therefore, the density of electrons (and positive ions) increases there the fastest, with a gradual expansion of the part of the channel in which the linear density is close to the minimum. For the initial (after the discharge gap is bridged by the streamer) electron density distribution, $N_1(z)$, we have the inequality

$$N_1'(z) > 0, \qquad (7)$$

due to the increase in the linear density of electrons and positive ions at the primary streamer head as it approaches the cathode. So, the linear density is close to the minimum one nearer to the anode, and the ionization intensity in the streamer channel is initially the greatest just there, and it is there that the linear density increases the fastest, approaching to the linear density in the adjacent, cathode-side, place and expanding the part of the channel with linear density values close to one minimal in the channel (and the minimal value increases over time). It is worth emphasizing that the given picture of the propagation of the process in space is a consequence of the relation (6) keeping, and the value of the quantity $\nu(E)$ in the corresponding part of the channel affects only the time of development of such propagation in that part.

The described propagation of ionization in the channel that has bridged the inter-electrode gap is like the propagation of luminescence observed in secondary streamers, so it is natural to assume that the phenomenon called the secondary streamer is a manifestation of the leveling (due to ionization) of the linear density of electrons in the channel. Such propagation of ionization resembles the filling of a man-made lake, if the movement of electrons to the anode is put in correspondence with the movement of water to the dam, the linear density of the plasma is put in correspondence with the height of the water surface, relative to some level above the sea, in the already filled part of the lake and upstream, and the propagation of luminescence (which accompanies ionization) in the cathode direction is put in correspondence with the propagation of approximately the same water level, close to the minimum one, in the direction opposite to the water flow direction.

At a not very large value of the applied voltage, the ionization process in the channel may stop. When considering the conditions for the termination of ionization, in accordance with the relation (6), we assume that the dependence of the ionization frequency on the field strength, $\nu(E)$, has a threshold E_a, i.e., $\{\nu(E) = 0, E \le E_a;\ \nu(E) > 0,\ E > E_a\}$. Then the ionization process in the channel stops when such a distribution of the linear electron density is achieved, for which the equalities are satisfied,

$$N_2(z) = \{N_a,\ z \le \zeta;\ N_1(z),\ z \ge \zeta\},\ \int_0^b dz\, E_2(z) = U_0,$$
$$e_0\mu_e E_2(z) N_2(z) = I_2\ (0 < z < b), \qquad (8)$$

in which the index 2, in the process characteristics, indicates the time instant when ionization stopped, the value ζ, of the coordinate z, refers to the point that separates those parts of the channel, in which ionization after the gap was bridged by the streamer, respectively, occurred $(z < \zeta)$ or did not occur $(z > \zeta)$, and $N_a = (e_0\mu_e E_a)^{-1} I_2$. From equalities (8) and inequality (7), the inequalities, $N_2(z) \ge N_a$, $E_2(z) \le E_a$, $U_0 < b\,E_a$, follow. For the field strength immediately after the gap is bridged by the primary streamer, we have $E_1(z) = [e_0\mu_e N_1(z)]^{-1} I_2$, $E_1'(z) < 0$. For the start and stop of ionization, the conditions $E_1(0) > E_a$ and $E_1(b) < E_a$, respectively, must be met, but the latter condition is not sufficient for the stop of ionization. Defining the function $U(\xi) = \xi\,E_a + \int_\xi^b dz\, E_1(z)$, we have the equation,

$$U(\zeta) = U_0, \qquad (9)$$

and equalities, $U(0) = U_0$, $U(b) = b\,E_a$,

$$N_1(\xi)U''(\xi) = E_1(\xi)N_1'(\xi), \qquad (10)$$

$$U'(\xi) = E_a - E_1(\xi), \qquad (11)$$

in which two primes in the function indicate the second derivative. From the equality (10) and inequality (7) we obtain the inequality $U''(z) > 0$, and the equality (11) converts the conditions for the beginning and end of ionization into inequalities $U'(0) < 0$ and $U'(b) > 0$, respectively, and the combination of the three written inequalities with the inequality $U(b) > U_0$ implies the existence of one root of equation (9) in the interval $(0,b)$.

For the value $U_{0\Delta} = b\,E_a - U_0$, by which the applied voltage must be increased for the propagation of ionization in the channel to stop just before the cathode, from equation (9) we obtain the equality $U_{0\Delta} = \int_\zeta^b dz\, [E_a - E_1(z)]$. If for a given voltage value the termination of ionization in the channel occurred at a place where the initial (immediately after the gap is bridged by the streamer) electron density is not much less than the maximum one (near the cathode), and therefore, $E_a - E_1(b) << E_a$, then for the ionization to propagate all the way to the cathode, such an increase in voltage is sufficient for which it is held the relation

$$U_{0\Delta} << b\,E_a. \qquad (12)$$

The value of the current in the channel must correspond to the conditions for electron emission from the cathode. When the primary streamer comes to the cathode, an ionization wave propagates over the cathode surface, which significantly increases the area of that part of the cathode surface from which intense ion-electron emission can then occur. The value of the quasi-stationary current in the channel is determined mainly by the applied voltage and the linear density and mobility of electrons, and the corresponding value of the emission current can be achieved through the formation of a cathode layer, the potential difference on which will only slightly reduce the potential difference in the rest of the discharge gap. Due to the relatively rapid propagation of the ionization process in the streamer channel, the change in emission conditions during such propagation can be neglected.

3. CHANNEL HEATING

In the presence of current, heat is released in the channel, with a power per unit length of the channel proportional to the field strength. Heating the channel lowers the field strength threshold, below which ionization is practically absent. To obtain estimates of the order of magnitude, when considering the process of heating the channel, we neglect the inhomogeneity of the linear electron density in the channel, and denoting the values of the process characteristics during heating the channel with the index 3, we consider them to depend only on time t. For the values of the characteristics at the beginning of the heating process, we use the index 1.

Heat removal from the channel is considered under the assumption that the heat flux density (power per unit area of the cylindrical surface of the channel) is determined by the equality $q_3 = \lambda_3(T_3 - T_1) / l_{T3}$, in which λ_3 is the thermal conductivity coefficient, T_3 is the channel temperature, l_{T3} is the characteristic distance between points with a temperature difference of the order of $T_3 - T_1$. Assuming $l_{T3} \sim 2\, r_{s3}$, for the linear heat flux density $Q_3 = 2\pi r_{s3}\, q_3$ (power per unit length of the cylindrical surface of the channel), we use the equality $Q_3 = \pi \lambda_3(T_3 - T_1)$, and the channel heating process is described by the equation

$$\pi r_{s3}^2(t)\, b\, c_{p3}(t)\, T_3'(t) = = U_0\, I_3(t) - \pi b \lambda_3(t)[T_3(t) - T_1], \qquad (13)$$

in which c_{p3} is the heat capacity per unit volume, in the process at constant pressure, at temperature T_3. The method used of considering thermal conductivity is suitable, by an order of magnitude, only for the beginning of the heating process, when it covers only the immediate vicinity of the channel.

A change in gas temperature changes the heat capacity, thermal conductivity coefficient, mobility of electrons and positive ions, channel radius, ionization coefficient, according to the equalities,

$$c_{p3} / c_{p1} = T_1 / T_3,\ \lambda_3 / \lambda_1 = (T_3 / T_1)^{1/2},$$
$$\mu_{e3} / \mu_{e1} = (T_3 / T_1)^{1/2},\ \mu_{p3} / \mu_{p1} = (T_3 / T_1)^{1/2},$$
$$r_{s3} / r_{s1} = (T_3 / T_1)^{1/2},\ \alpha_3 / \alpha_1 = T_1\, \alpha(E\, T_3 / T_1) / T_3,$$

which are based on relations (7.11), (22.4) and (22.17) from [9] and on proportionality in changes of temperature and volume. For the current, we have $I_3 = e_0\, N_3\, \mu_{e3}\, U / b$. The value of N_3 can vary due to ionization, but if there is only heating, then $N_3 / N_1 = T_1 / T_3$, and then

$$I_3 / I_1 = (T_1 / T_3)^{1/2}. \qquad (14)$$

If ionization is absent, but heating is present, then, according to equation (13), the process can be quasi-stationary at the temperature determined by the equation $U_0\, I_3 = \pi b \lambda_3(T_3 - T_1)$, from which, using equality (14), we obtain the equality

$$T_3 = T_1\{1 + [1 + 4\, U_0\, I_1\, (\pi b\, \lambda_3\, T_1)^{-1}]^{1/2}\} / 2,$$

and the condition of the absence of ionization, in the presence of a threshold $E = E_a$ in the function $\alpha(E)$, has the form $E_1(b) < E_a\, T_1 / T_3$.

Let us estimate the characteristic values of the time required for heat transfer from the streamer channel and for channel expansion. For the thermal diffusivity coefficient, $\kappa = \lambda / c_p$, the relation $\kappa \sim \upsilon_T\, l_c$ holds, in which υ_T is the thermal velocity, l_c is the characteristic mean free path of molecules. For the time t_h of heat propagation over a distance l, we have the relations $t_h \sim l^2 / \kappa \sim l^2(\upsilon_T\, l_c)^{-1}$, and for the time t_p of the increase in the channel size by an order of magnitude l due to the appearance of excess pressure, we have the relation $t_p \sim l / \upsilon_T$, and then for $l \sim r_s$ we obtain the relations, $t_h \sim r_s^2(\upsilon_T\, l_c)^{-1}$, $t_p \sim r_s / \upsilon_T$, $t_h / t_p \sim r_s / l_c$, and using the equality $l_{c3} / l_{c1} = T_3 / T_1$, we obtain the relation $t_{h3} / t_{p3} \sim (T_1 / T_3)^{1/2}\, r_{s1} / l_{c1}$, and for the relation $t_{h3} \sim t_{p3}$ to hold, the relation $T_3 \sim T_1(r_{s1} / l_{c1})^2$ should be held. Substituting the values, $\upsilon_{T1} = 330$ m / s, $r_{s1} = 100$ μm, $l_{c1} = 60$ nm, characteristic of atmospheric air under normal conditions, we obtain, $t_{h1} \sim 5{\cdot}10^{-4}$ s, $t_{p1} \sim 3{\cdot}10^{-7}$ s, $t_{h1} / t_{p1} \sim 10^3$, so, $r_{s1} >> l_{c1}$, $t_{h1} >> t_{p1}$, and the condition $t_{h3} \sim t_{p3}$, formally, may be held at $T_3 \sim 10^9$ K, but at such a temperature there are many processes, which are not taken into account in the present consideration, so, within the applicability of the assumptions made, the relation $t_{h3} >> t_{p3}$ takes place.

In the case when, after the streamer bridges the discharge gap, the ionization in the channel has propagate all the way to the cathode, to describe the beginning of the further change in the electron density in the channel due to ionization, neglecting spatial heterogeneity, we use the equation $t_{N1}\, N_3'(t) = N_3(t)$, in which $t_{N1} = [\alpha(U_0 / b)\mu_{e1} U_0]^{-1} b$. First, we consider the process in a gas without attachment, using the function $\alpha(E) = \alpha_a \exp(-E_a / E)$ for the dependence of the ionization coefficient on the field strength. For it, from equalities (4), we have the equalities, $E_{i\min} = E_a$, $U_{0\min} = \exp(1)\Lambda_i\, E_a / \alpha_a$, and then the equation $\mu_{e1}\, E\alpha(E)\tau = 1$, for E at a given τ, has the form

$$\mu_{e1}\, E\alpha_a \exp(-E_a / E)\tau = 1.$$

Denoting $t_{a1} = (\mu_{e1}\, E_a \alpha_a)^{-1}$, we have the equation

$$E_a / E = \ln(\tau / t_{a1}) - \ln(E_a / E),$$

from which for $\tau >> t_{a1}$ we obtain $E \approx E_a / \ln(\tau / t_{a1})$, and then for the relation $E << E_a$ to hold, the relation $\ln(\tau / t_{a1}) >> 1$ should be held. Substituting the values, $\mu_{e1} = 400$ cm^2(V·s)$^{-1}$, $\alpha_a = 2000$ cm^{-1}, $E_a = 200$ kV / cm, characteristic of nitrogen under normal conditions, we obtain $t_{a1} \sim 10^{-12}$ s, and using the relations $t_{h1} \sim 5{\cdot}10^{-4}$ s and $t_{p1} \sim 3{\cdot}10^{-7}$ s, we have $\ln(t_{h1} / t_{a1}) \sim 20$, $\ln(t_{p1} / t_{a1}) \sim 10$, and therefore, at an average field strength in the channel, U_0 / b, of the order of 6 kV / cm and less, the electron multiplication in the channel is so slow that the thermal conductivity has time to heat the gas in the space around the channel, and the channel expands, but at a much higher average field strength, the channel, practically without expanding, heats up rapidly, and spark breakdown of the discharge gap occurs.

The above consideration is also applicable to the case when there is attachment, but only in the range of field strengths where the difference between the ionization and attachment frequencies is positive, and it is this difference that must be taken as a function of $\nu(E)$ in the above relations. In a gas without attachment, the electron density can continue to increase at relatively low field strength to relatively large values limited by the recombination process, and heat removal is weakened with an increase in the size of the heated volume. And in the presence of attachment, when the field strength level decreases below a certain value, electron multiplication stops, and electron density begins to decrease.

Experimental observations [4] indicate that spark breakdown of the discharge gap occurs when the applied voltage exceeds those values at which secondary streamers propagate in the channel approximately to the middle of the discharge gap, with subsequent channel decay. Such a limitation on the range of voltage values at which spark breakdown does not occur is probably due to the fact that at the moment of bridging of the discharge gap by the primary streamer, in the part of its channel far from the needle-anode, but not very near to the cathode, the inhomogeneity of distribution of the electron linear density is relatively small, and in order for the ionization to propagate all the way to the cathode, it is enough to increase the voltage slightly, according to the relation (12). In addition, using the relation (5), for the increase of the current, I, and the heating power, $P = IU_0$, caused by an increase in the applied voltage, from the value $U_{0\min}$, we have the relations $I / I_{\min} \approx (U_0 / U_{0\min})^2$, $P / P_{\min} \approx (U_0 / U_{0\min})^3$, from which it follows that a small relative increase in the applied voltage gives small relative increases in current and power, but twice as much for current and three times as much for power, which further reduces the range of voltage values at which the secondary streamer propagation could stop in the part of the channel nearer to the cathode.

CONCLUSIONS

Secondary streamers observed in the channel of a cathode directed streamer after it has bridged the discharge gap are manifestations of the leveling of the linear density (quantity per unit length of the channel) of electrons, by means of ionization, with a primary increase in the linear density of electrons and a corresponding decrease in the electric field strength in those parts of the channel where the density was the lowest and the strength (which local value is inversely proportional to the local density value) was the highest. If the magnitude of the applied voltage is so small that the local values of the strength everywhere in the channel are insufficient to maintain a significant ionization intensity, then a slow decay of the channel occurs due to recombination, drift and diffusion of charged particles. In the opposite case, the spark breakdown occurs. Considering channel heating reduces the value of the applied voltage sufficient for spark breakdown.

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Article received 09.06.2025

ПОЧАТКОВА ЕВОЛЮЦІЯ КАНАЛУ СПРЯМОВАНОГО ДО КАТОДУ СТРИМЕРА ПІСЛЯ ПЕРЕКРИТТЯ РОЗРЯДНОГО ПРОМІЖКУ

В.В. Кадолін, В.М. Остроушко, Г.В. Таран

Для опису початку еволюції каналу спрямованого до катоду стримера після перекриття ним розрядного проміжку розглянуто спрощену модель, яка враховує іонізацію, нагрівання та відведення тепла через теплопровідність. Отримані з неї просторова картина та оцінки значень характеристик процесів відповідають тим, які спостерігаються у вторинних стримерів. Вказано на чинники, які практично унеможливлюють припинення поширення вторинного стримера у частині каналу, ближчій до катода.