The dynamics of ionization waves formation in a transverse nanosecond plasma-beam discharge with a slotted cathode in argon

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Abstract. The article presents the results of an experimental study and numerical simulation of the spatio-temporal dynamics of ionisation processes in the gap between the electrodes and inside the cathode cavity during the formation of a nanosecond discharge in argon at pressures in the chamber from 1 to 10 Torr. The correspondence between the density distribution of charged particles and the optical patterns of the discharge is established. A numerical simulation of the formation of a limited discharge in argon under various external conditions is constructed that accounts for the influence of the charge deposited on the surface of the dielectric wall, the coefficient of secondary emission of electrons from the cathode surface and the effect of the space charge on the distribution of electric potential between the electrodes. The role of the surface charge deposited on the dielectric walls in the formation of the spatial structure of the discharge is determined. The results of numerical simulation are compared with experimental data. It is shown that the electron concentration in a discharge limited by dielectric walls is an order of magnitude higher than in an unlimited discharge under the same external conditions. The general patterns of formation and development of a limited discharge in argon are discussed and the main physical processes affecting the dynamics of development and the spatial structure of the discharge are established.

1. Introduction

The physical properties of pulsed plasma-beam discharges (PBD) in inert gases and their mixtures – in which, in the process of electrical breakdown taking place within a gas, fast electron beams are formed directly in the discharge \cite{1–4} – have been actively studied in recent years. The scientific interest in these studies is associated in the first place with fundamental questions related to the physics of pulsed gas breakdown at high electric field values as well as with the establishment of consistent pulsed nanosecond PBD development dynamics along with the determination of mechanisms for generating accelerated electrons and observation of the energy relaxation effect of accelerated electrons on the dynamics of optical processes in nanosecond PBD \cite{1, 2, 4}. Moreover, non-equilibrium PBD plasma has wide practical application in various technological devices; in particular, for precision surface treatment and thin film deposition technologies in micro- and nano-electronics materials, in plasma chemistry, in the creation of powerful ultraviolet light sources and other associated areas \cite{5, 6}. A variant of PBD in inert gases already proposed and actively studied by the authors of this study
consists of a pulsed nanosecond discharge with a hollow cathode, featuring a transverse discharge formation scheme [7, 8]. The design choice of the discharge chamber and electrode system was determined by the possibility of forming a group of high-energy electrons during the breakdown of a gas based on the hollow cathode effect. The hollow cathode effect is observed to take place when electrons emitted from the cathode surface are accelerated in the cathode layer and reflected from the walls of the cathode cavity (more precisely, from the potential barrier of the cathode layer), crossing the cathode cavity several times and causing multiple ionization inside the cathode cavity. When the gas pressure in the discharge chamber is equal to a Torr unit, the mean free path of an electron emitted from the inner surface of the cathode due to an additional electron or thermionic emission is much greater than the thickness of the cathode layer and the relaxation length of the energy of accelerated electrons is greater than the width of the cathode slot. Under such conditions, the effect of a hollow cathode is fully manifested, leading to the formation of a high-density PBD [8].

The purpose of this work is to study the spatio-temporal dynamics of ionization wave development in a PBD bounded by dielectric walls with a slotted cathode in argon from the perspective of the spatial formation of plasma structures, affecting the modes and characteristics of high-energy electrons generated in the process of electrical gas breakdown.

2. Simulation of ionisation processes in nanosecond discharges with a hollow cathode

The experimental selection of optimal conditions for the formation of high-energy electrons in discharges with a profile-based cathode having a negative surface curvature is a rather complicated and time-consuming task. Under such conditions, it can be useful to carry out preliminary numerical simulation of ionization processes in a complexly configured gas-discharge system, as well as to determine critical parameters on which the homogeneity and generation efficiency of the high-energy part of the electronic discharge component depends. In this study, a numerical simulation of the problem is carried out using the geometry of a gas-discharge system that coincides with an actual experimental design.

The cross section of the discharge chamber and the geometry of the simulation area are shown in figure 1. The hollow aluminum cathode forms a rectangular cavity with a depth of $a = 0.6$ cm and a height of $h = 0.2$ cm. The anode consists of a flat plate of aluminum, which is located at a distance of $b = 0.6$ cm from the cathode. The discharge region between the cathode and the anode is bounded on both sides by dielectric plates made of fiberglass (figure 1a). As a result, the simulation area has a rectangular shape 1.2 cm long and 0.2 cm wide (figure 1b). When the discharge region is limited by dielectric plates, the formation dynamics and spatial discharge structure change. A limitation of discharge on both sides in argon leads to an increase in the intensity of optical radiation by several times and an increase in the current density by almost an order of magnitude [9]. The task of simulation is to study the development dynamics of ionisation processes and to obtain a qualitative and quantitative explanation of the experimentally observed features of the formation of spatial plasma structures of limited PBD in argon.

In the numerical simulation, a self-consistent system of equations, which combines Poisson's equation with continuity equations for electrons and ions, was solved. The energy balance equation for electrons was chosen in a two-dimensional approximation or by solving the Boltzmann kinetic equation, when the electron velocity distribution function is represented as the sum of the distribution functions for the high-energy part of electrons and plasma electrons:

$$\frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} = 4\pi \sum_j \rho_j = 4\pi e(n_i - n_e)$$  \hspace{1cm} (1)

$$\frac{\partial}{\partial t}(n_e) + \nabla \cdot \left[ -n_i(\mu_i E) - D_i \nabla n_i \right] = R_e, \quad \frac{\partial n_i}{\partial t} = R_e - \frac{n_i D_i}{\Lambda}$$  \hspace{1cm} (2)
Here, $E_x$ and $E_y$ are the projections of the electric field strength in the discharge gap; $n_e$ and $n_i$ are the density of electrons and ions, respectively; $T_e$ is the average electron energy; $D_e/\Lambda^2$ is the reciprocal value of the electron diffusion time in the walls of the discharge chamber; $\nu_i$ represents the ionization processes rates for argon atoms.

The value given by $R_{ei} = \sum_{j=1}^{M} x_j k_j N_n n_e$, where $N_n$ is the density of neutral atoms; $k_j$ represents the reaction rate constants; $x_j$ is the mole fraction of reaction targets; $\mu_e$ and $D_i$ are the coefficients of electron mobility and ion diffusion respectively.

The initial conditions $n_e(t=0,x,y) = n_i(t=0,x,y) = n_0$ were used, under which the background plasma density $n_0$ was selected by evaluating the actual experimental conditions.

The boundary conditions were also selected considering the conditions of a real experiment:

- $U(t,x=0,y) = 0$; $(0 \leq y \leq h)$
- $U(t,x,0) = U(t,x,h) = 0$; $(0 \leq x \leq a)$
- $U(t,x=a+b,y) = U_0$; ($U_0 \sim 0.7-1.5$ kV)
- $n_e(t,x=0,y) = n_i(t,x=0,y) = 0$.

Over the course of time, a charge accumulates on the dielectric walls of the discharge chamber and some potential $\varphi_{\text{dielectric}}$ is formed. The value of the dielectric wall potential is established from the boundary condition

$$-nD = \sigma_s + \varepsilon_0 \varepsilon_r \frac{V_{\text{ref}} - V}{d_s}$$

where $\varepsilon_r = 5$ is the relative dielectric constant of the fibreglass, $d_s = 3$mm is the thickness of the dielectric plate, $V_{\text{ref}} = 0$ is the reference potential, and $D$ is the vector of electric displacement.

$$\sigma_s = n J_i + n J_e$$

where, $J_i$ is the normal component of the total ion current density at the wall and $J_e$ is the normal component of the total density of the electron current at the wall.

The shape and parameters of the electric field potential were selected based on the oscillogram of the voltage pulse applied in the experiment to the electrodes.
For this task, a triangular grid was constructed in the simulation area and a computational cycle was initiated having a predetermined time step. The values of the electric field potential and the density of charged particles at each internal nodal point of the grid are calculated. Both elastic and inelastic electron-atom collisions that led to the excitation and ionisation of argon atoms were considered. The losses of charged particles on the surface of the electrodes and the dielectric, as well as the secondary electron emission of electrons from the cathode surface with a coefficient of 0.2, are additionally taken into account. The grid step varies within $(2–9)\times10^{-3}$ cm, while the time step is $10^{-12}$ s.

3. Results of the numerical simulation
Calculations of the electric field potential distribution in the discharge gap and inside the cathode cavity were carried out along with a determination of the formation and development dynamics of the ionization front in the discharge gap. Additionally, the space-time dynamics of the charged particles density distribution and formation of the discharge structure at gas pressures $p$ in the range from 1 to 10 Torr, as well as the voltages applied to the electrodes $U_0$ from 0.7 to 1.5 kV, were calculated.

Figure 2 presents the results of the numerical simulation of the electric field potential distribution along the discharge gap centre.

![Figure 2. Distribution dynamics of the electric field potential along the centre of the discharge gap.](image)

The simulation results allow us to trace the dynamics of the penetration of the electric field into the cathode cavity and to estimate the maximum values of the electric field strength inside of the cathode cavity at various gas pressures. It is clear from the calculation that the electric field starts to penetrate...
the cathode cavity approximately 10 ns after applying a voltage pulse to the gap. After about 15 ns, a significant electric field penetrates to the middle of the cavity; after 20 ns, the field reaches the bottom of the cathode cavity. At the same time, the magnitude of the electric field itself increases in the cathode cavity and in the gap (figure 2a).

The electric field inside of the cathode cavity reaches a maximum after about 60 ns and subsequently decreases in accordance with the potential decrease of the external electric field. The results of the numerical simulation show a clear dependency of the magnitude of the electric field penetrating into the cathode cavity on the gas pressure. At gas pressure $p = 2$ Torr, the cathode cavity penetrates up to 90% of the applied electric field. At a pressure of 10 Torr, the value of the field penetrating into the cavity drops to 55% of the applied value. Apparently, a denser plasma, which is formed at elevated pressures, prevents the penetration of the electric field inside the metal cathode.

The dynamics of ionization waves in the discharge gap was subsequently investigated. The simulation shows that an ionization wave begins to form in the discharge gap when the concentration of charged particles in a plasma reaches about $\sim 10^{10}$ cm$^{-3}$. At the same time, an ionization wave formed at the surface of the anode propagates to the cathode (figure 3).

The speed of the ionization wave front propagation depends on the gas pressure (see table 1). With gas pressure $p = 2$ Torr per 8 ns, the ionization wave reaches the cathode surface; during this time, the concentration of charged particles in the ionization wave front region increases by more than one order of magnitude to reach $\sim 3 \times 10^{11}$ cm$^{-3}$. Subsequently, the ionization wave front penetrates the cathode cavity and an area of maximum ionization in the form of an ellipse is formed about the cavity centre (figure 3a). A cathode layer is formed between the positively charged plasma and the cathode. Ions are accelerated in the region of the cathode potential drop (CPD) and, colliding with the cathode surface, knock out free electrons due to secondary electron emission. These secondary electrons pass through the CPD region ($d_e \sim 4 \times 10^{-2}$ cm) without collisions and gain energy $\Sigma = eU_c$ sufficient for multiple ionization of atoms during the oscillatory motions of the accelerated electron inside the cathode cavity. At the same time, the areas of negative luminescence in the cavity overlap and the effect of a hollow cathode is fully manifested (figure 4a). Plasma electrons and a portion of the accelerated electrons are carried into the gap under the influence of an applied electric field and migrate to the anode. The ionization in the gap between the electrodes decreases due to the plasma electrons not having enough energy to ionize the gas effectively.

At gas pressures $p = 2$ Torr, the region of maximum ionisation is located inside the cathode cavity where the concentration of charged particles is several times greater than in the gap (figure 4a). Calculations of the density distribution of the charged particles along the discharge gap center show that the concentration of electrons grows with an increase in the magnitude of the applied field, reaching a maximum value, and then decreases. The maximum electron concentration value of $\sim 8 \times 10^{13}$ cm$^{-3}$ is reached after approximately 90 ns in the center of the cathode cavity (figure 4b).

As the gas pressure increases from 2 to 10 Torr, the dynamics of the formation and propagation of the ionisation wave to the cathode remains the same, but the speed of the ionisation wave front propagation decreases twice, from $8 \times 10^{7}$ to $3.5 \times 10^{7}$ cm·s$^{-1}$ (figure 3). After reaching the ionization wave of the cathode surface, the dynamics of further development and formation of the discharge structure in the cathode cavity and in the gap significantly changes with a change in gas pressure (figures 4 and 6). With $p = 5$ Torr after penetration of the ionisation wave into the cathode cavity, the region of maximum ionisation does not contract into the cathode cavity, but extends from the middle of the cavity to the anode surface. Between the electrodes, the ionisation region and the density of charged particles are focused along the centre of the gap. In this case, the same processes take place inside the cavity as with $p = 2$ Torr: the CPD region is formed and electrons are accelerated in it, emitted from the cathode surface, which form a dense plasma in the cavity during oscillatory motion. Since the mean free path of accelerated electrons is comparable to the distance between the electrodes (table 1), the accelerated electrons that fall entirely into the gap donate their energy to the excitation and ionisation of atoms. Consequently, the ionisation processes proceed equally intensively inside the cathode cavity and in the gap between the electrodes.
Figure 3. Dynamics of the formation and propagation of an ionisation wave in the discharge gap with $U_0 = 1$ kV.

The contraction of the ionisation region and the density of charged particles towards the centre of the gap is apparently related to the predominant movement and focusing of the accelerated electrons along the centre of the gap (figure 5a). The results of the electron density calculations show that the concentration of electrons is approximately the same from the centre of the cavity to the surface of the
anode (figure 5b). In this case, the electron concentration reaches a maximum value of $\sim 3 \times 10^{14}$ cm$^3$ in about 90 ns (figure 5b). The simulation results obtained with a gas pressure of 10 Torr also show that an ionisation wave forms at the anode surface and reaches the cathode after about 15 ns. After overlapping the discharge gap and redistributing the electric field, a dark space is formed in the centre of the cavity inside the cathode and ionisation processes mostly take place in the gap between the electrodes (figure 6a). Such a spatial structure of the discharge at elevated pressures is explained by the ratios of the length of the mean free path of electrons to the width of the cathode cavity and the distance between the electrodes to the mean free path of accelerated electrons. The thickness of the cathode layer is approximately $\sim 0.008$ cm, which is an order of magnitude smaller than the width of the cavity and the areas of negative luminescence inside of the cathode cavity does not overlap. Electrons accelerated in the cathode layer completely lose their energy for excitation and ionisation as they move towards the opposite wall of the cavity and cannot oscillate in the cavity. Therefore, when $p = 10$ Torr in the discharge, the effect of a hollow cathode is absent. The electron mean free path is $\sim 0.01$ cm and ionization inside the cathode cavity is concentrated at the side surfaces of the cavity, which leads to a decrease in plasma density at the centre of the cavity.

\begin{equation}
\text{U}_c \left[ \left( \frac{E}{p} \right)_p \right]^{-1} = d_{c,p}
\end{equation}

\textbf{Figure 4.} Dynamics of electron density distribution in the discharge gap (a) and along the discharge gap centre (b) $p = 2$ Torr and $U_0 = 1$ kV.

The relaxation length of electron energy, accelerated at the exit from the cathode cavity, has a value of $\sim 0.25$ cm. These electrons completely lose their energy by ionising atoms in the gap, which leads to an increase in the plasma density in the gap by almost an order of magnitude (figure 6a). The electron density reaches its maximum in the gap between the electrodes after approximately 90 ns and has a value $\sim 8 \times 10^{14}$ cm$^3$ (figure 6b). To explain the simulation results and the qualitative description of the discharge formation pattern at various gas pressures, we will estimate the parameters of the discharge and accelerated electrons. To define the value of $d_c$ for argon, we use the well-known relation

\begin{equation}
\text{U}_c \left[ \left( \frac{E}{p} \right)_p \right]^{-1} = d_{c,p}
\end{equation}
and the values of cathode potential drop ($U_c$), electric field strength in the cathode layer ($E_c$) and $p$ for a normal glow discharge in argon from [10]. In this case, we obtain $d_{c\cdot n} \approx 0.2 \text{ cm}\cdot\text{Torr}$, where $d_{c\cdot n}$ is the length of CPD for normal glow discharge in argon. Further, using the similarity relation $d_c \cdot p = 0.37 \cdot d_{c\cdot n} \cdot p$, for ATP in argon we get [11]

\[ d_c \cdot p \approx 7.5 \times 10^{-2} \text{ cm}\cdot\text{Torr}. \] (7)

**Figure 5.** Dynamics of electron density distribution in the discharge gap (a) and along the discharge gap centre (b) $p = 5$ Torr and $U_0 = 1 \text{ kV}$.

**Figure 6.** Dynamics of electron density distribution in the discharge gap (a) and along the discharge gap centre (b) $p = 10$ Torr and $U_0 = 1 \text{ kV}$. 
According to equation (7), we calculate the values $d_e$ for all conditions of the simulation. The obtained values of $d_e$ are given in table 1. Here, the values of the electron mean free path relating to inelastic processes are also shown: $\lambda = 1/(N\sigma)$, where $N = 3.3 \times 10^{16} \text{p[Torr]} \text{cm}^{-3}$ and $\sigma = 2.8 \times 10^{-16} \text{cm}^2$ [12].

Table 1. The values of $d_e$ obtained in the calculations.

| $p$ (Torr) | $\nu_f$ ($10^4 \text{cm}^2\text{s}^{-1}$) | $d_e$ ($10^{-2} \text{cm}$) | $\lambda$ ($10^{-2} \text{cm}$) | $\Lambda$ (cm) |
|------------|---------------------------------|-----------------|-----------------|---------------|
| 2          | 8.0                             | 3.7             | 5.4             | 1.87          |
| 5          | 5.5                             | 1.5             | 2.2             | 0.68          |
| 10         | 3.5                             | 0.8             | 1.1             | 0.25          |

The mean path of electrons accelerated in CPD region is estimated by the equation $\Lambda = (\varepsilon/\varepsilon_i)\lambda$, where $\varepsilon = eU_c$ is the energy of accelerated electrons and $\varepsilon_i = 26 \text{eV}$ is the formation energy of an ion pair for argon. The speed of the ionization wave front is estimated from the simulation results (figure 3). The obtained values are given in table 1.

4. Comparison of a simulation results with an experiment

Let us now compare the results of the simulation with the experimental results obtained earlier for the discharge system configuration under consideration. Spatio-temporal pictures of the discharge optical radiation were investigated by recording the discharge glow in frame-by-frame mode using a high-speed Princeton Instruments PI-MAX3 ICCD camera [13, 14]. In order to obtain high-speed photo recording of the various discharge development stages, the PI-MAX3 ICCD camera has an optical shutter with a variable exposure time from 5 ns and a temporal resolution between frames about 3 ns. The signals from the PI-MAX3 camera were sent to a personal computer, where the optical images of the integral glow were established. As an example, figure 7 shows the optical pictures of the various discharge stages. The results of simulation of the same stages in argon are additionally presented here for comparison. It can be seen that the results of the experiment and simulation are in qualitative agreement with each other. The maximum density of charged particles, obtained in the gap between the electrodes in the simulation, is confirmed by the high intensity of optical radiation from the gap in the experiment (figure 7).

![Optical pictures and the distribution of the charged particles density in a limited discharge in argon $p = 10$ Torr and $U_0 = 0.7$ kV.](image)
The contraction of the radiation to the centre of the gap and its localization along the surfaces in the cathode cavity is in good agreement with the dynamics of the spatial distribution of the density of charged particles obtained in the simulation. It should be noted that the focusing of optical radiation along the centre of the anode surface, which is observed in the experiment, does not appear in the simulation. The distribution of the density of charged particles and radiation depends on the configuration of the electric field in the discharge gap. As is known, in the process of diffusion of charged particles from the discharge gap, electrons are trapped and deposited on the inner surface of dielectric plates, limiting the discharge region. The total electric charge on the dielectric surface leads to the appearance of a surface potential, which changes the configuration of the electric field in the discharge gap. In our opinion, a more rigorous analysis of these processes and their correct inclusion in numerical simulations will allow the experimentally observed effect of focusing the density of charged particles along the centre of the anode to be confirmed.

5. Conclusion
A numerical simulation of the space-time dynamics of ionization processes in a limited PBD, with a slotted cathode in argon at gas pressures from 1 to 10 Torr and at different values of the external field applied to the electrodes, provides a qualitative explanation of the patterns experimentally observed in a similar discharge configuration [14]. The simulation established that the ionization wave starts from the anode side, which is confirmed in the experiment by the registration of the first observed radiation at the anode surface. It was found that a completely different discharge structure is formed following discharge gap overlap depending on the gas pressure. At a gas pressure of 2 Torr, the discharge is concentrated inside of the cathode cavity and can be used to generate accelerated electrons with energies up to 1 kV. With the gas pressure of 5 Torr, the effect of a hollow cathode is fully manifested and accelerated electrons lose their energy to ionize atoms in the gap prior to reaching the anode, which leads to the formation of an equally dense plasma in the cathode cavity, as well as in the gap between the electrodes. When $p = 10$ Torr, the hollow cathode effect is absent, with the discharge inside the cavity of the cathode being localized along the internal surfaces of the cathode and in the gap between the electrodes. In this case, the maximum density of charged particles is formed along the axis of the discharge gap between the electrodes. The simulation results with $p = 10$ Torr are in good agreement with the experimental results.

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