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# Peculiarities of breakdown and current development in a pulsed „open" discharge

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We present the results of a study of the breakdown characteristics of a planar „open" discharge in helium when excited by pulses with nanosecond rising edge. It is demonstrated that the development of the discharge is characterized by considerably larger values of the reduced electric field strength than in the avalanche discharge. A similarity criterion was obtained for discharges with a predominance of the photoemission mechanism of electron generation, according to which the rate of discharge development is proportional to the square of the working gas pressure.

**Keywords:** nanosecond gas discharge, breakdown, delay time, similarity condition.

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Electrical breakdown in gases — the phenomenon of a sharp increase in current — occurs when a potential difference is applied to the gas gap, when it is exceeded, an self-sustained discharge is ignited in the gas. Paschen's similarity law [1] is known, according to which the static breakdown voltage $U_{br}$ in discharges is determined by the product of the density of neutral particles $N$ (pressure $p$) and the length of the discharge gap $l$ — parameter $Nl$ ($pl$). This means that the dependencies $U_{br} = f(pl)$ for different $l$ with a corresponding change in $p$ coincide. The situation becomes more complicated for pulsed initiation of the discharge. As the pulse width decreases, the voltages $U_{br}$ increase significantly and correspond to large values of $pl$ (see, for example, [2,3].

In cold-cathode devices depending on the conditions, in most cases the breakdown occurs by the Townsend or streamer mechanisms, which are based on the development of electron avalanches from the initial electron concentration [1]. In this paper, the object of study is a pulsed „open" discharge (OD) with a grid anode with high geometric transparency $\mu$, implemented in a short discharge gap with a typical length $l = 1-10$ mm, and characterized by a significant excess of the applied impulse voltage over the static breakdown voltage. Underthese conditions, the emission of electrons is mainly under the action Doppler shifted resonant photons generated by fast atoms, which in turn arise in the process of recharging ions moving towards the cathode [4]. A characteristic feature of such a discharge is the insignificant multiplication of electrons in the discharge gap [5]. Thus, the discharge current is determined mainly by the emission of electrons from the cathode and by the external electrical circuit. The physics of discharges of this type attracts interest due to their ability to generate an electron beam of keV energies with high efficiency with a rapid current development, which allows them to be used as a basis for creating efficient subnanosecond plasma switching devices operating at pulse repetition rates of tens to hundreds of kilohertz [6,7]. This mechanism of current initiation and development in the OD raises questions about the features of breakdown in such discharges. The purpose of this paper is to study the breakdown characteristics of nanosecond pulsed discharges in helium under conditions of the dominance of the photoemission mechanism of electron generation.

In the studies a planar discharge device was used, consisting of two discharge gaps (the length of each $l = 7$ mm) formed by flat round silicon carbide (SiC) cathodes with a total area of $12\,\mathrm{cm}^2$, grid anodes with $\mu = 0.92$ and a drift space between them 11 mm long. If the anodes are grounded and the same negative voltage pulse is applied to the cathodes, it is possible to study the characteristics of the discharge in the OD mode with the generation of counter-propagating electron beams. A two-stage electrical circuit was used for power supply. The first stage is a device for generating a preliminary voltage pulse based on a TGI 1-1000/25 thyratron and a step-up pulse transformer. The second stage is a device for forming the main voltage pulse, whith used as a fast commutator a coaxial eptron SW [7] (Fig. 1, $a$) allowed to form voltage pulses on the discharge cell with an edge duration of $\sim 5$ ns during the discharge of the working capacity $C = 100$ pF. The experiments were carried out in helium at a pressure of $p = 20-100$ Torr in the mode of regular excitation pulses with an amplitude of $U = 2-50$ kV and repetition rate of $100-200$ Hz. The voltage and anode current pulses were recorded, as well as the time parameters: the pulse duration and the discharge development delay time $\tau_d$ — the value from the moment reaching 0.1 of the cell voltage amplitude to the moment the

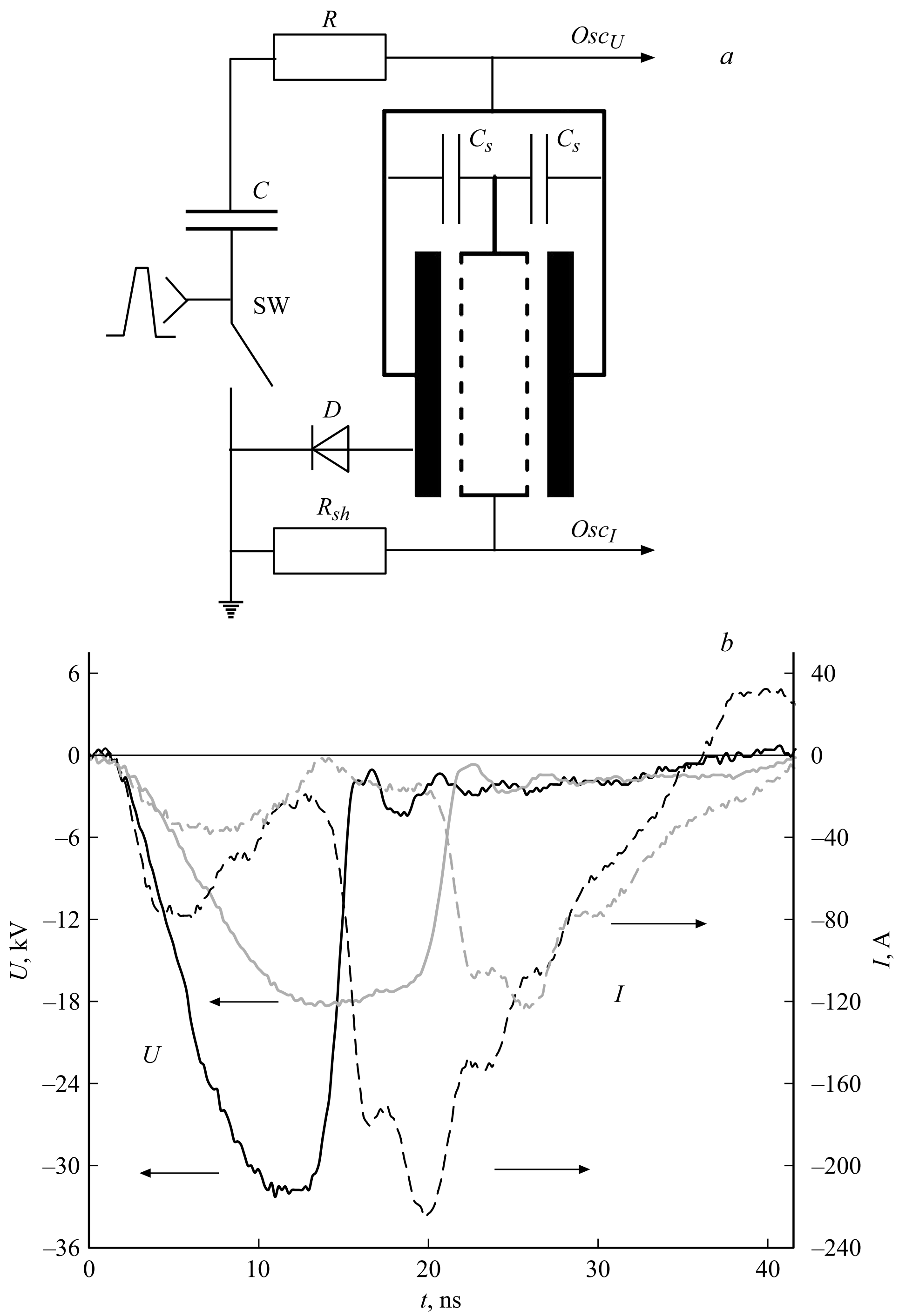


**Figure 1.** $a$ — discharge cell connection circuit: SW — eptron, $C$ — discharge capacitance, $C_s$ — discharge gap intrinsic capacitance, $D$ — shunt diode, $R$ — resistance load, $R_{sh}$ — current sense shunt. $b$ — oscillograms of $U$ and $I$ at $p = 20\,\text{Torr}$ and $U = 32\,\text{kV}$ (thick lines) and $18\,\text{kV}$ (thin lines).

current begins to rise, corresponding to the voltage drop to the level 0.9 of the amplitude value.

When the discharge cell is filled with gas, and voltage is applied to the cathode–grid anode gap, a discharge occurs. At a voltage above a certain value an electron beam is formed, which, with a further $U$ increase, penetrates behind the grid anode. In this case, a glow appears in the drift space. Since at high voltage the range of electrons is by many times greater than the linear dimensions of the cell, fast electrons, accelerating in the discharge gap, then oscillate between the cathodes until complete deceleration [5,6].

Oscillograms of voltage $U$ and current $I$ of gas discharge in helium at pressure $p = 20\,\text{Torr}$ and $U = 18$ and $32\,\text{kV}$ are

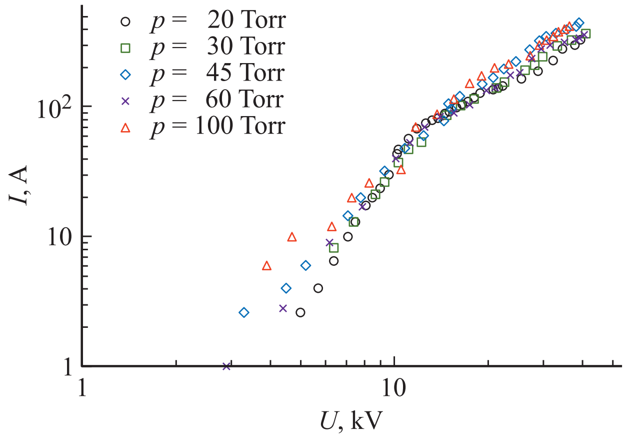


**Figure 2.** Dependencies $I(U)$ at different helium pressures.

shown in Fig. 1, *b*. The maximum voltage was limited by the electrical strength of the discharge gap. At $U \approx 40$ kV a pulsed current $I \approx 400$ A was obtained. From the processing of oscillograms obtained for different voltages and gas pressures, the $I(U)$ dependences are plotted (Fig. 2). For all pressures, the dependences are monotonically increasing and are generally approximated by the function $I \sim U^x p^y$. In the voltage range $U = 3-9$ kV, the behavior of the $I(U)$ curves depends on the pressure, and at large $U$ this dependence is weakly expressed. The power dependence $I \sim U^x$ for $U \leqslant 10$ kV is characterized by the exponent $x \approx 3-4$, and for $U > 10$ kV $x \approx 1.5-2$. The weak dependence of $I(U)$ on the gas pressure or its absence fundamentally distinguishes this type of discharge from an anomalous glow discharge [8] and is a feature of discharges with a predominance of the photoemission mechanism of electron generation both in the OD and in the discharge with hollow cathode [9,10]. This behavior of $I(U)$ can be explained by the fact that fast electrons, oscillating at a distance discharge gap–drift space–discharge gap up to their complete deceleration produce the same number of resonant VUV photons, regardless of the stopping power of the working medium. The presence of grid, that absorbs part of the beam energy, leads to data scattering for $I(U)$.

Fig. 3, *a* shows the dependence of the discharge development delay time on voltage $\tau_d = f(U)$ at gas pressure $p = 20$, 30, 45 and 100 Torr, which are monotonically decreasing curves, at that higher gas pressures correspond to lower values of $\tau_d$. Dependences $\tau_d = f(U)$ can be represented in a form consistent with the similarity law $(p\tau_d) = f(E/p)$, where $E$ is the electric field strength [11–13]. In the paper [11] for a number of gases under pulsed excitation, the coincidence of dependences was demonstrated, i. e. validity of the expression $(p\tau_d) = f(E/p)$ in the ranges $U = 4-30$ kV, $l = 0.1-6$ cm and $p = 1-760$ Torr.

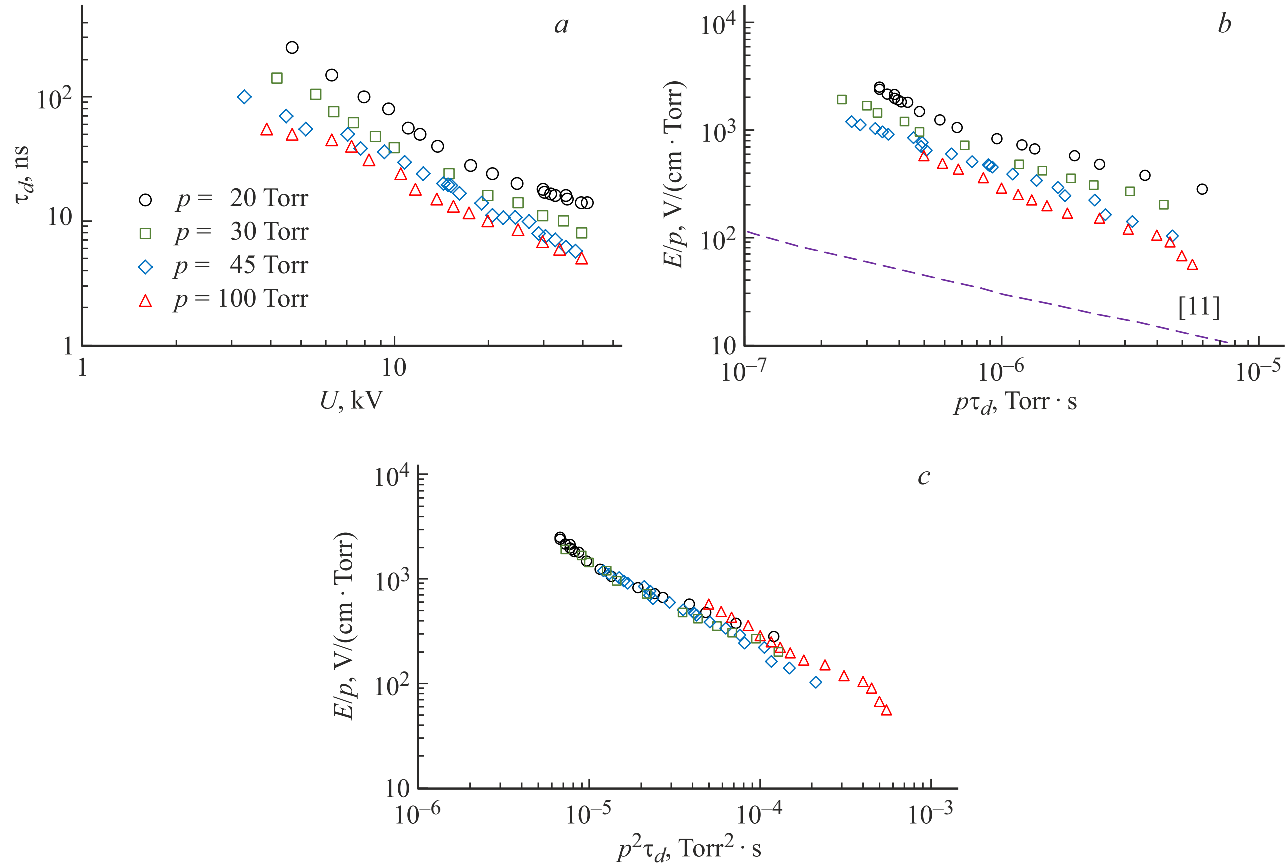


**Figure 3.** Dependencies in coordinates $\tau_d - U$ (*a*), $E/p - p\tau_d$ (*b*) and $E/p - p^2\tau_d$ (*c*).

Fig. 3, *b* shows the obtained dependences in the coordinates $E/p{-}p\tau_d$. It can be seen that they are very different curves, however, as the pressure increases, they converge. Identical OD development times correspond to significantly higher electric field strengths than for the breakdown in the paper [11]. The behavior of the dependences $(p\tau_d) = f(E/p)$ indicates that the similarity criterion in OD controlled by photoemission should be different.

To explain the results obtained, we use the ideas [5] that in OD, when a certain $U$ (or $E/p$) is exceeded, the self-sustained nature of the discharge and the rapid development of the current are ensured by resonant VUV photons generated in the discharge gap by fast excited atoms. In this case, the number of emitted electrons $n_e$ can be defined as $n_e \sim \gamma_{ph} R_s N^*$, where $\gamma_{ph}$ — photoemission coefficient, $R_s$ — fraction of radiation intercepted by the cathode, $N^*$ — number of excited fast atoms. In its turn $N^* \sim l\sigma_{\mathrm{RS}} N N_f \sim \sigma_{\mathrm{RS}} \sigma^+ N^2 l^2$, where $\sigma_{\mathrm{RS}}$ and $\sigma^+$ are the cross sections for the excitation of the resonant state of the atom by the fast atom and the cross section for the resonant charge exchange of the ion on the working gas atom accordingly, $N_f$ is the number of fast atoms appeared as a result of the re-charging the ion that crossed the discharge gap. Accordingly, the current rise constant can be defined as $\tau \sim l/\sigma_{\mathrm{RS}} N N_f R_s \upsilon_a \lambda$, where $\upsilon_a$ and $\lambda$ — speed and path length of fast atom. Thus, to characterize the OD one should use the dependencies $(p^2\tau_d) = f(E/p)$. Fig. 3, *c* shows the obtained experimental data in the coordinates $E/p{-}p^2\tau_d$. It can be seen that the dependences for different pressures practically coincide and, therefore, are determined by same processes associated with the photoemission of electrons under the action of VUV radiation generated with the participation of heavy particles. Compared to the classical concept of pulsed breakdown according to the mechanism background electrons−ionization multiplication−secondary emission processes, etc. in „open“ discharge the stage of ionization multiplication is reduced to a minimum, which leads to the occurrence of the similarity criterion in the form of the dependence $(p^2\tau_d) = f(E/p)$.

Thus, as a result of studying the breakdown characteristics of the planar „open “ discharge in helium when excited by pulses with nanosecond rising edge, it was demonstrated that the discharge development rate is proportional to the square of the pressure of the working gas. This feature is mainly determined by the photoemission mechanism of electron generation and the fulfillment of the runaway condition.


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## Conflict of interest

The authors declare that they have no conflict of interest.

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