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METHODOLOGICAL NOTES

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Legend about photoemission discharge

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Contents

Abstract. It is shown that the currently advertised 'new form of discharge' (open discharge) — photoemission with a virtually noneroding cathode and 'anomalously high' (near unity) energy efficiency of electron beam (EB) formation — cannot, in fact, be implemented. In reality, such a discharge fits well into the familiar pattern of glow discharges controlled by heavy particle emission. Thus, in known EB sources, an energy efficiency of up to ≈ 0.8 is ensured by fast atoms from ion charge exchange in strong discharge fields. However, charge multiplication and cathode-directed ion drift are both proportional to the flux of cathode electrons (including photoemitted ones), implying that the energy efficiency cannot increase through its contribution. It is this incorrect efficiency measurement methodology which gives the result of an efficiency approaching unity.

Keywords: open discharge, electron emission from the cathode, electron beams in discharge

1. Introduction

In the present article, attention is focused on discharges that generate electron beams with a high energy conversion efficiency. In such discharges, either most of the applied voltage U is concentrated in the cathode voltage drop (CVD) of the discharge gap d or U distribution results in high field strengths along the whole gap d (the CVD is not distinguished in d). The energy efficiency describes which part of the energy (power) consumed by the discharge was transferred to the electron beam.

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Photoemission discharge was believed to exist in an open discharge (OD) with a grid anode, resulting in the efficiency $\eta \approx 1$ [1], which led to a paradoxical situation.

On the one hand, the existence of a 'new discharge type' — a photoemission one — would be a big improvement in the understanding of discharge physics. This discharge could also be of great practical importance: $\eta \approx 1$, the minimal cathode erosion, resulting in a longer service life — characteristics which are impossible to achieve for other discharges. It was assumed in Ref. [1] that the photoemission is supported by emission from atoms excited by electrons up to the resonant state in the electron-beam drift space (DS) behind the anode grid.

On the other hand, the incorrectness of photoemission discharge representations was demonstrated by the author of the present article in many publications, starting with paper [2]. In discharges considered to be photoemission ones, the main mechanism is, in fact, the emission caused by cathode bombardment with heavy particles, as in the glow discharge. Still, the photodischarge idea is repeatedly considered in many Russian and foreign journals, is marked by a chapter in an encyclopedia [3], and is mentioned in the project that received the Russian Federation Government Prize (http://prometeus.nsc.ru/science/prize/laugovsc.ssi) in 2016. Of course, this leads to great confusion for readers and, a propos, reviewers. The situation is even more complicated, because the supporters of photoemission OD — P A Bokhan and colleagues (they are the only ones) — do not cite or analyze publications with the opposite point of view. An exception is review [4], where my publications are considered, but the response in paper [5] was not noted. Therefore, readers will be wasting their time by doing research based on opponents' arguments.

I will demonstrate the two simplest and obvious arguments that do not need complicated calculations in order to show the inconsistency of photoemission discharge conception.

(1) One of the opponents' mistakes is to equate the energy efficiency to the parameter η defined by currents flowing to the anode and collector. This leads to overestimation of the real efficiency (it can even exceed unity). In Ref. [6], for instance, this method resulted in the value of $\eta = 0.9988$ for He

and $U \approx 3$ kV. The corresponding energy losses for an electron flying from the cathode to the collector will be $-eU(1-\eta) = 3.6$ eV, which is even less than the energy of an atom in the resonantly excited state — 21.2 eV. Such a measurement does not take also into account the main losses accompanying the electron flight. Otherwise, where would the vacuum ultraviolet (VUV) photons supporting photodischarge come from?

(2) Charge multiplication inside gap d and the ion flux at the cathode are proportional to the electron flux away from it [7], including the photoemission current, which therefore cannot increase the efficiency. At the same time, if the photoemission strongly enhanced (it can not make the main contribution in any case!), the heavy particle emission would increase proportionally, and the discharge would experience a transition from, for example, the anomalous regime to another one with a sharp current increase as, for example, in a discharge with additional ionization. However, the measurements of the OD under a broad range of conditions do not demonstrate this current increase.

This could have been enough to prove the point of the article. The above considerations show that the OD is not a photoemission one, and it agrees with the known properties of the glow discharge. Nevertheless, we will discuss these two points in more details using data from both recent and old articles.

2. Analysis of methods to measure energy conversion efficiency in electron beam sources. Role of photoemission

I. Extensive data on the discharge behavior in technological electron beam sources, including efficiency measurements, are gathered in two monographs by Yu E Kreindel and coauthors. We will use the data presented in book [8].

Known forms of the glow discharge are self-sustained by the ionization charge multiplication in d and by the feedback — γ-emission of the electrons from the cathode. Generalized emission factor γ is the number of electrons knocked out from the cathode per ion (it is expressed through the EB and ion currents: $\gamma = j_{\mathrm{EB}}/j_{\mathrm{i}}$):

$$\gamma = \gamma_{\mathrm{i}} + \sum \gamma_{\mathrm{a}} + \alpha\gamma_{\mathrm{v}} + \sum \gamma_{\mathrm{m}}\,, \tag{1}$$

where γ_{i} is the contribution to γ from the ion, $\sum \gamma_{\mathrm{a}}$ is from fast atoms formed during charge exchanges of a single ion, γ_{v} is from the photon, $\sum \gamma_{\mathrm{m}}$ is from metastable atoms, and α is the number of photons per ion that reach the cathode and cause photoemission. According to estimates [8], in technological EB sources γ actually depends only on the first two terms: $\gamma \approx \gamma_{\mathrm{i}} + \sum \gamma_{\mathrm{a}}$ and, which is very important, is defined in the same way as the efficiency η from the calorimetric measurements of the power dissipation at the anode (P_{EB}) and cathode (P_{c}):

$$\gamma \approx \frac{P_{\mathrm{EB}}}{P_{\mathrm{c}}}\,, \quad \eta \approx \frac{P_{\mathrm{EB}}}{P_{\mathrm{EB}} + P_{\mathrm{c}}} \approx \frac{\gamma}{\gamma + 1}\,. \tag{2}$$

The efficiency (2) reaches values of up to ≈ 0.8, which corresponds to $\gamma = 4$. The initial mistake in work [1] that led to the consideration of another OD mechanism is the statement that the efficiency of the glow discharge does not exceed 0.2.

II. Coaxial configuration with a grid anode was first suggested for continuous wave lasers in Ref. [9], and the

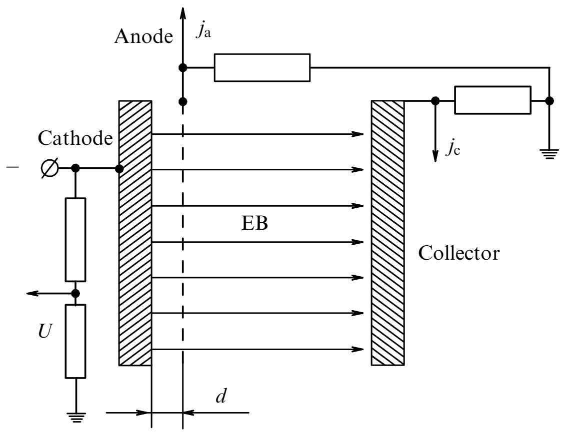

Figure 1. Schematics of an open discharge and the measurement methods for its electrical parameters: voltage U, anode and collector currents j_{a}, j_{c}.

planar one in technological EB sources [8, p. 124] with beyond-anode (no CVD in d) and pre-anode (CVD is present) plasmas. Detailed investigations of the discharge (Fig. 1), which was later called open discharge [1], started with paper [10]. In OD, typical values of U are from several kilovolts to several dozen kilovolts, often up to 10 kV, while the gas pressure p (air, inert gases, often He) can reach atmospheric values, but is typically several or tens of Torr. In pulsed OD, the pd parameter corresponds to either right-hand or left-hand Paschen branches close to $(pd)_{\min}$. Stationary OD can also be used.

Opponents define the energy efficiency through the parameter η, the ratio of the electron beam current j_{EB} to the full current j. The EB current is expressed through the collector current with the geometrical transparency μ of the grid anode taken into account, and the full current is defined as the sum of the anode current j_{a} and j_{c}:

$$\eta = \frac{j_{\mathrm{EB}}}{j} = \frac{j_{\mathrm{c}}}{\mu(j_{\mathrm{c}} + j_{\mathrm{a}})}\,. \tag{3}$$

The authors of Ref. [11] made the following assumption without any proof: if the discharge cross section diameter D is much larger than the CVD length l_{cf}, then the number of photons α reaching the cathode per ion becomes so large that one can omit other emission coefficients, and the discharge is defined purely by photoemission:

$$\gamma \approx \gamma_{\mathrm{i}} + \sum \gamma_{\mathrm{a}} + \alpha\gamma_{\mathrm{v}} \approx \alpha\gamma_{\mathrm{v}}\,. \tag{4}$$

Let us again note the statement made in the Introduction: charge multiplication in d and the ion flux at the cathode are proportional to the electron flux away from the cathode, including the photoemission current, so the latter cannot lead to an increase in efficiency. Photoemission cannot be the main contribution either! In an anomalous discharge, each ion that passes the CVD region in He generates approximately 20 fast atoms [12], which defines their decisive contribution to the emission.

An important aspect is connected with the numerator of the parameter $\eta \approx \gamma j_{\mathrm{i}}/(\gamma j_{\mathrm{i}} + j_{\mathrm{i}}) = \gamma/(\gamma + 1)$. This expression can be violated. For example, even when the anode plasma field is one order of magnitude lower than the near-cathode one, it is still high enough for the continuous acceleration of electrons [13, 14], and almost all electrons produced not on

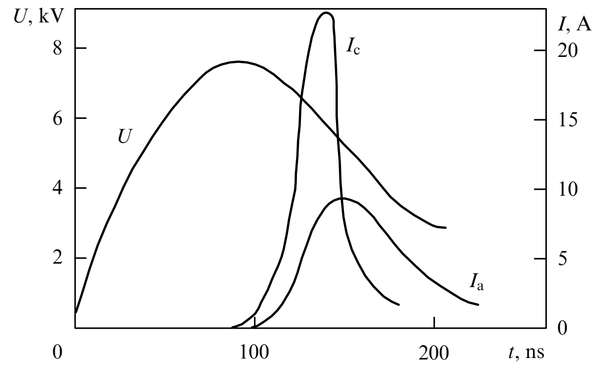

Figure 2. Typical U, I_a, I_c oscillograms for an open discharge [4] under the conditions: $p_{He} = 30.4$ Torr, $d = 0.5$ mm, $D = 10$ mm, and $\mu = 0.75$.

the cathode surface but in the bulk of the gap d contribute to the beam: $j_e = j_i$. Beam current γj_i with an additional contribution from j_e comes close to the full discharge current, and the parameter η comes close to unity, independent of the value and nature of γ. Electrons formed in the bulk d, for example, behind the CVD, will have incomparably smaller energy than the ones emitted from the cathode. It is clear that under such conditions the parameter η is not connected with the real energy efficiency in any way. This gives answers to the following questions: why can not the efficiency of technological EB sources, including the grid anode discharge, be so close to unity, and why is their service life defined by cathode erosion [8]?

Let us analyze typical oscillograms of the OD (Fig. 2) for $p_{He} = 30.4$ Torr and $\mu = 0.75$ (see Fig. 1 in Ref. [4]). At the beginning of the discharge, the collector current starts earlier than the anode one; therefore $\eta = 1/\mu = 1.33 > 1$. At the moment when $j_c = 0.5(j_c)_{max}$, the parameter η is also larger than one: $\eta = 1.05$. In the j_c maximum, $\eta = 0.98$. Such behavior of the parameter η goes against the laws of physics, but can be easily explained for a normal discharge without, of course, treating η as the real efficiency. At the beginning of the discharge, when the field E in d is weakly distorted by the charges, ions are mainly produced in the sagging field of the anode holes. They then follow the field lines and focus on the cathode opposite to the hole centers. While flying to the collector, the beam does not interact with the grid straps. The parameter E/p is large in d, and almost all electrons produced in it contribute to the beam formation and reach the collector. Moreover, part of U is scattered in the DS due to the sagging electric field in the anode holes and the discharge at the collector appears. All these processes lead to $\eta > 1$. During CVD formation, the beam is partially blocked by the grid straps, the sagging field weakens and η decreases. Let us also note that the full current reaches the maximal value at $U = 5.5$ kV and then, for some reason, starts decreasing. In paper [2] it was noted that in photodischarges the current has to further increase, because the decrease in U leads to a higher excitation efficiency of atoms by electrons in the beam due to their lower energy. It is still unknown why the photodischarge needs higher U in order to increase the beam current and the efficiency, as has been observed in all known experiments, including those with laser media. Another unexplained fact is the following: at lower pressure and weaker beam–gas interaction, in order to maintain the photodischarge current, one needs to further decrease this interaction by increasing U. All these examples manifest properties of the glow discharge and are completely incompatible with the photodischarge model. As U is increased, the ionization weakens, but the current and the emission become higher simultaneously due to the formation of faster atoms.

If $d < l_{cf}$, then, for a discharge with one hole in the anode, one can indeed obtain a high-efficiency EB in both the pulsed and continuous regimes. It is noted in Ref. [8, p. 123]: "The point character of the electron emission allows forming thin EBs with small convergence angles and producing electron fluxes with high brightness and specific power." The EB diameter can be an order of magnitude smaller than the anode hole, which is impossible for the photodischarge. For an anomalous discharge in He, one has

$$p_{He}\, l_{cf} = 0.49 \text{ Torr cm}\,. \tag{5}$$

For a discharge with a grid anode and $d < l_{cf}$ [15], the parameter $\eta = 1/\mu$ remained constant for 100 ns for current values up to the maximal one: $j = j_c \approx 8$ A cm^{-2}. From the oscillograms shown in Ref. [15], one can conclude that, if the photoemission contribution (independent of its nature) is the largest, then the discharge should also form on narrow grid straps illuminated by photons, but this has not been observed in experiments. This also refers to the initial phase of the discharge (see Fig. 2).

In an anomalous discharge with an anode hole of ≈ 17 cm(!), $d = 3$ cm, and the distance between the cathode and collector of ≈ 23 cm [16], the value of $\eta = 0.99$ (this means that $\gamma = 1/(1-\eta) = 100$ (!)) was obtained at $p_{Ne} = 0.3$ Torr and $U = 400$ V. According to data reported in Ref. [17], under such conditions, the mean free path of electrons with an energy of 400 eV should be 12 cm, which means that the EB does not reach the collector, and the latter registers the current of the discharge between the cathode and the collector. The list of such examples can be continued.

An overestimated value of the efficiency defined through the parameter η can also be obtained, when the resulting electric field in the near-anode region becomes opposite to the power supply field [18]. An opposite field appears due to the inertial reaction of the positive bulk charge in the gap d to the fall in U. The current at the U fall between the positive bulk charge and the anode leads to a partial or even complete compensation for the anode current from the external power supply. As a result, the values of the parameter η can exceed unity even when the U fall lasts several dozen microseconds.

III. Expression (3) for η assumes that the electrons registered through the collector and anode currents have an energy which corresponds to the applied voltage — that is, eU. This follows from relation (3) and the expression of η through the emission coefficients: $\eta = \gamma/(\gamma+1)$, which equate the efficiency and η. However, if there are fields and charges in the DS and behind the CVD in d, then slow electrons can also reach the collector and anode, resulting in the efficiency being not equal to η. If the real value of the efficiency weakly differs from the values obtained using the parameter η, then η approximately equals the efficiency, but the efficiency could never be as close to unity as opponents believe.

In any case, since the statement about the existence of an 'anomalously high efficiency' is of fundamental importance, the parameter η should have been checked with calorimetric measurements. In all investigations with OD, as was shown in this section, the photoemission contribution turns out to be negligibly small. At the same time, the presence of an anode grid in the OD eases the discharge development by the onset of gas ionization in the weakened field sagging into the grid holes. This allows maintaining the discharge without spark formation for large U and currents.

3. Calculations of discharge behavior and comparison with experiment

1. Paper [12] presents initial results of calculations for generalized emission coefficients γ, which were used to define the efficiency values under various conditions of the OD in He, with the assumption that the electron emission from the cathode is induced by ion and fast atom bombardment. The values of γ_i and γ_a were taken from the experimental results in Ref. [19], which agree with the measurements made by other authors. Under the considered typical OD conditions, the fast ion energy falls in the range of several hundred electron-volts, and their charge-exchange cross sections vary insignificantly, being $\sigma_{ce} \approx 1.2 \times 10^{-15}$ cm^2 [19], as was assumed in the calculations.

The field E distribution in the gap d was measured in Ref. [13] for an OD with the voltage $U = 5.1$ kV. For this case, the calculated value of the coefficient $\gamma = 6.7$ [12], which corresponds to the efficiency $\eta \approx \gamma/(\gamma + 1) = 0.84$. The authors of Ref. [12] used the calculated γ values to define the efficiency (shown in the figure there) for U in the range from 0.5 to 5 kV under the condition of a weakly distorted field ($E \approx$ const), as well as for various values of pd and under different discharge regimes, including the anomalous discharge (the latter is most often used in the OD, but it is not always able to fully form during the pulse duration). In all cases, the main contribution to γ has been given by the fast atoms from the ion recharge.

Calculations for an anomalous discharge (Fig. 3) were based on the assumption that all the applied voltage U is confined in the formed CVD with a linear fall of the field E in it. For U in the range of 1.5 – 5 kV, the following expression was derived to estimate the calculated values of γ (U is expressed in volts):

$$\gamma = -0.84 + 1.43 \times 10^{-3} U + 1.35 \times 10^{-8} U^2 . \qquad (6)$$

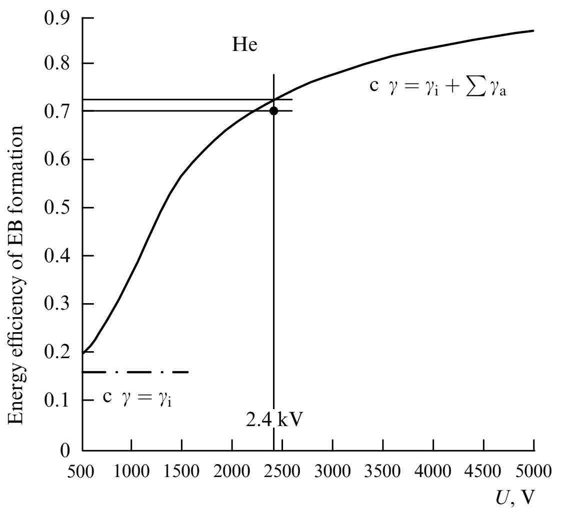

Figure 3. Calculated dependence of EB formation efficiency on voltage U for an open and other anomalous type high-voltage discharges [12]. Dark dot marks the efficiency value measured using a calorimeter in Ref. [20].

In Ref. [20], the efficiency of an anomalous discharge was measured using a calorimeter. At $U = 2.4$ kV, the efficiency turned out to be 0.7, which is in good agreement with the value of $\eta \approx 0.73$ obtained using expression (6) (Fig. 3). By taking into account (5) and the constant value of σ_{ce} in He, the number of ions exchanging their charges in the CVD is approximately 20 and does not depend on p or U. The ion energy before the last recharge (that is, the energy of the fastest atoms) is $\approx 0.1\,eU$, which agrees with the Bondarenko measurements [21] using a 'channel beam', which enters the vacuum through a small opening in the cathode.

Turkin [22] performed estimations of the CVD parameters in a static high-voltage discharge taking into account the non-local ionization and variations of the gas density caused by heating with the discharge current. It was noted in Ref. [22] that the "...calculations and estimates made for the efficiency of electron beam formation [12] are in good agreement with the available data for an open discharge, as well as for other types of a high-voltage glow discharge."

2. Numerical modelling results for the OD dynamics in a broad range of helium pressures are presented in Ref. [23]. The calculations were performed using the non-stationary kinetic model of a helium plasma modified for charge formation and the Plaser program package, while the values of γ_i and γ_a were taken from Ref. [19], as in the first part of this section. The calculation technique and the list of elementary processes taken into account can be found in Ref. [24]. In particular, it was believed that only one sixth of the radiation is directed towards the cathode. The resonant radiation confinement was also taken into account, which almost completely eliminated the appearance of photons from the DS at the cathode. For the typical OD conditions mentioned in part I of Section 2 and shown with oscillograms in Fig. 2, a good correlation was obtained between the calculated current oscillograms and the ones shown in Fig. 2. Partial contributions of the processes taking part in the discharge development were as follows: atom–electron emission — 96%; electron multiplication in the discharge gap — 2.3%; ion–electron emission — 1.7%; electron emission under the action of metastable atoms — 2×10^{-3}%, and photoemission from the cathode — 2×10^{-4}%. Notice that the value of the coefficient $\gamma_v = 0.03$ used in Ref. [23] is lower than in other papers. In Ref. [8], it is ≈ 0.1, and in measurements by opponents it is 0.3, but this does not influence the values of the main contributions to OD emission processes.

3. In Ref. [7], the numerical Monte Carlo method was applied to calculate the Paschen curve for He. It was demonstrated that the main processes responsible for charged particle formation in a discharge are the electron emission under the cathode bombardment by ions and fast atoms from the ion charge exchanging and gas ionization with electrons. The contribution to the emission made by atom emission after electron excitation was shown to be small with respect to γ_i and was not included in the calculations. The values of γ_i and γ_a were taken, as before, from Ref. [19]. The largest contribution to γ on the rising left-hand branch of the Paschen curve, as calculations have shown, is given by emission under the action of fast atoms, which leads to a well-known three-valued Z-like form of the left-hand branch for He, this is in good agreement with the experimental data from, for example, Ref. [25]. In both Ref. [7] and [26], the omitting of the fast atom contribution to the emission results in a two-valued Paschen curve.

4. In a notable publication [27], opponents presented calculations of processes in the discharge produced by counterpropagating EBs formed in He between two flat cathodes with dimensions of 16.8×3 cm^2 sharing a common grid anode ($\mu = 0.98$, grid hole diameter 1.5 mm). The distance between each cathode and the grid was $d = 3$ mm. Pre-breakdown voltages U_0 of up to 24 kV were used. Such discharge was induced in a fast commutator. First of all, let us note that the properties of the discharge discussed in Ref. [27] do not match with the typical OD. However, part of the obtained results is interesting for the processes happening in OD and EB sources based on glow discharge in general. Therefore, we will discuss paper [27] in more detail. We will not use the term 'open discharge' for the discharge observed in Ref. [27].

We will further discuss the most important findings of work [27]. The subnanosecond increase in the current in the pulsed discharge resulted in a fast decrease in voltage U in the gap d, while the counter-propagating EBs passed the CVD regions near the opposite cathodes and induced secondary electron emission from the cathodes. This emission turned out to play the decisive role. Another result: the time of photon drift to the cathodes after being emitted by the electron-excited atoms was estimated with radiation confinement taken into account and appeared to be 0.1–1 μs. This means that during the OD lifetime of several hundred nanoseconds the photons from even small near-anode discharge regions could not reach the cathode. However, a year before paper [27], opponents continued to state [28] that in a 'classical' OD the photoemission is supported by the emission from atoms excited by electrons in the DS. The objections noted in, for example, Ref. [2] and the calculations made in Refs [12, 23] (see parts 1 and 2 of this section) were not taken into account.

When calculating the photoemission contribution to the processes considered in Ref. [27], it was taken into account that atomic excitation with fast heavy particles was accompanied by the partial transfer of the oncoming particle momentum to the atoms. As a result of the Doppler shift of the emission frequency of such atoms, the emitted radiation propagates without confinement and takes part in the photoemission, just as the photons from the oncoming atoms, which can become excited after collisions.

Without discussing in detail the calculation method of Ref. [27] (it is possibly correct), let us mention a number of comments, which also include those related to the initial data used there.

The authors of Ref. [27] studied not only the P1 pulsed discharge realized experimentally, but also the hypothetical breakdown in the P2 discharge without a voltage drop, $U = U_0$, in the gap d and made a conclusion that the photoemission is the strongest process in P2. It is clear that in both cases at the beginning of the discharge, when only a small number of fast heavy particles reaches the cathode due to their inertia, the photoemission indeed plays an important role. This happens at low currents, which are incomparable with the currents during the consequent charge evolution, when the j_a contribution to the current becomes comparable to or even higher than that from the current j_v (see Figs 11, 12 in Ref. [27]).

In the P2 discharge, the largest value of the ratio between the sum of two currents j_a, j_i and the photon contribution was 2 (see Fig. 11 in Ref. [27]). The photoemission becomes significantly higher than other contributions only during the final stage of the breakdown in P2. Let us note that during the breakdown evolution l_{cf} decreases (see Fig. 5 in Ref. [27]) to $l_{cf} \approx \lambda_{ce}$ — the ion recharge length (for $eU = 20$ keV, the value of the charge-exchange cross section is $\sigma_{ce} \approx 5.6 \times 10^{-16}$ cm^2 [29], which for $p_{He} = 6$ Torr corresponds to $\lambda_{ce} = 0.09$ mm), as in the case of discharge with additional near-cathode ionization [30]. As the value of l_{cf} decreases, the number of fast ion recharges becomes smaller, together with the contribution to the emission from j_a.

Let us discuss the initial data used in Ref. [27]. Without sufficient explanation, the values of γ_a in Ref. [27] (see Fig. 4 therein) are lowered with respect to γ_a values that agree with experimental data [19] and that were used in the calculations above in parts 1–3. The deviation increases together with the energy w_a of the atoms. For example, when the energy $w_a = 200, 400, 1000$ eV, the deviation increases by 3, 4, and 5 times, respectively. For high values of w_a, which are specifically important for P2, the authors used values of γ_a obtained in ultrahigh vacuum measurements [31]. Measurements of γ_i and γ_a [19] were performed at energies up to $w_{a,i} = 1$ keV under technical vacuum conditions of $p = 10^{-5} - 10^{-6}$ Torr, when the cathode is covered with residual gas monolayers [32] and heavy particles are incorporated into it. The authors believe that these conditions are close to the discharge ones, when the emission from the cathode becomes significantly higher than the emission observed under an ultrahigh vacuum.

It is noted in Ref. [27] that 90% of the emitted photons reach the cathode (most probably, 45% per cathode). Even if this is true, then not all of the photons that reach the cathode cause emission, since the reflection from the cathode increases with the incidence angle and reaches 100%.

From the discussion above, one can make the following conclusion: the contribution of a heavy particle to the emission is lowered for both discharges by many times. This happens because of the incorrect definition of the initial data used by the main opponents in the calculations, as one can see from the text of paper [27]. As a result, for the real discharge P1, the photoemission contribution turns out to be negligible with respect to the contribution from fast heavy particles throughout the whole discharge time, except for a small-current starting phase. The same should happen in P2, especially after transitions during the breakdown, when fast ions are only present inside the CVD region.

5. Summing up the above considerations, one can say that the calculations shown in parts 1–3 of this section agree with the experimental data and indicate the negligible value of the photoemission contribution. At the same time, the calculations made in Ref. [27] (described in Item 4) need to be corrected because of a significant lowering of the emission coefficients $\gamma_{a,i}$.

4. Results of current measurements in anomalous and open discharges

Let us now consider the energy characteristics of the OD, which define the connection between the total current j and voltage U, and compare them with the characteristics of an anomalous glow discharge. The anomalous discharge is most often used in the OD, although in the pulsed regime, the CVD is not always able to fully form. Therefore, for clarity of measurements, one should use the discharge regimes with the fully formed CVD.

Expressions for the approximation of the similarity parameters j_{ad}/p^2 were experimentally obtained for an anomalous discharge and various gases by Güntherschulze many years ago [33]. In order to decrease the edge effects, a cathode with the diameter of $D = 40$ cm was used (the edge effect influence is clearly seen in the OD in the photograph shown in Ref. [34]). Experiments with He were performed under the following conditions: $p_{\mathrm{He}} = 0.03-0.25$ Torr, $U_{\mathrm{cf}} = 0.3-1.5$ kV, where U_{cf} is the CVD value. One can find approximation expressions for j_{ad}/p^2, which would be valid for a range of p and U values broader than in Ref. [33], with data from Ref. [33] included as well.

The results of experiments [33] were in good graphical agreement with measurements for discharges in He and N_2 in a broader range of conditions [35]. For example, in the case of Ne discharge, the pressure was in the range of $p_{\mathrm{Ne}} = 0.17-1$ Torr, and the voltage $U = 0.5-12.5$ kV.

The most interesting results are reported in Ref. [36] for an OD in He in a broad range of conditions: $p_{\mathrm{He}} = 2.5$–40 Torr, $d = 0.5-28$ mm, $U = 0.8-6.8$ kV, cathode area $S = 1-65$ cm^2. The measurements were performed at the stage when the CVD was fully formed. For this purpose, the discharge was excited by rectangular voltage U pulses with the duration of ≈ 160 ns formed in cable lines. The approximation expression for the parameter j_{ad}/p^2 was based on the experimental data from Refs [33] and [36]:

$$\frac{j_{\mathrm{ad}}}{p_{\mathrm{He}}^2} = 2.5 \times 10^{-12}\, U_{\mathrm{cf}}^3\ [\mathrm{A\ cm^{-2}\,Torr^{-2}}]\,. \tag{7}$$

In work [36], under high discharge voltages U, the registered currents were slightly less than calculated using expression (7). This was due to the fact that the authors used the value of U instead of U_{cf} in expression (7), and with the increase in U the fraction of it that falls on the anode plasma becomes higher.

Agreement with the results from Refs [33, 36] was also observed in experiments [37, 38]. Experiments with Ne [38] were performed under the most favorable conditions for the illumination of the cathode from the DS. The authors used a coaxial cell 33 cm in length and with the cathode cylinder diameter $D_{\mathrm{c}} = 10$ cm. From the oscillograms shown in Fig. 2a in Ref. [38] for $p_{\mathrm{Ne}} = 2.3$ Torr and $U = 2.2$ kV, one can obtain the following: $D_{\mathrm{c}} = 10$ cm, which is approximately equal to the electron mean free path of 10.7 cm, and the measured current was $j = 0.6 \approx j_{\mathrm{ad}} = 0.52$ A cm^{-2}, where the current j_{ad} was obtained from the expression for $j_{\mathrm{ad}}/p_{\mathrm{Ne}}^2$ shown in Ref. [33] without correcting it to the conditions in Ref. [38]. As can be seen, the photoemission due to atomic excitation in the DS did not play a significant role in this example either.

The given experimental results prove the following: the possible increase in the photoemission does not induce a transition of the OD from the anomalous regime with a current increase. This means that there is no significant increase in the photoemission in the OD, and its role in the OD remains negligibly small, as in high-voltage glow discharges. The contribution of the photoemission from atoms excited by fast heavy particles also turns out to be negligible, which is confirmed by the experiments and calculations described in Sections 2 and 3.

Comments. In a number of experiments performed by opponents, the EB was registered using a Faraday cylinder instead of a flat collector (see Fig. 1). This does not change the state of the discussion. The Faraday cylinder, just like the flat collector (see Section 2), registers not the electron energy, but the current with a contribution from low-energy electrons, in addition to those emitted from the cathode. In experiments [39] (see also review [40] and references cited therein) with ~ 1 ns pulses, voltage $U > 100$ kV, and a foil anode, the electron energy spectrum was estimated by blocking low-energy electrons using various continuous filters in front of the Faraday cylinder.

5. Conclusions

This article reviews the results of experiments and calculations concerning open gas discharge, which demonstrate that the photoemission contribution to the evolution and generation of the EB in the gas discharge is negligible, and this result agrees with the operation of all other known high-voltage discharge EB sources.

Let us provide citations from recently published articles that contain references to the publications by the author of the current paper. From Ref. [41]: "After experiments, the cathodes always have clearly manifested traces of erosion, which confirms our conclusion about the ion bombardment as the main electron emission channel [12]." From Ref. [42]: "Photoemission from the cathode as a result of illumination from the space behind the anode is disregarded in this work since the arguments against the photoemission nature of an open discharge [43] seem to be very convincing." From theoretical study [22]: "The calculations and estimates made for the energy efficiency of electron beam formation [12] are in good agreement with the available data for an open discharge as well as for other types of high-voltage glow discharges."

An opposite conclusion regarding the OD mechanism, which contradicts the known laws of physics, was made by my opponents, which state that the OD is a 'new form of discharge' — photoemission one.

Any new idea should agree with the long-time known facts, especially if these facts could stand the test of time and are widely accepted.

Controversial problems can be solved in a discussion. It is impossible to understand anything without this. However, if opponents do not respond to comments and do not even mention them (with only one exception — paper [4]), at the same time suggesting new confirmations for their ideas using a noncritical approach to the collection of facts, then this discussion can go on forever.

In order to understand the suggested idea, one needs to make it as simple as possible. In their publications, opponents try to make their proofs for the photoemission discharge existence as complicated as possible. The attempt to present them in a harmonious way fails, because the substitution of old arguments with new ones does not change anything. The categorical style of their conclusions (without corresponding references to known publications or analysis of known comments) can confuse readers, and these conclusions can be treated as the correct ones, which happens during the peer review of their work. One should not put great effort into additional investigations supporting the photoemission discharge model, because they are doomed to failure from the very beginning. Moreover, these considerations contradict long-established models of glow gas discharge. Statements that do not agree with experiments should be eliminated from science.

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