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High-voltage glow discharge with electric-arc grid plasma cathode

© R.A. Kartavtsov¹, S.Yu. Doroshkevich¹, D.A. Gorkovskaia¹, M.S. Vorobyov^{1,2},
A.A. Grishkov¹, N.N. Koval¹, M.A. Mokeev¹, P.V. Moskvina¹

¹Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences, Tomsk, Russia

²Tomsk Polytechnic University, Tomsk, Russia

E-mail: maks.mok@mail.ru

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The paper presents a new method for the high-voltage glow discharge (HVGD) generation based on using a discharge system involving an electric-arc grid plasma cathode and characterized by self-sustaining combustion caused by evaporation of the collector material. The HVGD electric power supply is provided from a single source and is a combination of two different mechanisms of the current flow: the arc-current flow associated with the cathode material evaporation by the arc-discharge cathode spot, and glow flow associated with evaporation of the HVGD anode material (collector), vapor ionization, and ion-electron emission from the grid plasma cathode electrodes.

Keywords: high-voltage glow discharge, arc discharge, cathode spot, grid plasma cathode, electron beam, anode plasma, vaporization of materials.

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At present, one of the main tools for target heating and evaporation is an electron beam (EB) [1,2]. Particular attention is attracted to electron-beam setups based on high-voltage glow discharge (HVGD) [3,4]. Setups of this kind allow performance of various technological processes: from the surface modification by heating and melting to the target evaporation in the ablation mode [5–7]. Among the key advantages of those setups there are the simplicity of design, long service life of the cathode, absence of heating elements (and, hence, no need to use refractory electrodes and insulators), and ability to operate under dynamical variations in working-chamber residual pressure (caused by melting and evaporation of the target material) due to self-consistent variations in the discharge characteristics.

Despite the existing advantages, electron sources based on cold-cathode HVGD have a number of restrictions that limit their application in technological processes. The maximum current density is limited by the discharge transformation into the arc mode upon reaching a certain critical value depending on the cathode surface material and condition. This limitation makes it necessary to use large-diameter cathodes in designing high-power HVGD-based electron guns, which, in turn, significantly complicates the design of such devices and raises requirements for the thermal and electrical stability of the system components.

As an alternative, electron sources with plasma cathodes (PC) operating on the basis of arc discharge are used, which provide high energy density of EB [8,9]. However, implementation of such systems needs the presence of an additional power supply ensuring stability of the PC discharge during the EB current pulse. That source has to be placed on the high-voltage side under the PC potential and significantly complicates the setup power-supply circuit.

In addition, in the mode of high average power, the total power consumption of the system increases considerably, which reduces its energy efficiency.

The goal of this study was to develop an HVGD-based electron source capable of generating a submillisecond high-current (hundreds of amperes) EB powered from a single high-voltage source.

To implement this idea, electron source „SOLO“ with a grid PC operating based on a low-pressure arc was chosen. The device circuit and operating principle are described in detail in [10,11]. Schematic circuit of the modernized electron source is given in Fig. 1; it differs from that shown in [10] in the PC electrode system and power-supply principle.

A significant challenge concerning initiation of the HVGD combustion is that its stable self-sustaining combustion is possible at pressures above 1 Pa which is one to two orders of magnitude higher than the operating pressure characteristic of electron source of the „SOLO“ type [10]. The pressure increase to 1 Pa and higher negatively affects stability of the „SOLO“ source operation in conventional modes of EB generations. However, in the case under consideration, self-sustaining of HVGD is possible only if, by the moment of ceasing the arc discharge current, operating gas pressure in the EB drift region reaches the value ensuring parameters necessary for the HVGD stability.

Another key issue of this-type power supplies is termination of the PC electron emission after turning off the arc discharge power supply U_d . Under these conditions, ion-electron emission from the emission grid 7 surface is insufficient to sustain the HVGD current in the accelerating gap, which leads to its exponential decrease [12]. The main reason for this is that the PC design involves electrodes

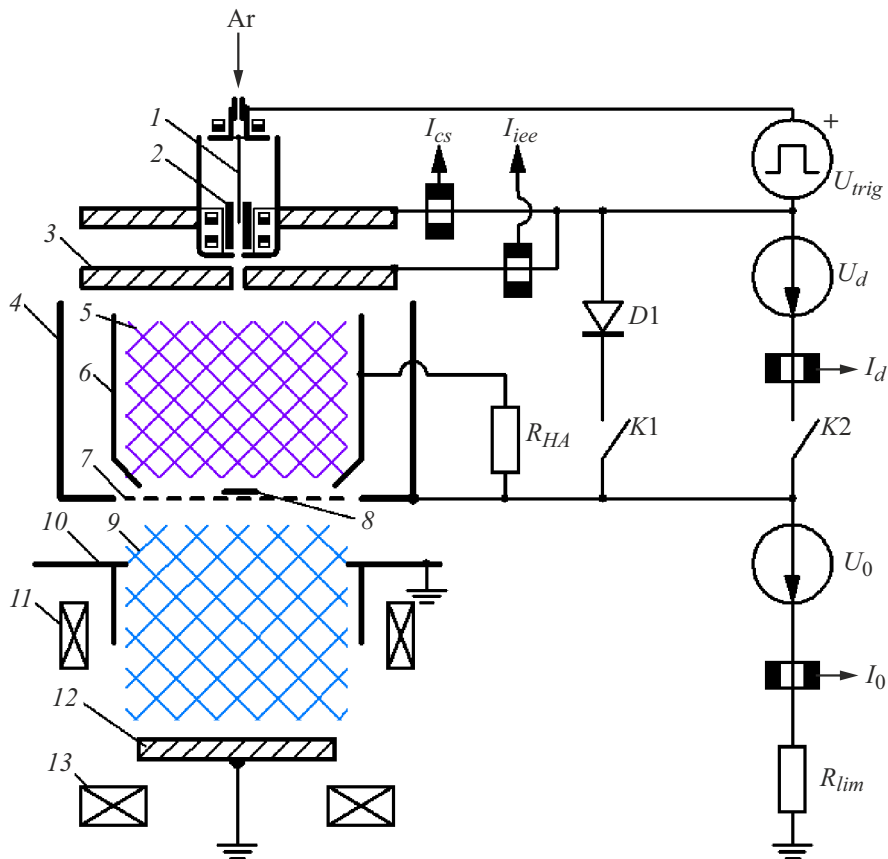


Figure 1. Schematic circuit of modernized electron source „SOLO“. 1 — ignition electrode, 2 — magnesium arc-discharge cathode, 3 — additional cathode, 4 — emission electrode, 5 — cathode/emission plasma, 6 — insert, 7 — emission grid, 8 — anode insert, 9 — anode/beam plasma, 10 — extracting electrode, 11, 13 — solenoids, 12 — collector.

which remain under floating potential at the moment of turning off the arc discharge current and are bombarded by accelerated ions. Under the ion flux impact, potential on those electrodes is subject to variations which may be compensated exclusively by low-energy cathode-plasma electrons. As a result, if no additional measures are undertaken, electron emission from the plasma cathode fully terminates.

To eliminate this effect, so-called „short-circuiting“ diode $D1$ is introduced into the source electric-power-supply circuit. If the arc discharge is powered ($I_d \neq 0$), this element is locked and does not affect the PC functioning. However, after turning off the arc discharge power, diode $D1$ ensures equipotentiality of the arc-discharge cathode and anode thereby creating conditions for the formation of a hollow cathode; this allows for initiation of the γ -electron release from PC into the accelerating gap and thus ensures ignition and stability of the self-sustaining high-current HVGD [13].

In this case, HVGD self-sustainability is ensured by evaporation of the target irradiated by the beam. Thereat, the evaporated material gets ionized, and metal ions are transported to PC first by diffusion in the anode plasma and then due to capturing by the accelerating field [14]. The effect is triggered upon achieving the target temperature

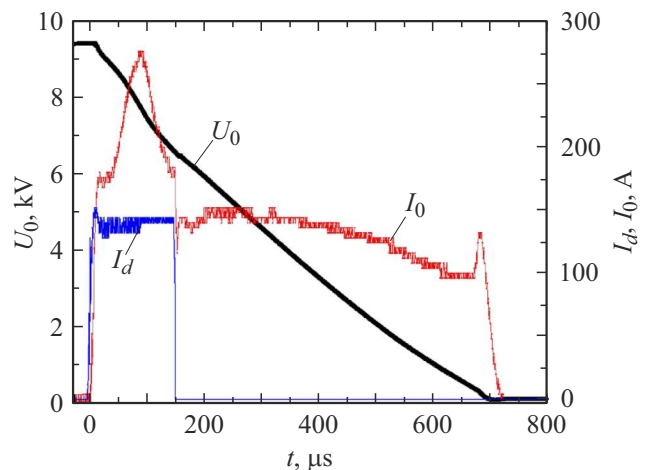


Figure 2. Typical oscillograms of ignition and combustion of HVGD with an electric-arc grid plasma cathode: $p = 35$ mPa, $U_0 = 9.5$ kV, $I_d = 140$ A.

threshold when the conditions required for the HVGD self-consistent stable combustion are created in the transport channel.

Fig. 2 presents oscillograms of the arc-discharge current, current in the accelerating gap, and accelerating voltage for the modernized source of electrons. The experiment was performed using collector *I2* made of stainless steel. The initial pressure of working gas (argon) in the vacuum chamber was $p = 35$ mPa. EB was generated in the arc discharge mode with the current pulse amplitude $I_d = 140$ A, duration $t = 150 \mu\text{s}$ and initial accelerating voltage $U_0 = 10$ kV. During the arc discharge generation pulse, the vacuum chamber operating pressure increases due to intense electron-beam-induced heating, melting and evaporation of the collector, which promotes formation of anode plasma of a higher concentration providing the required conductivity in the EB drift region.

When the arc discharge power supply ($I_d = 0$) is switched off, the plasma emitter turns over to the hollow-cathode mode, and plasma emitter current begins short-circuiting through diode *D1*. At the same time, the cathode spot continues to function on magnesium cathode 2, being powered by high-voltage power supply U_0 . The anode-plasma ions penetrating through the meshes of emission grid 7 initiate ion-electron emission from the surface of additional cathode electrode 3. The emerged γ -electrons get captured in an electrostatic trap and undergo multiple reflections from the hollow cathode walls thus promoting additional gas ionization. Joint action of the cathode spot and ion-electron processes results in maintaining such a cathode and anode plasma concentration that is sufficient for stable HVGD operation with a current of hundreds of amperes. The EB generation in the high-current HVGD mode with accelerating-gap current $I_0 = 140$ A and initial accelerating voltage $U_0 \approx 6.5$ kV continues for $550 \mu\text{s}$ until the high-voltage capacitor bank $12 \mu\text{F}$ in capacity is completely discharged.

To experimentally confirm the existence of the cathode spot in the absence of arc discharge current ($I_d = 0$), additional stainless-steel cathode electrode 3 was installed in the plasma emitter hollow. This electrode fully shields the surface of magnesium arc-discharge cathode 2 against the accelerated ion flux and contains a central hole 12 mm in diameter which allows electrons to be released from the cathode spot into the hollow cathode space. This design allows realization of conditions under which it becomes possible to separate the currents generated by different emission mechanisms [15]. Current I_{cs} associated with functioning of the cathode spot flows through electrode 2, while current I_{iee} caused by ion-electron processes initiated by accelerated ions flows through electrode 3.

The oscillograms presented in Fig. 3 show that the main portion of current flowing in the plasma emitter in the hollow-cathode mode short-circuits through electrode 2 and is due to the cathode spot functioning. In Fig. 3, the dashed line indicates the boundary separating two mechanisms of the discharge operation. To the left of it, the system detects arc-discharge source current I_d which ensures the cathode spot functioning. To the right of dashed line $I_d = 0$, the cathode spot functioning is provided by the

source of voltage U_0 . To create conditions that would allow the existence of HVGD with currents of hundreds of amperes, EB with the pulse duration of $150 \mu\text{s}$ was used, which was produced by a plasma emitter with arc discharge current $I_d = 100$ A. During this period (to the left of the dashed line), current I_{cs} associated with the cathode spot was almost fully identical to I_d , while current I_{iee} was lower than 20 A and was created both by the bombardment with accelerated ions and electrons knocked out by them, and by low-energy ions leaving the cathode plasma. After switching off the arc discharge power supply and turning over to the mode of self-sustaining HVGD, current I_{cs} decreased due to variation in the cathode potential drop but continued to flow in a quasi-stationary mode at $I_{cs} \approx 80$ A. This current was maintained during the entire EB generation pulse almost $700 \mu\text{s}$ in duration until high-voltage capacitor bank U_0 got completely discharged. Taking into account that arc discharge cathode 2 is shielded from the impact of accelerated ions by cathode electrode 3, we may conclude that the observed generation of current I_{cs} may be provided exclusively by stable arc discharge combustion and functioning of the cathode spot.

Thus, the current in the self-sustaining HVGD under consideration is determined by electron emission from the cathode spot supplied with power from the high-voltage source. In this case, a specific EB generation mode is realized, which is a combination of two different current-flow mechanisms: the arc one acting due to evaporating the cathode material by the cathode spot in the plasma emitter, and the glow one caused by the collector material evaporation, vapor ionization, ion acceleration and ion-electron emission from the electrodes of the grid plasma cathode. Note that the cathode spot and ion-electron emission exist simultaneously and ensure the HVGD current flow from one and the same high-voltage power source. This discharge form exhibiting characteristics of both types represents a new EB generation method which has not been previously described in the scientific literature; the

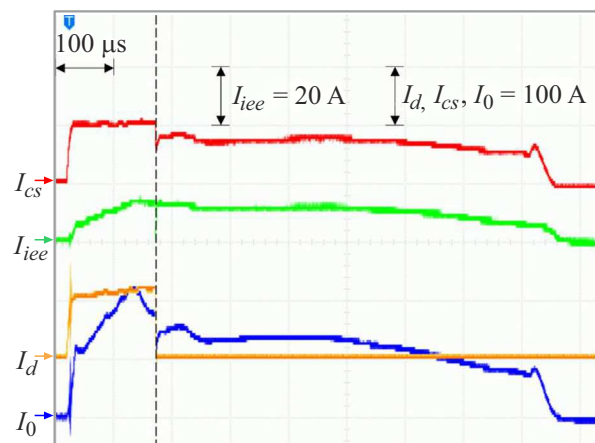


Figure 3. Typical oscillograms confirming the cathode spot current contribution to the formation of plasma emitter current in the hollow-cathode mode: $p = 25$ mPa, $U_0 = 10$ kV, $I_d = 100$ A.

authors of this paper called this method „high-voltage glow discharge with an electric-arc grid plasma cathode“. The possibility of realizing such a current-flow mode should be taken into account in implementing technological processes involving electron sources with plasma cathodes.

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Conflict of interests

The authors declare that they have no conflict of interests.

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