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PLASMA ELECTRON SOURCE WITH A BEAM OF LARGE CROSS SECTION

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We present the design and characteristics of a plasma electron source based on a discharge in crossed $E \times H$ fields, which provides the formation of technological high-energy beams with a large cross section in steady-state and pulsed regimes, and consider conditions for excitation of a high-current anomalous glow discharge forming an emitting plasma in a pulsed regime.

Electron-beam technologies are among the promising energy- and resource-conserving manufacturing methods; they provide a high quality of products and, in certain cases, are the only means for manufacturing parts. There are a number of methods for production of high-energy electron beams, which are based on thermal electron emission (thermal cathode guns) [1], explosive emission [2], extraction of charged particles from the plasma of anomalous glow or arc discharges (plasma electron sources (PESs)) [3], and high-voltage glow discharges (HVGDs) [4]. Thermal cathode guns forming focused electron beams in a wide power range have gained the largest acceptance, in particular, for electron-beam welding. However, the service life of such guns is short (50–100 ampere-hours) and their manufacturing cost is comparatively high because of the use of rare metals and the complex assembly procedures.

Plasma electron sources are free of the disadvantages characteristic of thermal cathode guns; therefore, they can be considered in a number of cases as an effective alternative to thermal cathode guns [5, 6]. The advantages of plasma electron sources are the most pronounced under heavy vacuum conditions and in the case of formation of electron beams with large cross sections necessary for a uniform treatment of large surfaces [3, 5, 6]. Because of this, it is expedient to use plasma electron sources for electron-beam processes of hardening and for other processes of thermal modification of large surfaces, which are usually accompanied by intense gas emission.

The characteristics of the thermal action of an electron beam on materials are controlled by variation of the power density of the beam and the time of action [1, 7]. Because of this, in the experiments on development of new technologies it is expedient to use universal electron sources that can operate in steady-state and pulsed regimes and form electron beams in a wide range of power density.

Experience [3, 6] suggests that in technological plasma electron sources it is better to use emitting-plasma generators based on low-voltage anomalous glow discharges. Such generators provide a longer service life, a fairly uniform distribution of the current density over the cross section in beams having large cross sections, and a higher stability of beam parameters as compared to the arc [3, 8] or high-voltage glow discharges [4].

Below we present the design of the electron source developed by us on the basis of an anomalous glow discharge in crossed $E \times H$ fields and its parameters in steady-state and pulsed regimes. We also present results of an analysis of the physical processes in the source, which aid in increasing the power density of the electron beam and extending the range of working pressures of the source.

Design of the Plasma Electron Source. The electrode structure of the plasma electron source proposed (Fig. 1) has been designed on the basis of a plasma electron source [9] intended to form focused electron beams. The electrode block of the gas-discharge structure is set on a high-voltage insulator 1. It comprises outer 2 and inner 3 cathodes, made of steel, an anode 4 made of copper, and an emitting plasma expander 5 with a grid 6 forming the emitting plasma boundary. In the body of the anode 4, there are special slots into which permanent magnets (not shown in the figure) are set. They provide a magnetic field with a radial induction of 0.06–0.08 T between the cathodes 2 and 3. The magnetic field in the region of the grid electrode 6 is so weak that the trajectory of electrons emit-

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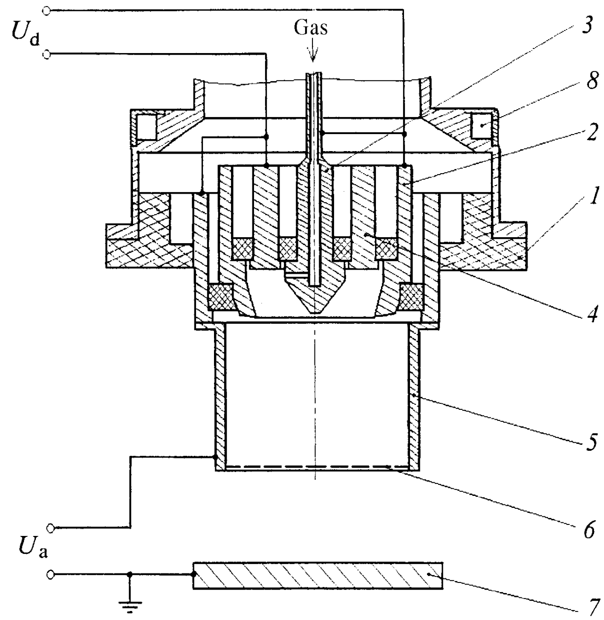


Fig. 1. Experimental electrode structure: 1) high-voltage insulator; 2) outer cathode; 3) inner cathode; 4) anode; 5) expander; 6) grid; 7) treated product; 8) space of water cooling.

ted from the plasma in the region of the grid and in the acceleration gap is determined predominantly by the electric field. A plasma-forming gas (air in the experiment) was bled into the gas-discharge structure through the channels in the inner cathode 3. In the region of exit of the gas from the channels, there arises a locally increased gas pressure. This, on the one hand, provides a stable ignition and burning of the discharge in the wide range of working pressures $10^{-4} - 10^{-2}$ mm Hg and, on the other, produces the inhomogeneity of the plasma density in the intercathode space.

The emitting surface with a large area is formed in the electron source using the passive expander of an emitting plasma with a cross section of up to 20 cm^2 [3, 6]. Because of this, the intense ionization processes occur predominantly in the region of the gas-discharge structure of the source with a radial magnetic field, while the passive expander is mainly acting as a limiter of the plasma diffusing into it and forms the emitting surface of the required area.

The length of the expander was optimized experimentally with the use of probe measurements of plasma parameters on the basis of two criteria. First, the plasma density in the expander in the region of the grid emitter electrode must be maximally high so as to increase the current density in the beam. This criterion requires minimization of the expander length since, as the experiments have shown, with its increase the plasma density in the region of the grid significantly decreases. In particular, in the case where the length of the expander is equal to its diameter, the plasma density in the region of the grid is almost an order of magnitude lower than that at the entrance to the expander. Second, the distribution of the plasma density over the cross section in the region of the grid electrode must be sufficiently uniform. Because of this, the length of the expander must be fairly large for the density of the plasma to be equalized in the process of its diffusion to the grid electrode. It has been established experimentally that the satisfactory density of the current in the beam and its uniformity are attained when the length of the expander is 0.5 to 0.8 of its diameter. Moreover, to increase the uniformity of the current density in the beam, we used the electron-optical properties of the acceleration gap. In particular, when the grid electrode bites deeper into the expander, in the near-cathode region of the gas there arises an electric field decreasing the divergence of the beam in its peripheral region The optimum depth of penetration of the grid electrode into the expander is 0.05–0.1 of the expander diameter.

In the experiments, we used, as the accelerating electrode, a metallic plate which models the surface of the product 7 treated by the electron beam (Fig. 1), since the use of a special accelerating grid electrode is accompanied by a high heat load on it and decreases the power density in the electron beam. It has been established that at pressures from 10^{-3} to 10^{-2} mm Hg, a secondary plasma layer arises near the surface interacting with the electron beam [10, 11]. In this case, the accelerating pressure is applied only to the electric double layer between the grid electrode

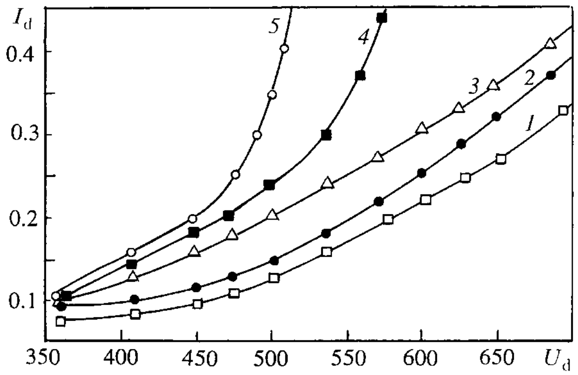


Fig. 2. Volt-ampere characteristics of the discharge: 1) system with an open emitter electrode; 2) $\xi = 0.64$; 3) double grid, $\xi = 0.64$; 4) grid, $\xi = 0.44$; 5) emission channel in the form of a single hole with a diameter of 3 mm; 1–4) $p = 2 \cdot 10^{-3}$ mm Hg; 5) 10^{-3} $Q = 400$ atm·cm^3/h. I_d, A; U_d, B.

and the secondary plasma, and the thickness of the secondary plasma layer is sufficient to coat a possible relief of the surface treated by the beam. As a result, the possible relief of the treated surface has no significant influence on the distribution of the current density in the beam.

Characteristics of the Discharge and Plasma Parameters. The emission current in a plasma electron source I_e is ultimately determined by the current of the discharge formed I_d and the efficiency of switching α of its electronic component in the acceleration gap [5, 6], which depends, in particular, on the transmission factor (transparency) of the grid emitter electrode ξ. For the purpose of formation and stabilization of the emitting plasma surface with a large area [12, 13], we investigated grid electrodes having different geometric transparency. The experiments have shown that the transmission factor ξ of the emitter electrode significantly influences the efficiency of switching α of the electronic component of the discharge current in the acceleration gap ($\alpha = I_e/I_d$) and, though to a lesser degree, the discharge current and the plasma parameters.

It has also been established that the discharge has different properties in the regime of steady-state combustion and in the regime of short pulses.

Figure 2 shows the volt-ampere characteristics of the discharge in the steady-state regime. Although in the experiments we used thin grids, their transparency ξ influenced markedly the volt-ampere characteristics of the discharge. This is, apparently, due to the fact that for the gas-discharge structure studied, just as for other structures with electron oscillation [3], the pressure range used is the range of change from the low-voltage types of discharge to high-voltage ones, in which the current is significantly dependent on the pressure. For the same bleeding-in of the gas there arises a pressure gradient between the gaseous-discharge structure and the technological vacuum chamber depending on the transmission factor ξ of the grid electrode. Because of this, as the transmission factor decreases, the pressure of the plasma-forming gas in the structure and the slope of the volt-ampere characteristic increase (Fig. 2). In our experiments, the maximum pressure in the gas-discharge chamber corresponds to curve 5. It is possible to realize such a pressure when the bleeding-in of the working gas is suitable for the system used for vacuum treatment of the technological chamber and the transparency of the grid electrode ξ is satisfactory. In the absence of a grid electrode, the discharge can be excited only for high values of the bleeding-in of the plasma-forming gas and at a pressure in the technological chamber unsuitable for high-voltage acceleration of an electron beam.

The characteristics of the discharge show that in the region of permissible values of the flow rates of the plasma-forming gas and of the pressure, the discharge-burning voltage U_d is workable from the viewpoint of the power expended on forming the emitting plasma. In this case, the discharge-ignition voltage was no higher than (1.5–2)U_d, which is also acceptable from the viewpoint of the efficiency of the discharge power supply. The upper limit of the discharge current in the steady-state regime is determined by the change of the discharge to an arc regime, and it is 1.5–2 A under the conditions studied.

The pulsed regime of discharge was investigated with the aim of attaining a maximally high density of the emission current at the stage of glow discharge prior to its change to an arc discharge. The vacuum conditions of the pulsed discharge were identical to the conditions of the steady-state regime of burning. The discharge was supplied

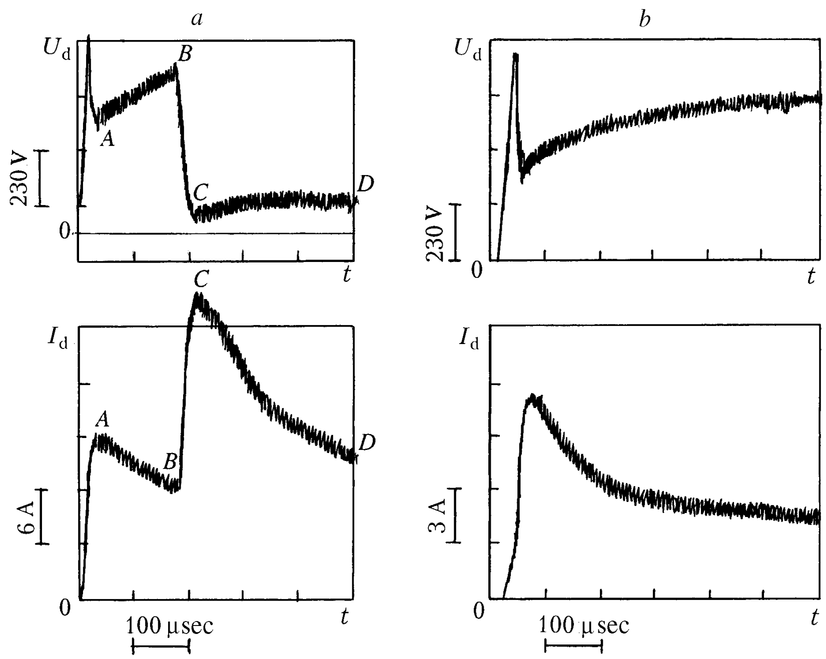


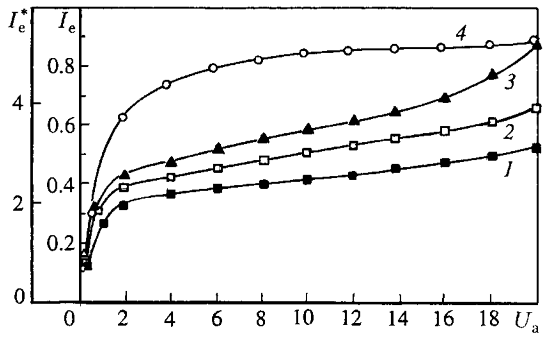
Fig. 3. Oscillograms of burning-voltage and discharge-current pulses: a) glow discharge (region AB) transformed to an arc discharge (region CD); b) glow discharge that does not transform to an arc.

from an artificial forming line (LC line) with controlled charging voltage. Figure 3 shows a typical oscillogram of the discharge current.

When the charging voltage of the artificial forming line is comparatively high and the ballast resistance R_b (limiting the discharge current) is low, the discharge has two stages (Fig. 3a): the portion AB of the oscillogram of the current corresponds to the regime of a volume anomalous glow discharge, and the portion CD corresponds to the regime of an arc discharge. When the charging voltage decreases or the ballast resistance R_b increases, no change to an arc regime occurs (Fig. 3b) if the discharge current at the stage AB does not exceed 12–15 A.

As is seen from the oscillogram, a characteristic feature of the pulsed discharge is that the decrease in the current of the discharge after its ignition is accompanied by an increase in the burning voltage. Moreover, the amplitude of the discharge current on the portion AB depends only slightly on the pressure in the discharge chamber in the range $6 \cdot 10^{-4}$–$4 \cdot 10^{-2}$ mm Hg and exceeds the limiting value of the discharge current in the steady-state regime by a factor of 5–7. These features of the initial stage of the pulsed discharge (portion AB of the oscillogram) can be explained by the "burst" of the pressure in the discharge chamber due to the desorption of gas molecules from the working surface of the cathodes under the action of the ion current arising as a result of the discharge ignition. As the estimates have shown, within the approximation of a monomolecular adsorbed gas layer on the cathode surfaces, the amplitude of the pressure "burst" can reach the value $p_m \approx 10^{-1}$ mm Hg. Because of this, due to the pressure "burst," the amplitude of the discharge current in the pulsed regime must exceed the current of the steady-state regime by approximately a factor of p_m/p_0, i.e., by an order of magnitude, and it must be independent of the bleeding-in of the plasma-forming gas and the pressure in the source p_0. According to the estimates, the time of increase of the pressure in the volume of the discharge chamber due to desorption for an energy of the desorbing molecules corresponding to $T = 300$ K does not exceed ten milliseconds. The time of formation of a monomolecular adsorbed layer is equal, according to the estimates, to units of milliseconds. It can be considered as a minimum time interval between the pulses, at which the value of the current will be the same from pulse to pulse.

To synchronize the current pulses with the discharge-voltage pulses (to eliminate the uncontrolled time lag of ignition of the discharge) we used a stationary low-current initiating discharge. For an initiating-discharge current of 0.05–0.1 A, the amplitude of the pulsed current approaches the current in the steady-state regime at an analogous burning voltage. In the case where the initiating-discharge current is less than 50 μA, it does not influence the amplitude of the pulsed discharge current and the time lag in the pulsed-discharge is practically absent. The strong depend-



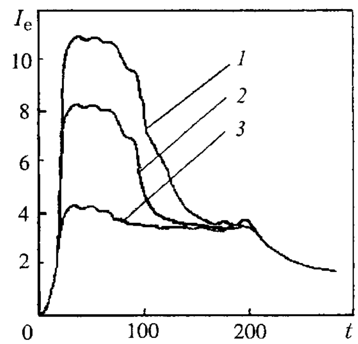


Fig. 4. Volt-ampere characteristics of the extraction: 1, 2, and 3) in the steady-state regime – I_e: 1) $I_{d0} = 150$ mA; 2 and 3) $I_{d0} = 200$ mA; 1 and 2) $Q = 720$ atm·cm^3/h; 3) $Q = 850$ atm·cm^3/h; 1, 2, and 3) $\xi = 0.472$; 4) in the pulsed regime – I_e^*: $I_{d0} = 11$ A; $p_0 = 10^{-3}$ mm Hg, $Q = 630$ atm·cm^3/h, I_e, A; U_a, kV.

Fig. 5. Emission-current pulses in different operating regimes: 1) pulsed regime; 2) pulsed regime with an initiating-discharge current of 100 μA; 3) pulsed regime with an initiating-discharge current of 50 mA. I_e, A; t, μsec.

ence of the discharge current in a pulse on the initiating stationary discharge can be considered as a fact lending support to the view that a pulsed discharge is initially formed in the gas desorbed from the surface of the electrodes.

The parameters of the emitting plasma were determined using plane probes positioned in the plane of the grid emitter electrode. The plasma concentration was determined from the ion current of saturation of the probes and was equal to 10^{16}–$5{\cdot}10^{16}$ m^{-3} in the steady-state regime and 10^{17}–$5{\cdot}10^{17}$ m^{-3} in the pulsed regime. The nonuniformity of the plasma concentration along the radius of the expander does not exceed 10%. The electron temperature was calculated from the "floating" potential of the probe [14] and from the slope angle of the electronic branch of the volt-ampere characteristic of the probe [15]. It was equal to 4–6 eV in the steady-state regime and to 5–7 eV in the pulsed regime.

Emission Characteristics of the Source. The volt-ampere characteristics $I_e(U_a)$ (Fig. 4) have a form typical of a plasma electron source with a characteristic region of quasisaturation of the emission current I_e at an accelerating voltage larger than a certain value which provides a field strength in the acceleration gap, sufficient to compensate for the near-wall ion layer field retarding the plasma electrons in the cells of the emitter grid electrode. On the quasisaturation portion, the ratio of the emission current to the discharge current corresponds to the value of the transmission factor ξ of the emitter electrode (Fig. 4). At a comparatively high pressure in the acceleration gap of the accelerating electrode there arises a secondary plasma with a potential close to the potential of the accelerating electrode, and the accelerating voltage is applied to the double layer between the emitting and secondary plasmas. Since the length of the electric double layer is shorter than the distance between the electrodes of the acceleration gap, the strength of the field near the grid electrode increases. This can lead to an increase in the penetration of the accelerating field into the cells of the grid electrode and to the switching of the electrons from the plasma in the acceleration gap. For smaller strengths of the accelerating field these electrons enter the grid electrode. Such an increase in the switching coefficient α can take place at a low pressure in the acceleration gap, but at a fairly high accelerating voltage (curve 3, Fig. 4).

The emission characteristics of the source which represent the dependences $I_e(I_d)$ are close to linear ones, and the slope of (dI_e/dI_d) corresponds (for the portion of quasisaturation of the current I_e on the volt-ampere characteristics) to the transmission factor of the emitter electrode ξ in a wide pressure range.

Figure 5 shows oscillograms of the emission current in the pulsed regime. They illustrate, first, the dependence of the gas-pressure "burst" in the discharge chamber at the initial stage of the discharge on the number of adsorbed molecules, which is related to the current of the initiating stationary discharge and, second, the decrease in this pressure during a current pulse (trailing edge) down to the value p_0 which is due to the bleeding of the gas into the gas-discharge structure.

Thus, the plasma electron source developed provides the formation of high-energy (up to 25 keV) electron beams having a large area (as large as 20 cm^2), which can be used in a number of electron-beam technologies in a steady-state regime with a beam current of up to 0.5 A and in a pulsed regime with a current of up to 10–15 A at pressures from $5 \cdot 10^{-4}$ to 10^{-2} mm Hg.

NOTATION

p, pressure in the technological vacuum chamber; p_0, initial pressure in the discharge chamber (pressure in the vacuum chamber); p_m, pressure after the "burst"; U_a, accelerating voltage; U_d, discharge-burning voltage; I_d, discharge current; Id_0, initial discharge current; I_e, emission current; α, switching coefficient (efficiency of extraction); *Q*, flow rate of the gas bled into the discharge chamber; *t*, time; R_b, ballast resistance; ξ, geometric transparency of the grid electrode. Subscripts: b, ballast; 0, initial; d, discharge; a, accelerating; e, emission; m, maximum.

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