A Forevacuum Pulse Arc-Discharge-Based Plasma Electron Source

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Abstract—An arc-discharge-based electron source is described, which is designed for forming a pulsed wide-aperture electron beam in the forevacuum pressure range (4–15 Pa). At an accelerating voltage of 12 kV, a current of 80 A was extracted from the emitting surface with an area of 80 cm² in the submillisecond range of pulse durations. The current density distribution over the beam cross section is close to a Gaussian function, and the surface-averaged beam energy density in a pulse reached 10 J/cm².

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INTRODUCTION

Pulsed electron beams with large cross sections are used to modify the surface properties of processed articles [1, 2]. The generation of such beams at elevated pressures in the forevacuum pressure range (10–100 Pa) [3] made it possible to perform electron-beam processing of the surfaces of electrically nonconducting materials, in particular, various ceramics [4, 5]. In the plasma electron source we developed earlier for this purpose [6], a hollow-cathode glow discharge was used to generate emission plasma.

Despite a number of fundamental advantages of hollow-cathode discharge systems (uniformity and stability of plasma parameters and a low noise level), an excess of a certain threshold level by the discharge current leads to the formation of a cathode spot and a transition to the arc mode. In this transition, a cathode spot randomly arises at any point on the surface of the cathode cavity, and the arc-formation process sharply disturbs the plasma uniformity in the cavity, thus finally leading to a breakdown of the accelerating gap.

Conditioning (aging) of the electrodes of the discharge system or pulse-duration shortening provides a certain increase in the diffusive-discharge current. However, this current increase is insufficient for numerous applications of a pulsed electron beam, when its effect is determined by the energy density in a single pulse.

The problem of limiting the maximum possible current in glow-discharge-based pulsed plasma electron sources is known: it is conventionally solved by replacing the glow discharge with an arc discharge [7]. Because, in this case, the forced localization of the arc’s cathode spot is provided in a limited region far from the emission plasma surface, this substantially reduces the influence of instabilities, which are inherent in the arc discharge on the electron-beam parameters.

Evidently, it is also desirable to use an analogous approach in order to further increase the beam current in pulsed electron sources that operate under forevacuum pressures. This paper describes the design of a forevacuum pulsed plasma electron source in which an arc discharge is used to produce emission plasma.

PLASMA ELECTRON SOURCE

Figure 1 shows the design of the forevacuum pulsed plasma electron source. Cathode 1 of the source is a 5-mm-diameter copper rod encased in ceramic tube 2. The tube restricts the working cathode region to its end surface and simultaneously serves as its electrical insulation. Anode 3 (made of copper) of the source is a hollow cylinder whose base has a 90-mm-diameter emission window covered with a fine-structure mesh (0.3 × 0.3 mm).

The accelerating gap is formed by the flat part of the anode and grid electrode—extractor 4, which is attached to the flange of vacuum chamber 5. The anode and extractor grids are made of stainless steel. Caprolon insulator 6 serves for electrical insulation of the anode and extractor.

The electron source is placed in the vacuum chamber, which was evacuated by a mechanical pump. The operating pressure (4–15 Pa) was controlled by supplying air to the chamber.

An arc was stably ignited in the so-called triggerless mode [8] by an auxiliary discharge over the ceramic surface between cathode 1 and igniter electrode 7, which is electrically connected to the anode through a resistor.
Pulse discharge supply unit 8 provided a discharge current amplitude of \( I_d = 40 - 120 \) A in the submillimeter range of pulse durations (<1 ms). The pulse repetition rate was 1 pulse/s in all experiments. A constant accelerating voltage \( U_a \) was formed by power-supply unit 9 and controlled from 1 to 12 kV. Discharge \( I_d \), emission \( I_e \), and beam \( I_b \) currents were measured using current transformers (Rogowski coils) with sensitivities of 50 A/V (discharge and emission currents) and 10 A/V (beam current) the signals from which were fed to a TDS 2004B Tektronix oscilloscope.

The electron-beam transport in forevacuum is accompanied by the formation of quite dense plasma near the collector. When electrons and ions from this plasma fall on the collector, the results of measuring the current of the accelerated electron beam may be considerably distorted. Therefore, studies of the characteristics of the electron source were based on measurements of the electron emission current \( I_e \), which was recorded in the circuit of the power supply of the accelerating gap.

The beam current was evaluated under the assumption that the emission-current loss at the accelerating grid correspond to its geometrical transparency (70%). The discharge-burning voltage was measured using an HVP-15HF resistive divider with a division ratio of 1 : 1000. The beam-current density distribution was registered with flat probe 10, which was placed in metallic grounded shield 11 with a 3-mm-diameter collimating hole. The probe was fixed on a two-coordinate displacement system. The radial coordinate \( r \) was measured from the symmetry axis of the electron source in an interval of from −55 to +55 mm. The vertical coordinate, i.e., the distance \( L \) between the extractor and probe, was measured from 135 to 225 mm.

**CHARACTERISTICS AND PARAMETERS OF THE ELECTRON SOURCE**

Experiments showed that the stable arc ignition was observed at voltages of 2–3 kV. Such arc-initiating
Voltages are rather high as compared to those from [8], and the observed difference is evidently related to the larger length of the interelectrode gap of the auxiliary discharge (2 mm instead of 1 mm).

A change from a glow discharge to an arc discharge in the forevacuum plasma electron source had no appreciable effect on the stability and reproducibility of the parameters of a pulsed electron beam. Typical oscillograms of the discharge and electron-emission currents are shown in Fig. 2. The emission current reaches values that are close to the discharge current, thus indicating a high extraction efficiency.

The clearly pronounced segment of the emission-current saturation in the current–voltage characteristics (CVCs) of the electron source at discharge currents of up to 70 A (Fig. 3) unambiguously shows an insignificant contribution of the current of secondary electrons, which are knocked from the emission grid by the reverse ion flow from the region of electron-beam acceleration and transport to the total beam current. The nonmonotonic dependence $I_e(U_a)$ for a discharge current of 120 A is apparently associated with the penetration of the emission plasma into the accelerating gap. A decrease in the gas pressure virtually does not modify the behavior of the CVC but leads to a decrease in the saturation current.

The radial current-density distribution is an important parameter that characterizes wide-aperture electron beams. It was observed that, as the beam propagates, its diameter measured at the distribution half-height decreases. As was pointed out in [6], this decrease may be caused by a distortion in the plane–parallel shape of the accelerating gap owing to the beam plasma, which penetrates through the extractor grid into the accelerating gap. The accelerating voltage in a range of 4–10 kV has almost no effect on the form of the radial distribution (Fig. 4). This can be considered as an advantage of the described source.

The source was tested for the attainment of the limiting parameters, and the following results were obtained. At an accelerating voltage of 12 kV and a pulse duration of up to 1 ms, the emission current could be maintained at a level of 80 A. Our estimates showed that the total energy of the electron in a single pulse was 600 J and the surface-averaged beam energy density was as high as 10 J/cm$^2$.

These parameters exceed those attained in an analogous source on the basis of a hollow-cathode glow discharge [6]. In the latter source, stable emission could not be attained at such a pulse duration because of a breakdown of the accelerating gap, which is initiated by the uncontrolled formation of cathode spots on the walls of the cavity and, as a consequence, discharge pinching with the subsequent plasma penetration into the accelerating gap.

Long durations of the beam current pulse made it possible not only to use the developed electron source to modify the surfaces of ceramic articles, but also to use it for bulk sintering of ceramics (in this case, the pulse repetition frequency was 10 pulse/s). The problem of nonuniform heating is still unsolved, but the fundamental possibility of sintering a compacted zirconium oxide powder has been experimentally confirmed.

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