Volt-ampere characteristics of planar diode in mode of emission limitation

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The experimental investigation of volt-ampere characteristics of planar diode with graphite explosive emission cathode in the initial period of electron current formation has been performed. The analytical expression for the sum area of discrete emission centers in the approach of cell structure and persistence of centers quantity during the current pulse formation has been obtained. It has been shown that the increase of electron current at the discrete emission cathode surface is satisfactorily described by the modified Child-Langmuir correlation at the reduction of form-factor from 6 to 1.

1. Introduction

The planar diodes with explosive emission cathode are widely used for the generation of electron beam with the current density of 100 A/cm^2 and over. The investigation of volt-ampere characteristics of diodes with different cathodes (planar, edged, multi-edged, annular and others) the review of which is presented in the monograph of G.A. Mesyats [1] showed that the value of electron beam current is limited by the emission ability of cathode and volume charge in the anode-cathode gap. According to the modified Child-Langmuir correlation the electron current at the unlimited electron emission from the total cathode surface is described by the following equation [1]:

$$I_{Ch-L} = A \cdot U^{3/2} \cdot \frac{S_0}{d_0^2} \cdot F \qquad (1)$$

where A = 2.33 μA/V$^{3/2}$, U is voltage applied to the diode, S_0 is cathode area, d_0 is initial anode-cathode gap, F is form-factor introduced for the coordination of experimental data to the known Child-Langmuir correlation.

At the speed of cathode plasma spread equal v, the gap between anode and plasma surface will reduce in time according to the law $d(t) = d_0 - v \cdot t$ [1, 2]. The explosive emission plasma spreads also crosswise the gap. This leads to the increase of emission surface area. Then, the correlation (1) at the solid emission surface on the cathode looks as follows:

$$I_{Ch-L} = A \cdot U^{3/2} \cdot \frac{\pi \cdot (r_0 + v \cdot t)^2}{(d_0 - v \cdot t)^2} \cdot F \qquad (2)$$

In [3] the results of experimental investigations of volt-ampere characteristics of planar diode with explosive emission cathode made of graphite in the conditions of coordination of diode impedance to the output resistance of nanosecond generator are presented. It was obtained that in 20-25 ns after the voltage pulse application (400 kV, 60 ns) to the diode a solid emission surface forms at the cathode and the diode volt ampere characteristics are described by the correlation (2) at F = 1. The investigations showed that the plasma spread speed is constant during the electron current pulse generation and is 2.5·10^6 cm/s for the graphite cathode 45 and 60 mm in diameter at the various anode-cathode gaps.

The change of electron current value in the planar diode from the moment of voltage application till the solid emission surface formation is insufficiently explored. In [4, 5] the theoretical analysis of average density of electron current in the planar diode with discrete emission surface at the cathode during its evolution from separate emitters to the solid plasma surface is performed.

The aim of the present work is the experimental investigation of volt-ampere characteristics of planar diode with discrete emission surface at the cathode.

2. Experimental Set-up

The experiments were carried out at the pulsed electron accelerator TEU-500 [6] which has the following parameters: voltage – 350-450 kV, pulse duration at the half-height – 60 ns, sum kinetic energy of electrons in pulse – up to 250 J. The pulse frequency rate in the experiments was 0.5 – 1 pulse per second. The capacitor divider was used for voltage measuring. The total current of electron beam was measured by the Faraday cup, the planar collector of which was used as a cathode. The inaccuracy of time binding of electric signals did not exceed 0.5 ns. The calibration tests of the diagnostic devices showed that it correctly reflects the accelerator operation in the mode of short-circuit failure (U=50-60 kV) as at the operation to the resistive load up to 60 Ω (U=150-200 kV) so at the operation to the planar diode (U=350-500 kV).

3. Research of Emitted Surface Area Variation

We assume that the electron current is limited by the volume charge in the anode-cathode gap from the moment of voltage supply to the diode and that the electron current beam increase to the saturation is conditioned by the increase of discrete emitted cathode surface from 0 to the geometrical area of planar diode. Such approach is used by the authors of work [4] while simulating the change of average density of electron current during the electron beam generation in the planar diode with the discrete emission cathode surface. Then, the value of emitted surface area of graphite cathode with the discrete emission surface can be calculated from the correlation of experimental data of electron beam current to the calculated data according to the correlation (2):

$$S(t) = S_0 \cdot \frac{I_e}{I_{Ch-L}} = \frac{I_e \cdot r_0^2 \cdot (d_0 - v \cdot t)^2}{A \cdot U^{3/2} \cdot (r_0 + v \cdot t)^2}$$

where S_0 – geometrical area of cathode equal $\pi \cdot (r_0)^2$.

The obtained dependences at $v = 2.5 \cdot 10^6$ cm/s are shown in Fig.1.

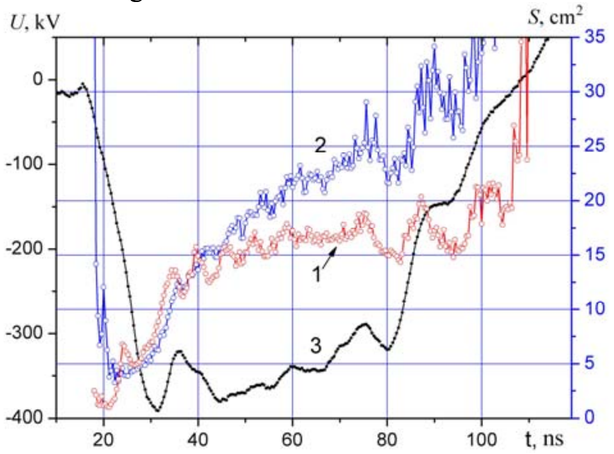

Fig. 1. The change of emitted surface area of cathode during the electron current pulse generation for the graphite cathode 45 mm in diameter, S=16 cm^2 (1) и 60 mm, S=28 cm^2 (2). The curve 3 represents the voltage oscillograms.

For the graphite cathodes with different diameters the process of discrete area increase at the beginning of electron beam generation goes similarly. For the cathode of smaller diameter the explosive emission plasma has time to fill in the entire cathode surface during the voltage pulse. For the graphite cathode with the area of 28 cm^2 the emitted plasma surface in our experimental conditions for 80 ns has time to form only by the end of voltage pulse.

At the change of anode-cathode gap the speed of discrete plasma surface increase at the cathode changes insignificantly. Figure 2 shows that the change of emitted surface area of graphite cathode during the electron current pulse generation for the cathode 60 mm in diameter at the anode-cathode gap of 10.5-15 mm takes place.

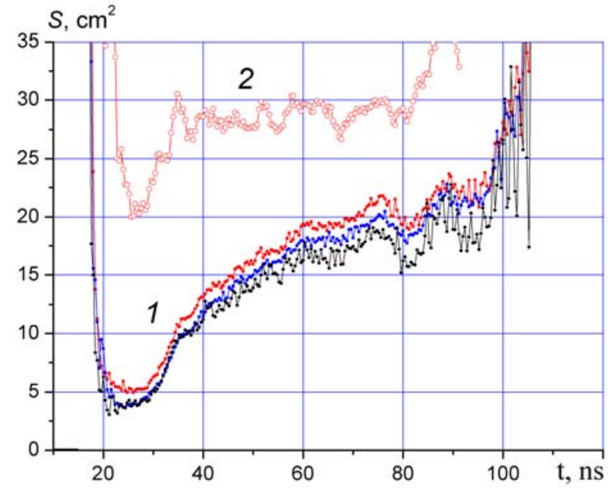

Fig. 2. The change of emitted surface area of cathode during the electron current pulse generation for the cathode 60 mm in diameter (S=28 cm^2) made of graphite (1) and carbon fiber (2).

Figure 2 also shows the dependence of emitted surface increase for the cathode 60 mm in diameter made of carbon fiber. The presence of micro inhomogeneity at the surface of such a cathode significantly simplifies and fastens the formation of solid plasma surface. The speed of discrete emitted area increase at the cathode is not determined by the parameters of nanosecond generator but only by the cathode properties.

4. Simulating the Change of Surface Area

While simulating the change of discrete emitted surface area the following assumptions were taken: emitted centers are placed at the similar distance from each other in the form of cell structure. They are formed simultaneously and their quantity stays the same during the electron beam generation.

Then the number of emitters is

$$N = \frac{\pi \cdot r_0^2}{3.46 \cdot (v \cdot t_1)^2} = \frac{0.91 \cdot r_0^2}{(v \cdot t_1)^2}$$

where t_1 is the time of contact of neighboring emitted centers.

The area of a single emitted center equals the area of circle the radius of which is the composition of explosive emission plasma spread speed and the time from the moment of center formation [1]. The given dependence is correct until the emitted center does not overlap the next center, i.e. it does not go out the borders of hexahedron which it is inscribed in. Further it is necessary to subtract the area of 6 segments which go out the borders of hexahedron from the area of a circle. Then the sum emitted cathode area equals:

$$S_{cal} = N \cdot (v \cdot t)^2 \cdot [\pi - 3 \cdot (\alpha - \sin\alpha)] \quad (3)$$

where $\alpha = 2\arccos(t_1/t)$, in radians.

Figure 3 shows the calculated dependence of change of sum area of discrete emitted surface. The calculation is performed in relation to (3) for the cathode 60 mm in diameter and for the plasma spread speed of $2.5 \cdot 10^6$ cm/s и $t_1 = 70$ ns.

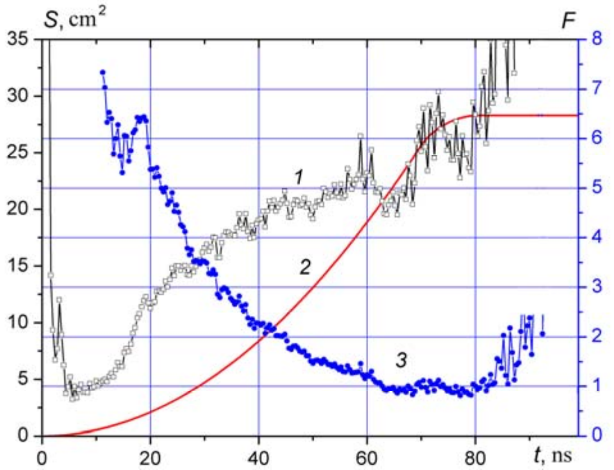

Fig. 3. The experimental (1) and calculated (2) values of area of emitted cathode surface during the electron current pulse generation for the graphite cathode 60 mm in diameter at 12 mm gap. The curve 3 shows the change of form-factor *F*.

Figure 3 represents the change of form-factor value which equals the correlation of experimental data of electron current to the calculated data according to the expression (2) at $v = 2.5 \cdot 10^6$ cm/s. In the initial period of time when the correlation of radius of emission center to the distance between the neighboring centers is less than 0.14 ($t < 20$ ns in Fig.3) the value of form factor is constant (within the limit of measurement accuracy) and equals 6. With the increase of emitted center size the value F decreases down to 1. This corresponds to the solid emission surface of the graphite cathode [3]. The similar change of form-factor value was obtained also for different gaps.

In the papers [1, 2] it is shown that the volt-ampere characteristics for the system with planar electrodes and single emitter appeared at the place of artificially created micro protrusion ($U = 20$ - 40 kV, $d = 0.3$ - 1 mm), with good accuracy in the initial phase of emitter evolution, when $v \cdot t \leq d/3$ is described by the following correlation:

$$I_{Ch-L} = 44.4 \cdot 10^{-6} \cdot U^{3/2} \cdot \left(\frac{v \cdot t}{d}\right)^2$$

This correlation is obtained from the equation (1) under the condition that the cathode area is $\pi \cdot (v \cdot t)^2$ and the form factor is $F = 6$.

5. Conclusion

The performed investigations showed that the experimental volt-ampere characteristics of planar diode with graphite cathode in the initial period of time (at the discrete emission surface of cathode) is satisfactorily described by the modified Child-Langmuir correlation under the condition of simultaneous appearance of separate emitters and increase of their radius at a constant speed. In the initial period of time when the emitter radius is significantly smaller than the distance between the neighboring emitters the value of form-factor in the modified Child-Langmuir correlation corresponds to the experimental data obtained while investigating a single emitted center. With the increase of emitter size the form-factor value decreases to 1. This corresponds to the volt-ampere characteristics of planar diode with solid emission surface at the cathode.

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