A Planar Diode Operating in the Mode of Limited Electron Emission[1]

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Abstract – The current-voltage characteristics of a planar diode with a graphite explosive-emission cathode have been experimentally studied in the initial stage of electron current formation (mode of limited electron emission). An analytical expression has been obtained for perveance of diode in the cellular structure approximation, assuming that the number of such emitting centers operative during the current pulse formation is constant. It is shown that the electron current buildup for a cathode surface with discrete emitting centers is satisfactorily described by a modified Child–Langmuir formula with the form factor decreasing during electron beam generation from 6 to 1.

1. Introduction

Planar diodes with explosive-emission cathodes are widely used for the generation of pulsed electron beams with current densities above 100 A/cm2. Study of such diodes with various cathodes (planar, point, multipoint, circular, etc.) showed (see, e.g., [1]) that the electron current is limited by the cathode emissivity and the space charge in the inter-electrode gap. After the formation of solid plasma surface at the cathode, the diode shifts to the mode of current limitation by the volumetric charge, and the total diode current is satisfactorily described by a modified Child-Langmuir formula.

The process of variation of the electron current magnitude in a planar diode in the initial stage, which lasts from the inter electrode voltage application to the continuous emitting surface formation, is still insufficiently studied. Variation of the average electron current density in a planar diode with an emitting surface evolving from discrete explosive-emission centers on the cathode to a continuous plasma surface has been theoretically analyzed in [2, 3]. The simulation conditions are the constant voltage and constant speed of explosive emission plasma expansion.

The behavior description of diode with discrete emission surface by the alteration of average current density used in [2, 3] makes more complicated the physical explanation of processes in the surface of explosive emission cathode. The total current of beam depends on the voltage applied to the diode and on the sum area of emission surface of cathode. The planar diode analysis by perveance would give a more visual result. Its value for current limited by the volumetric charge is determined only by the diode geometry (anode-cathode gap and area of emission surface) and their alterations during electron beam generation. This paper presents the results of an experimental investigation of the current-voltage characteristics of a planar diode with discrete explosive-emission centers on a graphite cathode.

2. Experimental setup

The experiments were performed on a TEU-500 pulsed electron accelerator [4] with the following parameters: accelerating voltage pulse amplitude 350–450 kV; full pulse duration 100 ns; total kinetic energy of an electron pulse up to 250 J; pulse repetition rate 0.5–1 Hz. A special feature of the accelerator design was the presence of a matching transformer between a double pulse-forming line of the generator and the diode. In the case of a preliminary demagnetization of the core of this transformer, the shape of a voltage pulse formed by the nanosecond pulse generator circuit (including the double line and the transformer) was close to the optimum with allowance for a decrease in the diode impedance related to the explosive-emission plasma expansion [5]. As a result, the diode is matched to the pulse generator during the entire period of electron beam formation.

The voltage was measured using a capacitive divider. The total electron beam current was determined using a Faraday cup with a flat collector, which served as the anode. The configuration of the diode unit and position of the diagnostics equipment are given in detail in [6]. The registration of the electric signals coming from sensors was performed by the oscillograph Tektronix 3052B (500 MHz, $5 \cdot 10^9$ acts of measurements per second). The inaccuracy of electric signals synchronization did not exceed 0.5 ns. The calibration of the diagnostics equipment showed that it correctly reflects the accelerator operation in the mode of short circuit (U = 50–60 kV), when operating for resistance load up to 60 Ω (150–200 kV) and the planar diode (350–450 kV). The achieved accuracy of measurement of voltage by the capacitor divider and of total current of electron beam by Faraday cup, as well as their frequency performance allows measuring volt-ampere characteristics with not more than 10-% inaccuracy.

The investigations have been done for the planar configuration of the diode. The plane cathode is 60 mm in diameter. As anode the plane metal mesh with the cuts 6-mm in width and luminescence of 70%

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was used. The distance between anode mesh and Faraday cup collector was 5 mm. The Faraday cup was pumped out together with the diode chamber up to pressure not more than 0.05 Pa.

3. Calculation of diode perveance

For the vacuum diode with planar electrodes of infinite area (without considering edge effects) the analytical expression for current density limited by space charge can be obtained by the solution of Poisson equation. Under the condition that all electrons leave cathode with zero speed, the field and charge distribution in the gap is permanent, current density is (Child–Langmuir law)

$$j = \frac{4\varepsilon_0}{9}\left(\frac{2e}{m}\right)^{1/2}\frac{U^{3/2}}{d^2} = 2.33\cdot 10^{-6}\,\frac{U^{3/2}}{d^2}, \qquad (1)$$

where ε_0 is the absolute dielectric penetrability, e and m are the charge and mass of electron, U is the voltage, d is the gap.

For the diode with explosive emission cathode in correlation (1) it is necessary to consider the reduction of anode-cathode gap of the expanding plasma [1] $d(t) = d_0 - v_1 t$. Our investigation showed when the cathode area is less than 50 cm^2 the increase of emission surface due to the plasma expansion in the transverse direction should be considered in correlation (1). Taking this into account the current of the diode will be described as follows [7]:

$$I_e = \frac{2.33\cdot 10^{-6}\cdot U^{3/2}\left(1+\frac{v_2 t}{r_0}\right)^2}{(d_0 - v_1 t)^2} S_0 \qquad (2)$$

where S_0 is the geometric area of the cathode; v_1 are v_2 are the speeds of cathode plasma expansion to anode and crosswise to anode-cathode gap, respectively.

It is well known that the emission plasma in the high-current diode with cold cathode forms as the result of explosion of micro edges on its surface [1]. Plasma expansion after edge explosion is a hydrodynamic process, and speed of its expansion in the hemisphere must be equal. That is why the speed of plasma spread in the direction to anode and crosswise to anode-cathode gap while expanding to vacuum is taken as equal. For experimental determination of plasma spread speed crosswise to axis the anode erosion effect under the action of electron beam appearing after explosive emission of electrons was used [1]. When the edged cathode was used, the erosion trace looked like a circle. The average cross-section speed of cathode plasma expansion was estimated by the speed of erosion spot radius growth. The experiments were performed at $d = 0.35$ mm, $U_0 = 35$ kV with the use of edge made of tungsten and plane copper anode. From the dependence of erosion spot radius at the anode on the pulse duration, it was found out that the erosion radius growth speed is (2.2–2.3) cm/µs. This corresponds to the speed of transverse plasma expansion. The obtained value is close to the speed of longitudinal expansion of tungsten plasma to anode.

There are also indirect experimental measurement data of explosive emission plasma spread velocity along the cathode surface. For the case of hemisphere emitting surface on the planar cathode it was found out [8] that the experimental data are well-described by the equation where the plasma spread speed in the direction of anode and crosswise to anode-cathode gap are equal. The plasma area expansion uniform in all directions on the edge cathode is also shown by the optical observations.

The diode shifts to the mode of current limitation by the volumetric charge after the formation of solid plasma surface at the cathode. Let us assume that (i) the electron current is limited by the space charge in the interelectrode gap from the first moment of voltage application to the diode and (ii) the electron beam current growth until saturation is determined by an increase in the surface of discrete emitting centers from zero to the total geometric area of the cathode. This approach has been successfully verified [2] in modeling the variation of the average electron beam current in a planar diode with a discrete emitting surface.

Then the perveance of diode with discrete emission surface can be written down as following:

$$P_{calc} = \frac{I_e}{(U)^{3/2}} = \frac{2.33\cdot 10^{-6}\cdot (r_0 + vt)^2}{r_0^2 (d_0 - vt)^2} S(t), \qquad (3)$$

where $S(t)$ is the sum area of plasma emission surface on the cathode.

An analytical expression has been obtained in [9] for the total area of discrete emitting centers during the current pulse formation. In modeling the law of variation of the area of a discrete emitting surface, we used the following assumptions: (i) the emitting centers are equidistant from each other and form a uniform cellular structure on the cathode surface; (ii) the emitting centers are formed simultaneously, and (iii) their number remains the same during the entire period of the electron beam generation. The total area of discrete emitting centers is

$$S_{calc} = N(vt)^2\left[\pi - 3(\alpha - \sin\alpha)\right], \qquad (4)$$

where N is the total number of emitting centers; $\alpha = 2\arccos(b/vt)$ (in radians); b is the distance between the adjacent emitting centers.

The total number of emitting centers can be estimated as the ratio of the cathode area to the area of a hexagonal unit:

$$N = \frac{3.63 r_0^2}{b^2}.$$

Then the perveance of diode with discrete emission surface is

$$P_{calc} = \frac{8.5\cdot10^{-6}\cdot(vt)^2\left[\pi-3(\alpha-\sin\alpha)\right](r_0+vt)^2}{b^2(d_0-vt)^2}. \quad (5)$$

For the description of electron current of diodes with various cathodes (flat, edged, multi-edged, ring-type, and others) in [1] a generalized formula is offered. In this formula a fitting parameter (form-factor) F is introduced for the matching of experimental data to correlation (1). For the planar diode with flat cathode F equals 1.

It was demonstrated [1, 8] that the current–voltage characteristic of a planar diode with flat electrodes (U = 20–40 kV) and a single emitter arising at an artificial microprotrusion on the cathode surface (d = 0.3–1 mm) in the initial stage of the emitter evolution ($vt \le d/3$) is well (to within 10%) described by the following relation:

$$I_e = 44.4\cdot10^{-6}\cdot U^{3/2}\left(\frac{vt}{d_0}\right)^2. \quad (6)$$

Note that this expression is obtained from Eq. (1) for a cathode with an emitting area of $\pi(vt)^2$ and form factor $F = 6$.

In the process of discrete emission surface growth at the cathode from separate emission centers to the solid plasma surface when describing electron current in correlation (5) it is necessary to consider the form-factor showing the electric field voltage deviation by the emission centers. Then the expression for planar diode perveance with the discrete emission surface at the cathode will be

$$P_{calc} = \frac{8.5\cdot10^{-6}(vt)^2\left[\pi-3(\alpha-\sin\alpha)\right](r_0+vt)^2}{b^2(d_0-vt)^2}F(t). \quad (7)$$

The divider is placed in the oil volume and measures the sum of voltage applied to the anode-cathode gap and the voltage drop on the inductance of cathode holder L. That is why the calculation of the experimental values of diode perveance is done by the correlation

$$P_{\exp} = \frac{I_e}{(U - L\frac{dI_e}{dt})^{3/2}}.$$

The inductance value while calculating was accepted as 160 nH. This value was obtained when calibrating the diode unit in the short-circuit mode.

4. Research of diode with carbon cathode

For carbon, the threshold intensity of the electric field when the explosive emission of electrons starts is lower than for copper and for other metals. That is why it is easier to use carbon for measurement of plasma expansion speed. The investigations of volt-ampere characteristics of diode with cathode of 60 mm in diameter made of graphite were performed. Fig. 1 shows the typical oscillograms of voltage and total current of electron beam.

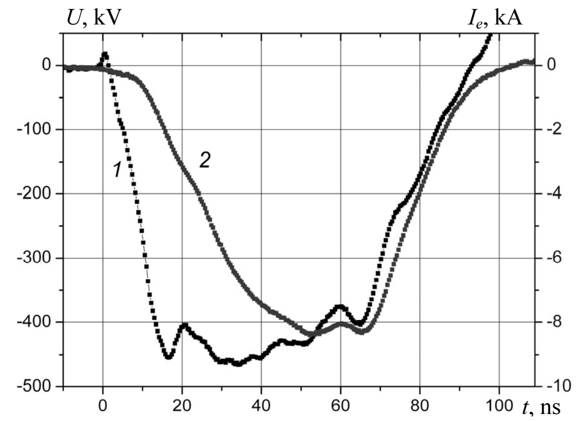

Fig. 1. Oscillograms of voltage (*1*) and electron current (*2*) for diode with graphite cathode; *a–c* gap is 15 mm

The oscillograms are averaged by 10 pulses going with the frequency 1 pulse per second after cathode action by 10–20 pulses. In this series of experiments as anode the metal mesh was used. The current registered by Faraday cup was corrected for the value of optical transparency of mesh [6].

Figure 2 shows the perveance change of the diode with graphite cathode of 60 mm in diameter during electron current pulse generation when anode-cathode gap is 12 mm. The calculation is performed by correlations (2) and (7) with a plasma speed of 2 ± 0.5 cm/μs and distance between two neighbor emission centers of 2.8 mm.

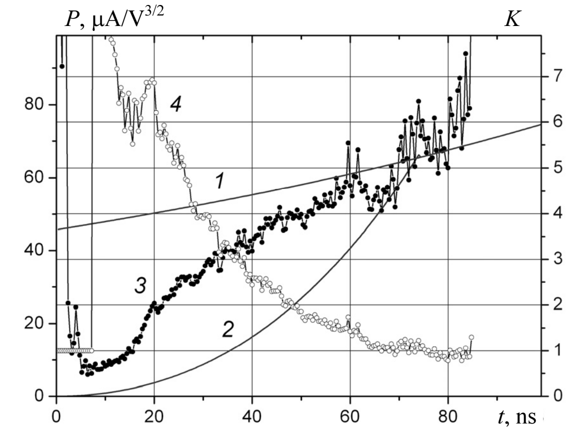

Fig. 2. The change of diode perveance during electron current pulse generation: calculation for solid (*1*) and discrete (*2*) plasma surface at the cathode, curve *3* shows experimental data, curve *4* shows the relation of experimental data of perveance to calculation ones by correlation (5)

Figure 2 shows the relation of experimental values of perveance to the calculated ones by correlation (5) presenting the change of form-factor during electron beam generation.

In the initial period of time when the relation of distance between neighbor emission centers and center radius is more than 7 (t < 20 ns in Fig. 2), the form-factor value is constant (withing the measurement accuracy) and equal to 6. Such form-factor value corresponds to the diode perveance with edged cathode (see correlation (6)). With the increase of emission center size and overlapping of neighbor centers the value F decreases to 1. This corresponds to the solid emission surface of graphite cathode [6].

Similar change of form-factor value was obtained for other gaps. In Fig. 3 the change of diode perveance (calculation and experiment) is shown at various initial gaps. The calculation has been performed by correlation (7) for a plasma spread speed of 2 cm/μs and b = 2.8 mm.

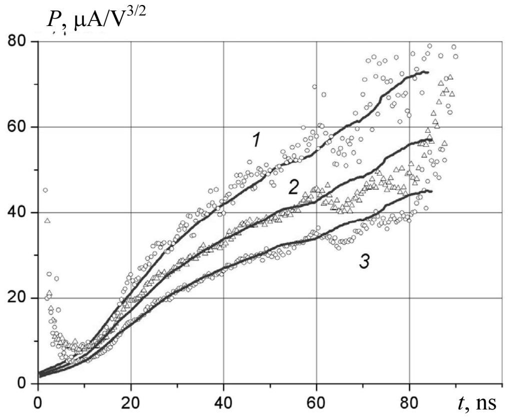

Fig. 3. The experimental (*1*) and calculation (*2*) values of diode perveance during electron current pulse generation for graphite cathode 60 mm in diameter when the gap is 12 (*1*), 13.5 (*2*), and 15 mm (*3*)

The performed study has shown that experimental values of perveance of planar diode with graphite cathode in the initial period of time (with the discrete emission surface of cathode) is satisfactorily described by the modified correlation of Child–Langmuir 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 emitter radius is much smaller that the distance between neighbor emitters the form-factor value in the modified Child–Langmuir correlation corresponds to the experimental values obtained while studying the single emission center. With the increase of emitter centers and their overlapping the form-factor values goes down to 1. This corresponds to the current of planar diode with solid emission surface at the cathode.

5. Conclusion

The performed studies showed that the experimental volt-ampere characteristic of planar diode with graphite cathode in the initial period of time (with the discrete emission surface of cathode) is well 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 much smaller than the distance between neighbor emitters, the form-factor value in the modified Child–Langmuir correlation corresponds to the experimental values obtained while studying a single emission center. With the increase of emitter size the form-factor value reduces to 1. This corresponds to the volt-ampere characteristics of planar diode with solid emission surface at the cathode.

References

[1] G.A. Mesyats. *Pulsed Power and Electronics* Moscow, Nauka, 2004.

[2] S.Ya. Belomyttsev, S.D. Korovin and I.V. Pegel' Technical Physics **44**, 695 (1999).

[3] G. Djogo and J.D. Gross, IEEE Trans. Plasma Sci. **25**, 617 (1997).

[4] G.E. Remnev, E.G. Furman, A.I. Pushkarev et al., IEEJ Trans. Fundam. Mater. **124**, 491 (2004).

[5] G.E. Remnev, A.I. Pushkarev, and E.G. Furman, Tech. Phys. Lett. **30**, 603 (2004).

[6] A.I. Pushkarev, Yu.N. Novoselov, and R.V. Sazonov, Instr. and Exp. Tech. **50**, 694 (2007).

[7] A.I. Pushkarev, Technical Physics. **53**, 367 (2008).

[8] A.F. Shubin and Ya.Ya. Yurike. Izv. Vyssh. Uchebn. Zaved. Fiz., No. 6, 134 (1975).

[9] A.I. Pushkarev and R.V. Sazonov., Tech. Phys. Lett. **34**, 292 (2008).