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GENERAL EXPERIMENTAL TECHNIQUES

Studying the Effect of Adsorbed Molecules on the Operation of a Diode with an Explosive-Emission Cathode

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Abstract—The results of an experimental study of the effect of an adsorbed gas and surface contaminations of an explosive-emission cathode on the operation of a diode during generation of a high-current electron beam of nanosecond duration are presented. The effect of contaminations was revealed from the change in the rate of expansion of the planar-diode cathode plasma for cathodes of different designs manufactured from different materials and different initial anode–cathode gaps. The plasma velocity was calculated from the experimental perveance of the diode with a resolution of 0.2 ns. Experiments were performed on a ТЭУ-500 pulsed electron accelerator (350–450 kV, 100 ns, and 250 J/pulse) in a mode of matching the diode impedance to the output impedance of the nanosecond generator. It has been found that the velocity of cathode plasma is constant for 70–90 ns after applying voltages to different cathodes at different anode–cathode gaps. The velocities were 2.0 ± 0.5 cm/μs for carbon cathodes (of different diameters), 3 ± 0.5 cm/μs for multispike tungsten cathodes, and 4.0 ± 0.5 cm/μs for copper (solid or multispike) cathodes. An appreciable dependence of the plasma velocity on the cathode material shows an insignificant influence of the adsorbed gas and cathode surface contaminations on the expansion velocity of the explosive-emission plasma in a planar diode during generation of the electron beam (10–15 ns after a voltage is applied).

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INTRODUCTION

Planar diodes with explosive-emission (EE) cathodes are widely used for generating electron beams with large cross sections and high current densities. During analysis of their operation, many researchers point to a substantial contribution of the adsorbed gas and cathode surface contaminations on the process of formation of EE plasma. It is shown in [1] that the pressure of the residual gas and the technique for producing vacuum in a chamber affect the stability of current collection from the cathode. Upon a change from oil-free high vacuum to oil-assisted evacuation and to a pressure raised to 0.1 Pa, cathodes operate more stably and their service life is $>10^6$ operations. The results presented in [1] prove that surface contamination affects the excitation of emission centers. If it is present, the delay time of the appearance of the cathode emission shortens.

Papers [2, 3] present the results of studies of an EE cermet cathode made from oxide nanoceramics, inside which metal particles are homogeneously distributed over the volume. The authors suggest that plasma is produced due to the development of a gas discharge in near-surface micropores between the dielectric and metal. A substantial contribution of gas liberation to the operation of EE cathodes with felt and velvet coatings was noted in [4] during generation of electron beams with current densities of 20–30 A/cm^2 at accelerating voltages of 300–400 kV.

It is known that the expansion velocity of EE plasma mainly depends on the cathode material from which plasma is produced [1]. The influence of the adsorbed gas and surface contaminations of an EE cathode on the diode operation can be determined from the plasma-expansion velocity when using cathodes of different designs (solid, multispike, or carbon-fabric-coated cathodes) produced from different materials. In measurements of the propagation velocity of cathode plasma under comparable vacuum conditions (the same adsorbed molecules and equal adsorption rates), the decisive effect of contamination on the plasma production leads to equal cathode-plasma velocities (at least, during the initial period of the electron-beam generation) for different cathodes.

The objective of this study was to investigate the effect of the adsorbed gas and surface contaminations of an EE cathode on the change in the expansion velocity of cathode plasma during generation of an electron beam.

EXPERIMENTAL SETUP

Experiments were performed on a ТЭУ-500 pulsed electron accelerator [5] with the following parameters: an accelerating voltage of 350–450 kV, a pulse duration (at the base) of 100 ns, and a total electron energy of up

to 250 J per pulse. The pulse repetition rate was 0.5–1.0 s^{-1}. A distinguishing feature of this accelerator is the use of a step-up autotransformer connected between the double forming line and the diode for matching the high impedance of the diode to the low characteristic impedance of the forming line [6].

The voltage measurements were performed using a capacitive divider placed in an oil-filled chamber. The total electron-beam current was measured with a Faraday cup, which was evacuated together with the diode chamber down to a pressure of 0.04–0.05 Pa by an oil-diffusion pump. The vacuum level in the diode chamber was monitored during measurements with a magnetic electric-discharge manometric transducer and a ВМБ-8 vacuum gage. The high evacuation rate of the vacuum system ensured the recovery of vacuum in the diode chamber within the period between pulses.

The electric signals arriving from probes were recorded with a Tektronix 3052B oscilloscope (500 MHz, 5×10^9 readings/s). The synchronization error of electric signals was within 0.4 ns. The measurement errors of the voltage and total current of the electron beam allowed measurements of the diode perveance with an error no larger than 10%.

A diode of planar configuration was studied. Its flat cathode was 43–60 mm in diameter, and a flat grid with 6-mm-wide slits and a transparency of 70% served as the anode. The distance between the anode grid and the Faraday-cup collector was 5 mm. In some experiments, a 92-mm-diameter flat copper collector of the Faraday cup was used as the anode. The design of the diode unit and the arrangement of diagnostic instruments are described in detail in [7].

DETERMINATION OF THE PLASMA VELOCITY

The highest time resolution is attained when the cathode-plasma velocity is calculated from the experimental current–voltage characteristic (CVC) of the diode. Optical observations of motion of cathode plasma yield a time resolution no better than 5 ns [8, 9], thereby hindering the determination of the velocity in the initial period of formation of a pulsed electron beam.

Studies of diodes with different cathodes (flat, pointed, multispike, etc.), which are reviewed in [1], have shown that the electron current in the mode of limitation by the space charge is described by the expression

$$I_e = AU^{3/2}\frac{S_0}{d_0^2}F,$$

where $A = 2.33$ μA/V$^{3/2}$, U is the voltage applied to the diode, S_0 is the cathode area, d_0 is the anode–cathode gap, and F is the form factor determined by the cathode design.

With allowance for the expansion of the plasma-emitting surface of the flat cathode, the diode current is [10]

$$I_e = \frac{AU^{3/2}F\pi(r_0 + vt)^2}{(d_0 - vt)^2}, \quad (1)$$

where r_0 is the cathode radius and v is the velocity of cathode-plasma expansion.

The following expression for the cathode-plasma expansion velocity can be obtained from formula (1):

$$v(t) = \frac{Kd_0 - r_0}{t(K+1)}, \text{ where } K = \sqrt{\frac{I_e}{2.33 \times 10^{-6} F\pi U^{3/2}}}. \quad (2)$$

The cathode-plasma expansion velocity can be correctly calculated from the diode CVC only if it operates in the mode of electron-current limitation by the space charge. It is convenient to determine the operating mode by comparing the experimental and calculated values of the diode perveance. The coincidence of these values corresponds to the diode-current limitation by the space charge. In the initial period of electron-beam generation (in the mode of a discrete emitting surface) and in the saturation mode, the current is limited by the electron emission from the cathode; therefore, the experimental values of the perveance are lower than the calculated values.

The diode perveance in the mode of electron-current limitation by the space charge is

$$P_{\text{calc}} = \frac{I_e}{U^{3/2}} = \frac{2.33 \times 10^{-6}\pi F(r_0 + vt)^2}{(d_0 - vt)^2}. \quad (3)$$

The voltage divider of the ТЭУ-500 accelerator is placed in the oil-filled volume and measures the sum of the voltage applied to the anode–cathode gap and the voltage drop across inductance L of the cathode holder. Therefore, the experimental values of the diode perveance were calculated from the formula

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

The inductance used in calculations was taken to be equal to 160 nH, a value obtained in the calibration of the diode unit in the short-circuit mode.

STUDYING A DIODE WITH A CARBON-FABRIC CATHODE

The threshold electric-field strength at which explosive electron emission is initiated is lower for carbon than for copper or other metals; therefore, carbon is most frequently used as a material for EE cathodes. The cathode-plasma expansion rate can be correctly calculated from formula (2) only in the operating mode of current limitation by the space charge, which corre-

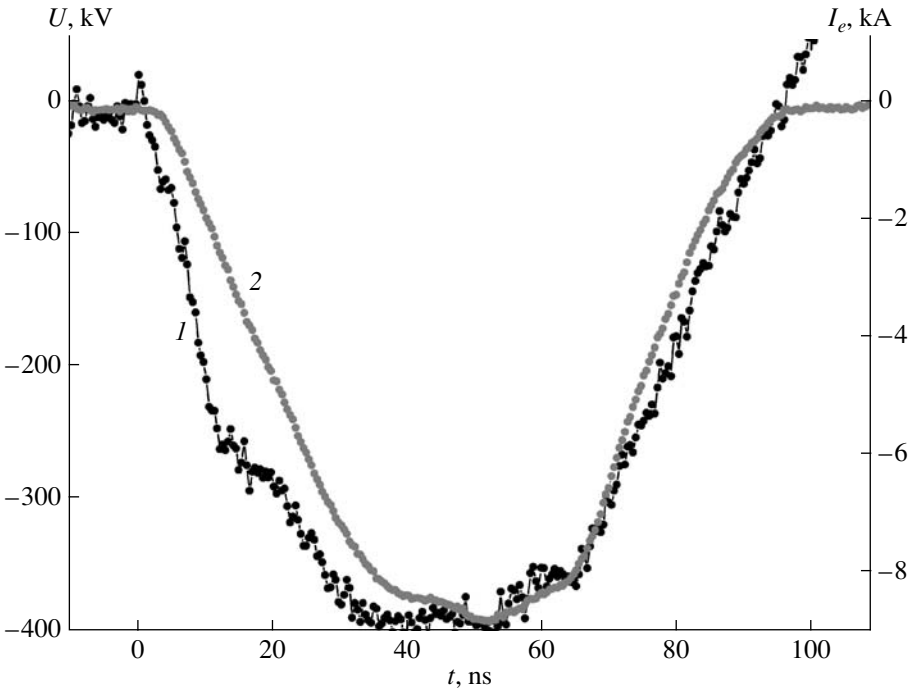

Fig. 1. Oscillograms of (*1*) the voltage applied to the diode and (*2*) the total current of the electron beam.

sponds to the entirely plasma-filled cathode surface. However, the formation of a continuous emitting surface on graphite requires >40 ns, thus complicating the analysis of the influence of surface contaminations on the diode operation.

In [11], it was proposed to use a carbon fabric as a cold cathode. The performed studies have shown that the use of carbon (graphite) fabric allows a significantly accelerated change of the diode to the mode of electron-current limitation by the space charge [10]. Figure 1 shows oscillograms of the total electron-beam current and the voltage applied to the diode with a 45-mm-diameter cathode made from aluminum and coated with a carbon fabric. The oscillograms are averaged over ten successive pulses following at a frequency of 0.5 s^{-1} after the cathode was aged during a period of 10–20 pulses. In this experimental run, a flat grid with slits was used as the anode. The current measured with the Faraday cup was corrected taking into account the grid transparency [7].

Figure 2 shows the experimental values of the diode perveance during generation of the electron beam and the values calculated from (3) at $F = 1.7 \pm 0.05$ and $v =$ 2 cm/μs. The experimental values of the perveance (and the electron current) were lower than the calculated ones within 15–20 ns after the voltage application, thereby indicating that the electron current is limited by the cathode emissivity. Subsequently, the experimental and calculated values of the perveance were in satisfactory agreement; i.e., the diode operated to the end of a pulse in the mode of electron-current limitation by the space charge. An increase in the gap width from 11 to 14 mm corresponds to a change in the diode impedance from 25 to 40 Ω, a value close to the output impedance (35 Ω) of the generator [5, 6].

Figure 3 shows the time dependences of the cathode-plasma expansion velocities calculated from (2) for different anode–cathode gaps. During the initial 80–90 ns, the plasma velocity is constant (within the limits of the measurement accuracy)—its value is 2.0 ± 0.5 cm/μs. The expansion rate of EE graphite plasma is close to the value (2 cm/μs) obtained during static breakdown of vacuum gaps for graphite electrodes [12].

The performed investigations have shown that the process of an increase in the discretely emitting surface transforming into the totally emitting surface proceeds identically for graphite cathodes with different diameters [13]. For a cathode with an area <16 cm^2 under our experimental conditions, the voltage-pulse duration is sufficient for EE plasma to fill the entire cathode surface. For a graphite cathode with a 60-mm diameter, the totally emitting surface is completely formed only at the end of a pulse. The use of the carbon fabric substantially promotes this process.

Figure 4 shows the calculated (at $F = 1.7 \pm 0.05$ and $v = 2$ cm/μs) and experimental values of the diode perveance (the diode has a 60-mm-diameter cathode coated with the carbon fabric). In this experimental run, the collector of the Faraday cup served as the anode.

Figure 5 shows the expansion velocities of cathode plasma calculated from formula (2).

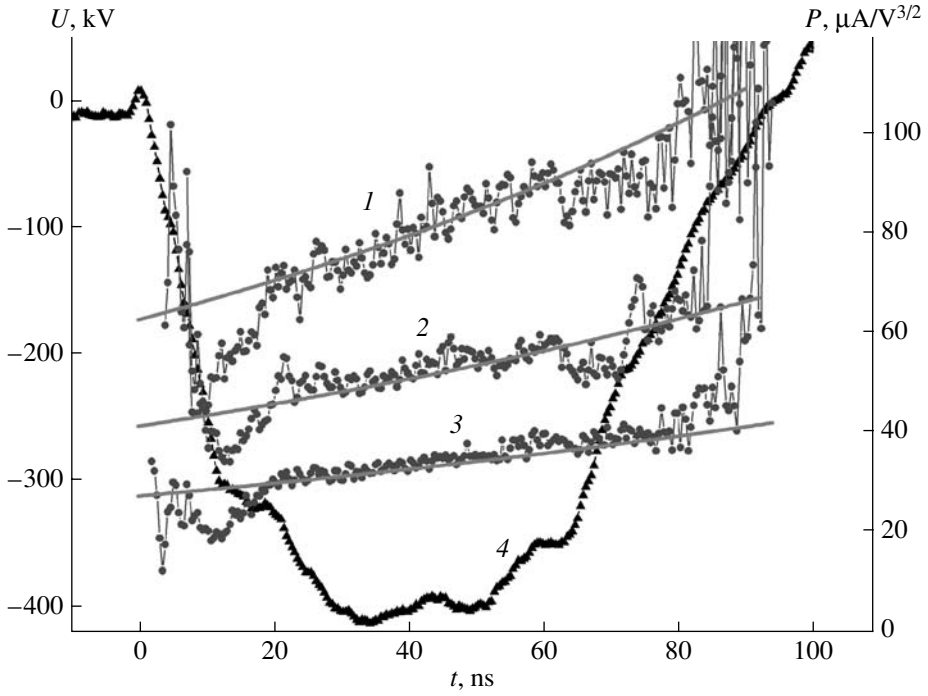

Fig. 2. Experimental (dots) and calculated (lines) values of the planar-diode perveance at anode–cathode gaps of (*1*) 9.5, (*2*) 12.0, and (*3*) 15.0 mm. Curve *4* is the voltage applied to the diode at a 15-mm gap.

As for the diode with a 45-mm-diameter cathode, the plasma velocity is constant (within the limits of the measurement accuracy) within the first 60–70 ns and amounts to 2.0 ± 0.5 cm/μs. When the collector of the Faraday cup served as the anode of a planar diode, the plasma-expansion velocity began to increase 65–70 ns after the voltage application, and the velocity change is independent of the initial width of the anode–cathode gap.

For cathodes based on the carbon fabric and different anode–cathode gaps and cathode diameters, the experimental values of the diode perveance obtained during the first 60–80 ns are properly described by the Child–Langmuir formula with allowance for both a constant velocity of 2.0 ± 0.5 cm/μs of the expanding EE plasma and a form factor. The value of the form factor (1.70 ± 0.05 cm/μs) is constant for all anode–cathodes and diameters of carbon-fabric cathodes studied and corresponds to the presence of microinhomogeneities on the cathode surface.

STUDYING A DIODE WITH A COPPER CATHODE

A cathode manufactured from segments of a copper wire set perpendicularly to the surface is one of the widespread designs of EE cathodes [14]. During material erosion, the diameter of individual emitters does not change, thereby resulting in a long service life of this cathode. We have studied a diode with a 45-mm-diameter solid copper cathode and a multispike cathode, in which segments of 0.1-mm-diameter copper wire are fixed in a 43-mm-diameter sleeve closely to one another. Figure 6 shows the experimental and calculated (from (3)) values of the planar-diode perveance with solid (at $F = 1.00 \pm 0.05$ and $v = 4$ cm/μs) and multispike (at $F = 1.3 \pm 0.05$ and $v = 4$ cm/μs) copper cathodes. For the solid copper cathode, the electron-beam generation is initiated later than for the multispike copper cathode. In the first and second cases, the delays of formation of a continuous plasma surface are >40 and 15–20 ns, respectively.

Figure 7 shows the expansion velocities of cathode plasma calculated from formula (2).

Analysis of these curves shows that the expansion velocity of copper cathode plasma changes insignificantly during the interval of electron-beam generation, but it is much higher than the velocity of carbon plasma. The fact that the plasma velocity is mainly determined by the cathode material indicates that adsorbed molecules and surface contaminations weakly affect the operation of the diode.

STUDYING A DIODE WITH A MULTISPIKE CATHODE

We have performed experimental studies of a planar diode with a multispike cathode consisting of 140 1-mm-diameter tungsten needles. Their height is 11 mm, and the distance between them is 4 mm. The total diameter of the cathode is 43 mm. For a multispike cathode, for which the spacing between needles far

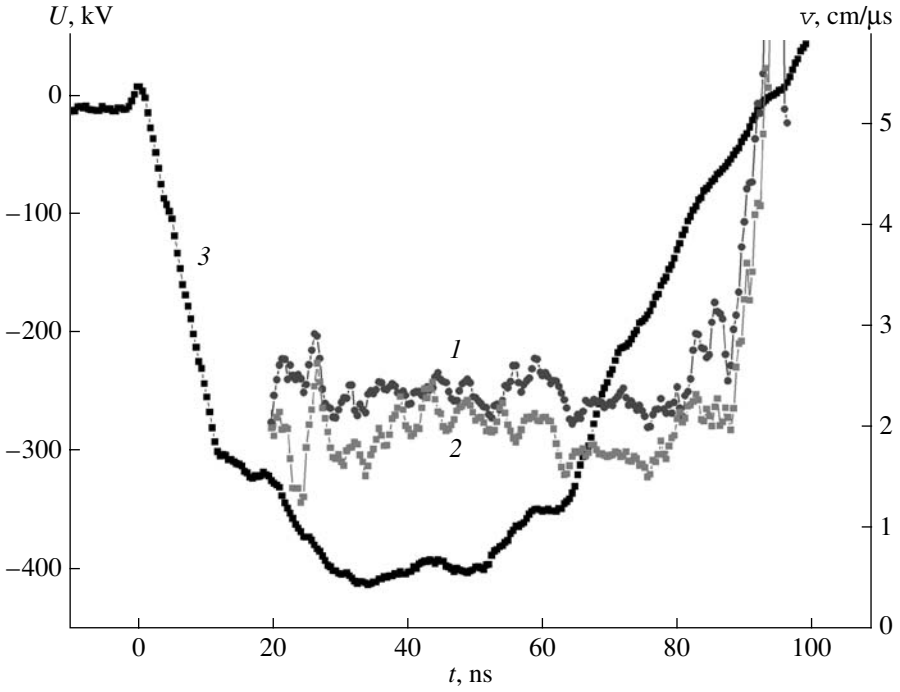

Fig. 3. Change in the EE-plasma expansion velocity during generation of an electron beam in a planar diode with a 45-mm-diameter carbon-fabric cathode at anode–cathode gaps of (*1*) 9.5 and (*2*) 15.0 mm. Curve *3* is the voltage applied to the diode.

exceeds the product of the plasma-expansion velocity and the applied-voltage pulse duration, individual needles can be regarded as independent emitting electron sources. As is shown in [1, 15], the current of a diode with flat electrodes and a single cathode flame, which appears at the point of an artificially created microprotrusion (U_0 = 20–40 kV, and d = 0.3–1.0 mm), is described by the formula

$$I_e = 44.4 \times 10^{-6} U^{3/2} \left(\frac{vt}{d_0}\right)^2.$$

This relationship follows from Eq. (1) provided that the cathode area is $\pi(vt)^2$ and the form factor is $F = 6$. If the anode–cathode gap is reduced by the moving plasma according to the law $d(t) = d_0 - vt$ and the plasma-expansion velocity is constant during the electron-beam formation process, the perveance of the diode with N needles is

$$P = \frac{6N \times 2.33 \times 10^{-6} \pi (vt)^2}{(d_0 - vt)^2}. \quad (4)$$

Figure 8 shows the experimental values of the perveance of the multispike diode during generation of an electron beam and the values calculated from (4) at v = 3 cm/μs (curve *2*). Curve *3* corresponds to the calculation using formula (3) that describes the behavior of the multispike cathode as a uniform emitting surface (with an initial diameter of 43 mm), which expands at a constant velocity of 3 cm/μs. To achieve agreement between the experimental and calculated data, a form factor of $F = 1.6 \pm 0.05$ is introduced into (3). As is seen, in our case, the description of the multispike cathode by the sum of independent emission centers yields a significant discrepancy with respect to the experimental values of the diode perveance.

When the anode–cathode gap changes, the perveance of a diode with a multispike cathode is described well by formula (3) at a constant plasma-expansion velocity of 3 cm/μs and a form factor of 1.6 ± 0.05.

Figure 9 shows the change in the diode perveance during the formation of an electron beam at different anode–cathode gaps. The velocities of expanding cathode plasma calculated from relationship (2) are plotted in Fig. 10.

At a cathode-plasma expansion velocity of 3 cm/μs, adjacent emission centers are superimposed only 70 ns after a voltage is applied to the diode. However, the experimental and calculated values (for a continuous emitting surface) of the perveance for the diode with a multispike cathode coincide (within the limits of the measurement accuracy) already in 10 ns (see Figs. 8 and 9).

DISCUSSION

The cathode-plasma expansion velocity calculated from the experimental current and voltage oscillograms can be determined by a simultaneous influence of several physical processes. Therefore, let us briefly con-

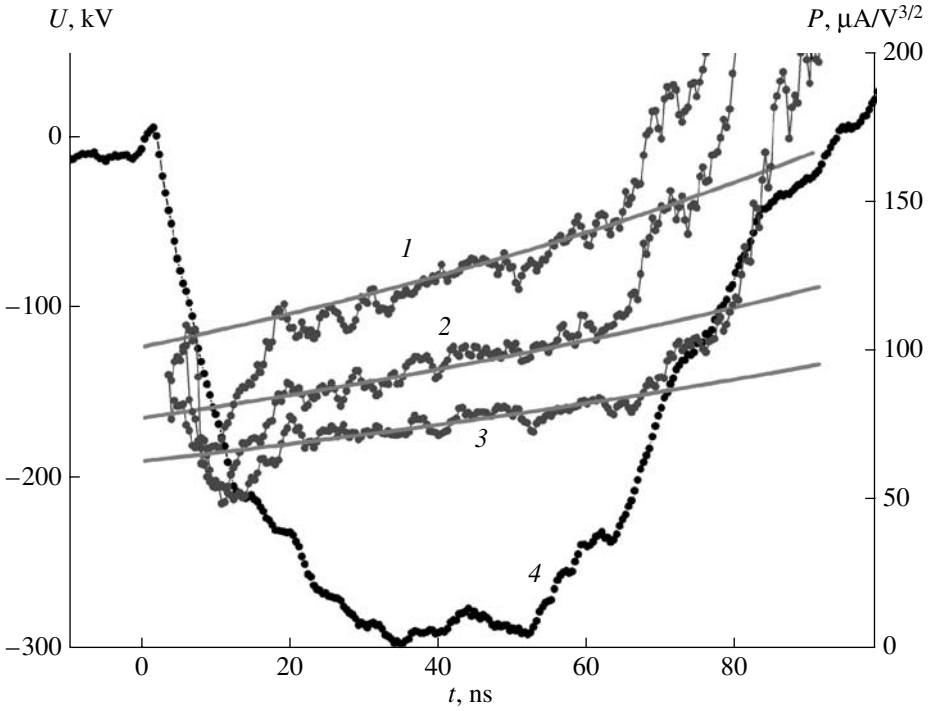

Fig. 4. Experimental (dots) and calculated (lines) values of the planar-diode perveance (the diode has a 60-mm-diameter carbon-fabric cathode) at gaps of (*1*) 10.5, (*2*) 12.0, and (*3*) 13.5 mm. Curve *4* is the voltage.

sider the possible causes of deviations from the model described by (1)–(3).

After plasma fills the cathode surface, the total diode current is limited by the electron charge in the anode–cathode gap, thereby leading to the formation of a negatively charged layer on the surface of the cathode plasma (virtual cathode) [1]. The field of the double charged layer may additionally accelerate positively charged plasma ions and increase the plasma-expansion velocity. The energy that can be gained by an ion in the electric field is 20–40 eV, which corresponds to an increase in the velocity of 1–2 cm/μs [1]. The evaluating calculation [16] has shown that, if a virtual cathode forms, the increase in the plasma velocity may reach 10 cm/μs.

We recorded an increase in the cathode-plasma velocity at the end of a pulse only when the collector of the Faraday cup served as the anode (Fig. 5). This effect was not observed when a supporting anode grid was used (see Figs. 3 and 7); therefore, the influence of the virtual cathode on the plasma velocity under our experimental conditions is insignificant and the velocity increased by at most 0.2–0.3 cm/μs.

An increase in the calculated values of the cathode-plasma expansion velocity may be due to the influence of anode plasma on the diode operation, primarily because of an additional reduction of the anode–cathode gap. As was shown in [1], the velocity of motion of copper-anode plasma is 0.4–0.9 cm/μs. Therefore, the increased plasma velocity observed at the end of a pulse and reaching 6 cm/μs cannot be related to the movement of the anode-plasma boundary to the cathode.

Anode plasma is the source of positive ions extracted by the diode field and moving to meet the electron flow. The ion and electron emissivity of anode plasma is high—up to several kiloamperes per square centimeter [1]. The total diode current under these conditions exceeds the value determined by relationship (1), because the current of counter ions has the same direction as the current of electrons arriving from cathode plasma. However, the ion current is much lower than the electron-beam current because, even if the spatial ion and electron charge densities are comparable, the ion velocity is much lower than the electron velocity.

As a result of compensation of the space electron charge by positively charged anode-plasma ions, the total diode current may be higher than the value defined by the Child–Langmuir formula. It is known that the spatial charge of beam electrons in the anode–cathode gap is distributed very nonuniformly and concentrated mainly near the cathode. Anode-plasma ions are produced at the cathode surface and, to compensate the spatial electron charge, they need a certain time to pass the anode–cathode gap. Therefore, when the spatial electron charge is compensated by anode-plasma ions, an increase in the initial anode–cathode gap must result in a delay of the electron-current increase (caused by the anode plasma) by time $\Delta t = \Delta d/v_a$, where Δd is the increase in the gap and v_a is the anode-plasma expan-

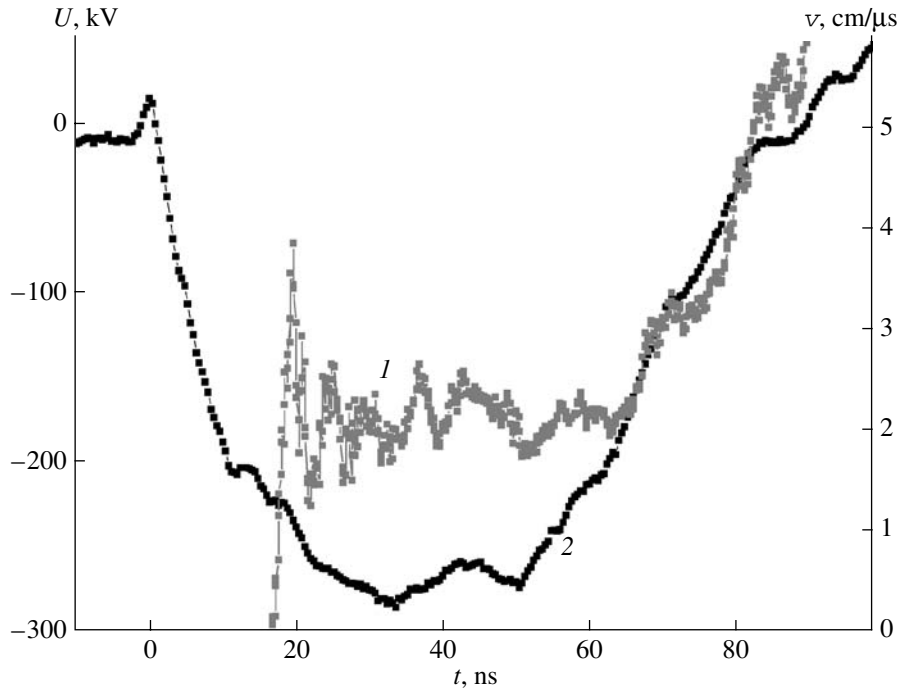

Fig. 5. Time-dependent expansion velocity of EE plasma in a diode with a 60-mm-diameter carbon-fabric cathode calculated from formula (2) at gaps of 10.5–13.5 mm (curve *1*). Curve *2* is the applied voltage.

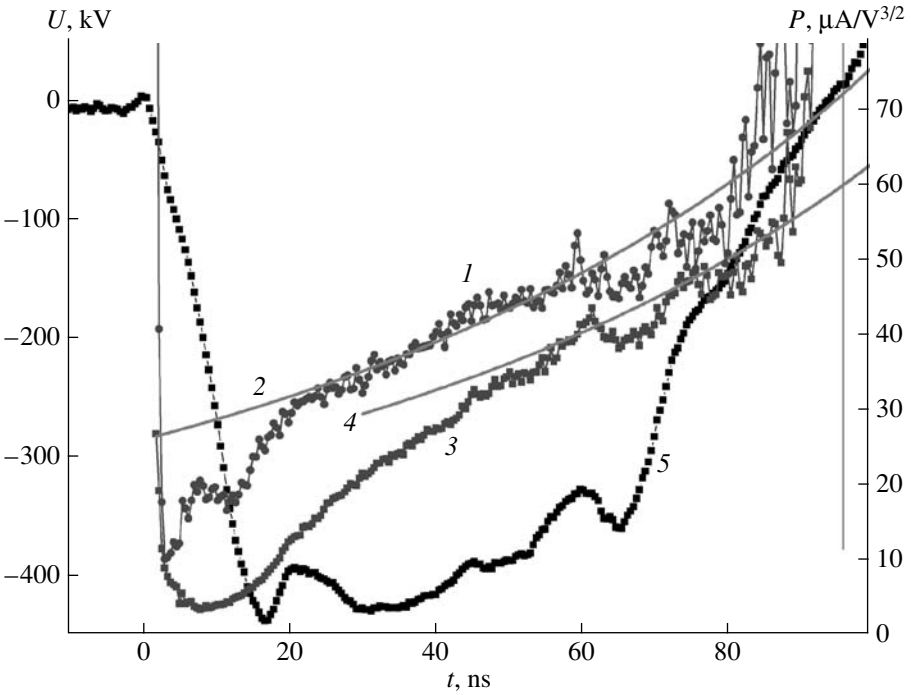

Fig. 6. (*1*, *3*) Experimental and (*2*, 4) calculated values of the planar-diode perveance for (*1*, *2*) multispike and (*3*, *4*) solid copper cathodes at an anode–cathode gap of 12 mm. Curve *5* is the voltage applied to the diode with the copper cathode.

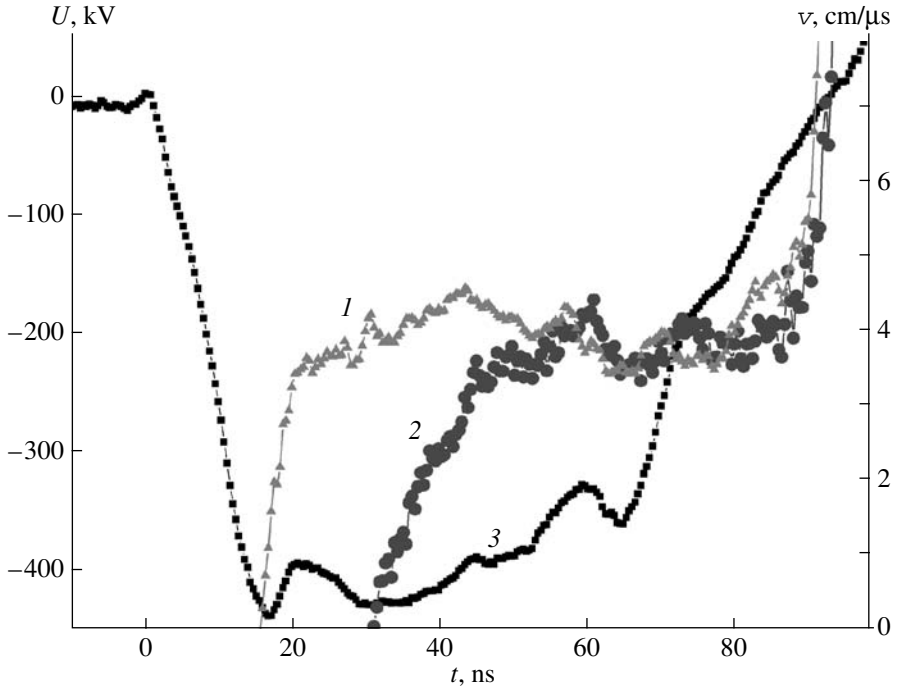

Fig. 7. Change in the cathode plasma expansion velocity during generation of an electron beam in a planar diode with (*1*) multispike and (*2*) solid copper cathodes. Curve *3* is the voltage.

sion velocity. At an anode-plasma expansion velocity of 1 cm/μs, an increase in the anode–cathode gap of 1.5 mm must lead to a 150-ns delay of the electron-current increase (caused by the compensation of the spatial electron charge by anode-plasma ions). This effect was discovered in [17] in studies of a planar diode involving an increase in the initial anode–cathode gap from 2.80 to 5.08 mm.

According to our results, a 3-mm increase in the initial gap (see Fig. 5) has no effect on the beginning of the increase in cathode-plasma velocity during generation of the electron beam. In addition, even at comparable values of the spatial charge densities, the compensation of the spatial electron charge by anode-plasma ions leads to an increase in the electron current by a factor of only 1.86 [18]. With allowance for this value, formula (2) yields an increase in the cathode-plasma velocity of only 36%.

A probable mechanism of distorting the planar-diode perveance (and, correspondingly, the cathode-plasma velocity) is related to an additional contribution of anode-plasma electrons to the total current. When the collector of the Faraday cup is used as the anode, electrons of anode plasma formed at its surface are pulled by the electric field to the collector and initiate an additional current during motion. The total current in an external circuit increases owing to a displacement current in the vacuum gap between the anode and cathode plasmas (in addition to the conduction current of beam electrons).

It has been experimentally revealed that, at a total electron-beam charge of 800 μC (5×10^{15} electrons), the charge arriving from the anode plasma is 60 μC (3.8×10^{14} electrons). It is known that the action of a beam with an electron energy of 100–200 keV on the anode surface leads to a gas desorption with an efficiency of ten molecules per electron [19]. Then, the total number of molecules desorbed from the anode may reach 5×10^{16}. The required number of electrons in the anode plasma is produced at a degree of ionization of these molecules of 0.008.

At an operating pressure in the diode chamber of 0.006–0.065 Pa, the time of formation of one monolayer on the surface is 1 ms [1]. If the average size of molecules adsorbed on the anode surface is 0.2 nm (the interatomic spacings in O_2 and N_2 molecules are 0.12 and 0.11 nm, respectively), their amount in one layer on the surface of the Faraday's cup collector (in our case, a 92-mm-diameter disk) is 2×10^{17}. This value is four times higher than the number of molecules desorbed by the electron beam per pulse. However, the additional contribution of anode-plasma electrons to the total current manifests itself only at the end of the pulse and introduces no error into the calculated cathode-plasma velocity at the beginning.

Hence, under our experimental conditions, the virtual cathode and anode plasma do not make an appreciable contribution to the recorded current, thereby permitting one to use model (1)–(3) for calculating the cathode-plasma expansion velocity and determining the influence of the adsorbed gas and surface contami-

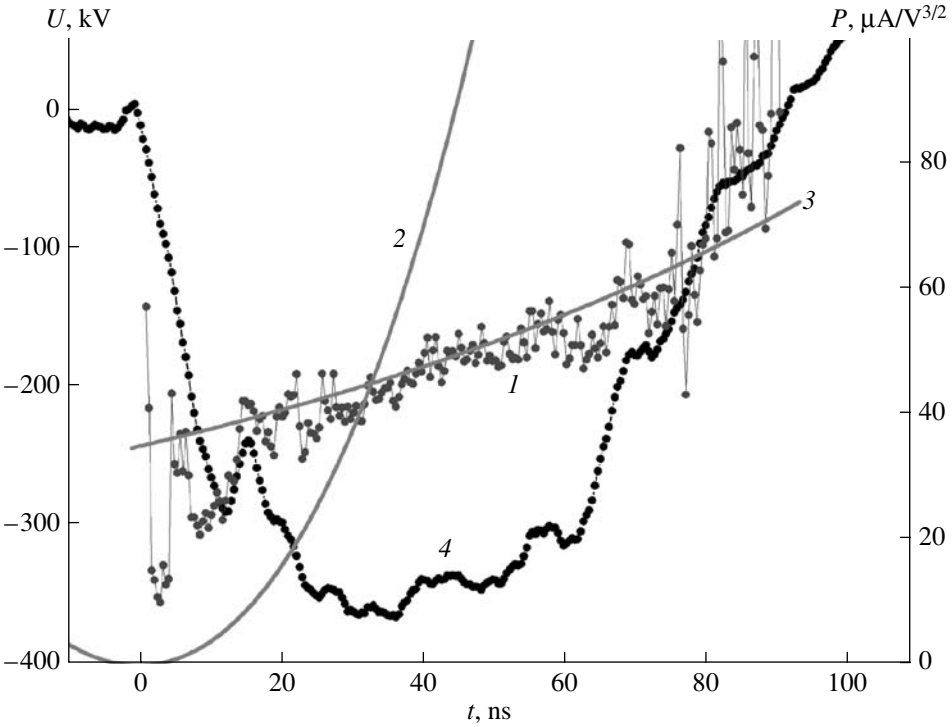

Fig. 8. (*1*) Experimental (dots *1*) and (*2*, *3*) calculated (from (*4*) and (*3*), respectively) values of the perveance of a planar diode with a multispike cathode at a gap of 12.5 mm. Curve *4* is the voltage.

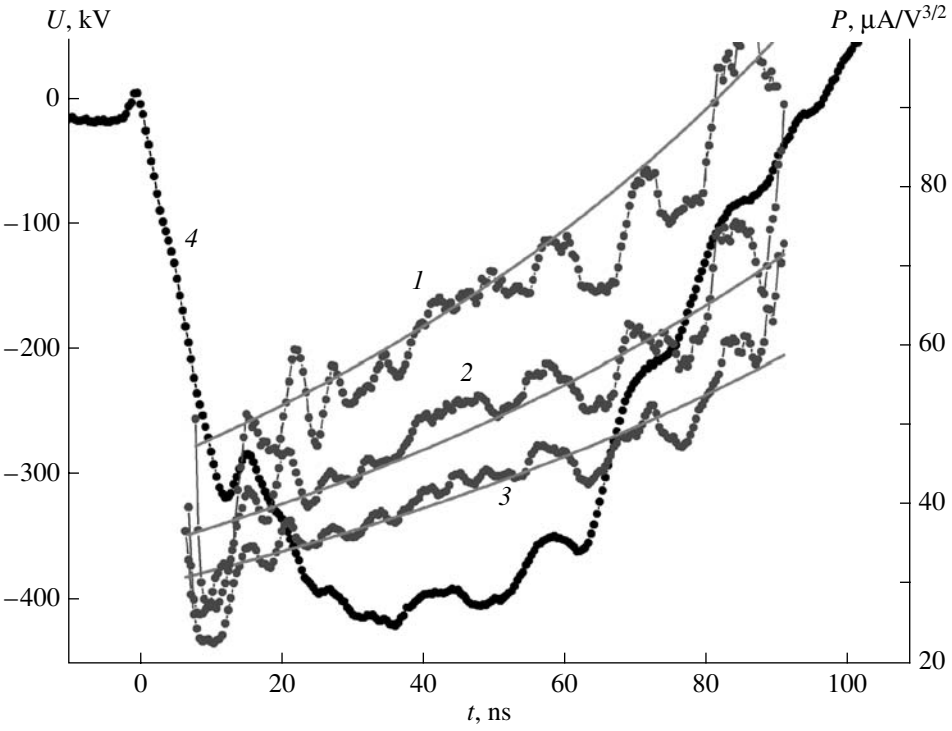

Fig. 9. Experimental (dots) and calculated (lines) values of the perveance of a planar diode with a multispike cathode at anode–cathode gaps of (*1*) 11.0, (*2*) 12.5, and (*3*) 14.0 mm. Curve *4* is the voltage.

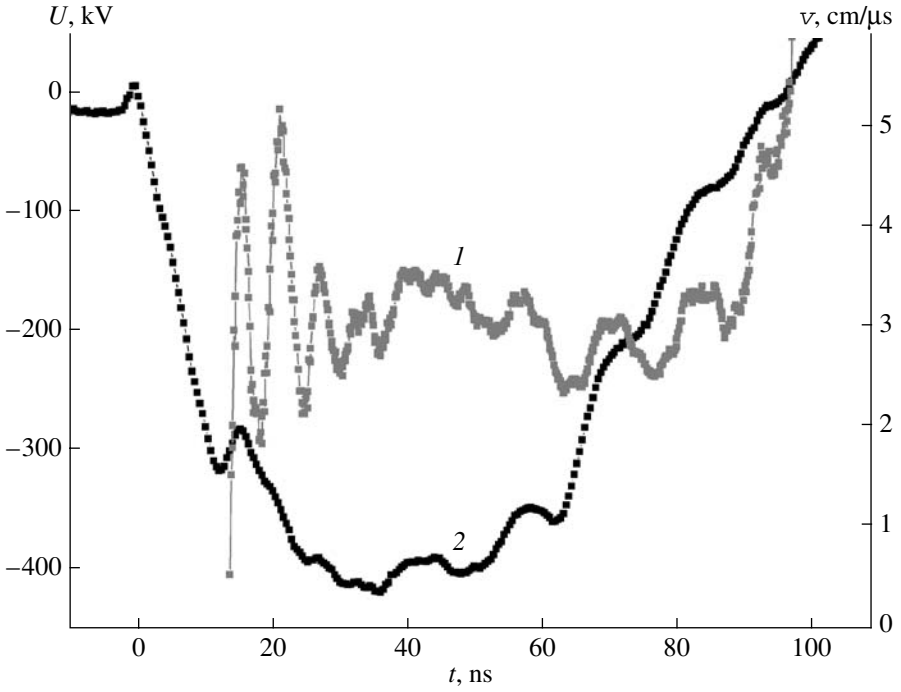

Fig. 10. (*1*) Time-dependent expansion velocity of EE plasma in a diode with a multispike cathode calculated from formula (2) at anode–cathode gaps of 11–14 mm. Curve *2* is the applied voltage.

nations of the EE cathode on the diode operation during generation of a high-current pulsed electron beam. The additional current caused by anode-plasma electrons is detected only at the end of a pulse when the collector of a Faraday cup serves as the anode.

CONCLUSIONS

Studies of the cathode-plasma expansion velocity in planar diodes with EE cathodes manufactured from different materials have shown that the plasma velocity is constant for 70–90 ns after the voltage application for different cathodes and different anode–cathode gaps. The velocity is 2.0 ± 0.5 cm/μs for carbon-fabric cathodes of various diameters, 3.0 ± 0.5 cm/μs for a multispike tungsten cathode, and 4.0 ± 0.5 cm/μs for solid and multispike copper cathodes. The influence of the adsorbed gas and cathode-surface contaminations on the expansion velocity of EE plasma in a planar diode during generation of an electron beam (within 10–15 ns after application of a voltage) is negligible. When the collector of a Faraday cup is used as the anode of the planar diode, the plasma expansion velocity begins to increase 65–70 ns after a voltage is applied, this velocity change being the same at different initial anode–cathode gaps. This effect is due to an additional current of anode-plasma electrons.

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