Low-energy ions source of plane geometry on the basis of plasma-beam discharge with a slot cathode

N A Ashurbekov, K O Iminov, G S Shakhsinov and A R Ramazanov
Dagestan State University, 43a M. Gadjiev Str., Makhachkala, 367002, Russia

E-mail: nashurb@mail.ru

Abstract. In this paper, we present the results of experimental studies of the process of "plasma sheet" creating based on a ribbon electron beam formed in a nanosecond discharge with a slot cathode. The slot cathode and the flat anode are made of aluminium and placed at a distance of 0.5 cm from each other. An emission window of 0.5×5 cm closed off with a fine-grained tungsten grid is made in the anode. The magnitude of the accelerating voltage varied within the range of 1-1.5 kV at gas (neon) pressures in the chamber of less than 0.5 Torr. The ribbon electron beam formed in such a system is transported and received with a collector placed at a distance of 3 cm from the locking anode. Concurrently, a plasma sheet with an area of 5×3 cm and a thickness of about 0.5 cm is formed. Experimental studies of the conditions for the plasma sheet formation were performed depending on the gas pressure, the amplitude of the accelerating voltage pulses at the anode and the voltage at the collector.

1. Introduction
The processes of controlled plasma deposition and plasma treatment for etching the surfaces of micro- and nanoelectronics materials afford exceptionally wide possibilities for practical application [1, 2]. These technologies are based on the use of reaction products formed as a result of degradation of the molecules and atoms of working gas under the action of ionization. Gas degradation products either react with each other depositing on the substrate surface in the form of a new compound or react with the substrate material forming volatile compounds. Therefore, it is necessary to identify plasma sources for the generation of energetically and chemically active particles that meet certain requirements. First and foremost, attempts should be made to ensure that the forming particles have definite energies and are distributed uniformly across defined areas using adequately powered plasma sources. In this regard, plasma sources that exploit the plasma cathode principle appear to be highly promising [3, 4]. These systems can be used to obtain ribbon electron beams within a range of operating gas pressures from pre-vacuum to several Torr. One such type of ribbon electron beam source consists in the pulsed nanosecond transverse discharge with an extended slot cathode [5, 6]. The use of ribbon electron beams allows the creation of plasma-beam discharges with an area of tens of square centimeters, which can be further used as extended sources of energetically- and chemically-active particles, e.g., for atomic layer etching technologies [7]. In terms of surface etching, the main advantages of this method (compared to liquid technologies) involve its anisotropy and formation of gaseous reaction products, which can be easily removed from the reaction volume. These considerations demonstrate the relevance of extended research into the characteristics and properties
of beam plasma discharges (BPD) with a slot cathode in inert gases in order to enhance the efficiency of ribbon electron beam generation.

This paper presents the results of a study carried out to investigate the electrical and optical characteristics of a nanosecond beam plasma discharge with a slot cathode in neon, along with an evaluation of the energies of accelerated electrons during the discharge. In addition, preliminary experimental results are presented, which prove the feasibility of forming a plasma sheet using a ribbon electron beam plasma source generated in the process of electrical gas breakdown in a nanosecond discharge with an extended slot cathode.

2. Experimental methods and technique
In the search for effective gas-discharge systems, in which electron beams are generated directly in a gas medium during electrical breakdown, the choice of the electrode profile and the construction of the gas-discharge chamber is of particular significance. For these purposes, most high-current electronics devices use the pulsed nanosecond gas discharge, which provides the possibility of attaining higher overvoltage values in the gas gap. Under such conditions, electrons can transit into the mode of continuous acceleration [8-10]. Another advantage of the pulsed nanosecond excitation of gas is the possibility of increasing the gas pressure of the working medium while maintaining the uniformity and volume of the discharge. The electrode system was designed taking into account the possibilities of generating a ribbon electron beam in the process of electrical gas breakdown and making use of the hollow cathode effect. Hollow cathodes are known to provide higher current densities in comparison with flat electrodes.

The experimental setup consisted of a high voltage nanosecond pulse generator (VPG), designed according to the Blumlein scheme; a synchronisation generator; a discharge chamber; the system of gas inlet, evacuation and pressure monitoring; the system for determining electrical and optical discharge characteristics. The details of this setup are given in [6]. The measurement of the discharge current and voltage across the discharge gap was performed using an ohmic shunt and a calibrated voltage divider. As recording devices, a two-channel analogue-to-digital converter (ASK-3151) connected to a PC and a Tektronix TDS 3032B oscilloscope were used. The spatial structure of the optical radiation of the discharge was investigated using a LTV-CMH-400 CCD camera.

The discharge chamber was a quartz tube with a diameter of 5 cm, in which two 5 cm long aluminum electrodes located at a distance of 0.6 cm from each other were placed. The cathode consisted in a cylindrical rod with a length of 5 cm and a diameter of 1.2 cm, along which a rectangular cavity with a width of 0.2 cm and a depth of 0.6 cm had been cut. The anode was a flat plate 5 cm long, 2 cm wide and 0.5 cm thick [6]. The design of the discharge chamber allowed the observation of the discharge structure and recording of the spatial distribution of optical radiation both across the discharge gap and in the cathode cavity. The system was vacuumed using a TSM 3A 1001 vacuum station designed on the basis of a turbo molecular pump.

3. Results and discussions
Measurements of the electrokinetic and optical characteristics were performed, along with examination of the spatial structure of a nanosecond discharge with an extended slot cathode in neon under gas pressures \( p \) and applied voltage values \( U_0 \) within a range of 0.1-20 Torr and 0.1-5 kV, respectively.

Figure 1 shows the typical oscillograms and optical images of the discharge in neon. At high values of the applied voltage, the electrical gas breakdown occurs at the leading edge of the voltage pulse, thus making discharge proceed in an overvoltage gap. In this case, the length of the leading edge is approximately 100 ns. An increase in the burning voltage \( U_{br} \) from 1200 to 4500 V leads to an increase in the discharge current values \( I_{br} \) from several dozen to 500 A, whereas the current pulse duration gradually decreases reaching \( I_{br} = 500 \) at 30 ns. Under a gradual increase in the values \( U_{br} \), a second current peak appears on the oscillogram of the discharge current, with its amplitude reaching approximately 30\% of the value of the first main maximum (figure 1a).
Our analysis of the characteristic images of the spatial optical radiation distribution in the discharge gap and in the cathode cavity have shown that, for small values of $U_{br}$, a first faint discharge glow – diffuse in nature – appears at the outer cathode surface and occupies its cavity up to the middle. Under an increase in $U_{br}$, optical radiation gradually fills the whole gap between the cathode and the anode, with the maximal radiation intensity being observed in the cathode cavity (figure 1b). If $U_{br}$ is raised even higher, a bright-luminous plasma column extending around the discharge centre reaches the anode, making the radiation from the gap become more intense than that from the cathode cavity.

The concentration of free electrons in the discharge was estimated according to the plasma conductivity. The mobility of ions is known to be hundred times lower than that of electrons; therefore, the ion contribution to the electric current can be neglected. Taking this into account, the density of the discharge current can be calculated as follows:

$$j = en_e v_{dr},$$  \hspace{1cm} (1)

Where $e$ is the electron charge, $n_e$ is the concentration of free electrons, $v_{dr}$ is the drift velocity of electrons. The current density $j_0 = I/S$ was calculated from the experimental values of the current intensity $I$ and the cross-sectional area of the discharge $S$. The electron drift velocity was determined from the graphs on the basis of the reduced electric field strength $E/N$, where $N$ is the concentration of gas atoms [11]. The values of the main discharge parameters are given in table 1.

| $U_{br}$, V | $U_0$, V | $j$, A/cm$^2$ | $E/N$, Td | $n_e$, $10^{12}$ cm$^{-3}$ |
|-------------|-----------|---------------|------------|-----------------|
| 700         | 700       | 6.33          | 354        | 2               |
| 1500        | 1020      | 86.67         | 515        | 18              |
| 2000        | 1500      | 129.93        | 758        | 21              |

It can be seen from Table 1 that the values of current density, reduced electric field and electron concentration are high compared to an equivalent abnormal glow discharge [12].
The transverse nanosecond discharge with a slot cathode is a pulsed self-sustained volume discharge at medium working gas pressures, which generates ribbon electron beams under certain conditions. Since the transverse nanosecond PBD with a slot cathode is a specific form of electric discharge, it is of interest to verify whether the known similarity relations hold for this discharge.

Provided its internal physical consistency, a theoretical model of the near-cathode region of the glow discharge, in which the drift approximation for describing the motion of charged particles and the local Townsend ionization coefficient are used, gives a good theoretical description of the normal glow discharge [13, 14]. The drift model allows the calculation of the burning voltage, current density and cathode layer length for a normal glow discharge. The use of this theory for the calculation of the anomalous glow discharge parameters shows that, while the width of the cathode layer decreases, the respective voltage drop increases. Under a strongly anomalous regime that takes place in our case, the drift approximation becomes unacceptable. Therefore, the gas ionization should be calculated taking into account the nonlocal distribution function and an additional mechanism for shock gas ionization. On this basis, when analyzing a discharge with a complex cathode geometry, only main parameters can be estimated.

A similarity parameter that is important and easy to determine during experiments is the dependence \( J/p^2 = f(E/p) \). In order to examine whether this similarity law is fulfilled, a series of experiments was performed in neon within a range of gas pressures from 0.1 to 20 Torr and applied voltages from 0.5 to 2 kV. The data obtained are summarized and presented in figure 2.

![Figure 2. Dependence of the reduced maximum current discharge density \( J/p^2 \) in neon on the parameter \( E/p \).](image)

The approximation of the experimental results provided in figure 1 gives the following dependence

\[
\frac{L}{p^2} = 6 \cdot 10^{-7} (E/p)^{2.4}
\]  

(2)

The formula (2) works well in the given range of discharge conditions, which confirms that the similarity relation \( J/p^2 = f(E/p) \) is fulfilled for the discharge under investigation.

Another important similarity parameter is \( pd_c \), where \( d \) is the length of the cathode potential drop (CPD) and \( p \) is the gas pressure. Under the conditions of our experiments, as well as under the conditions of anomalous glow discharges, the product of \( pd_c \) tends to the value \( pd_c = 0.37pd_{cn} \), where \( pd_{cn} = 0.7 \) Torr·cm is the similarity parameter of the cathode layer for a normal glow discharge in neon [14]. Therefore, for a plasma source with a slot cathode \( pd_c < 0.26 \) Torr·cm. The obtained dependence is
also confirmed by high current densities in a beam plasma discharge with a slot cathode. Due to the oscillations of electrons in the cathode cavity, additional ionization arises that leads to the formation of a dense cathode plasma in the cathode cavity, which subsequently plays the role of a plasma cathode. High electron emission from the plasma cathode leads to current densities exceeding those for an equivalent abnormal glow discharge by several orders. Therefore, the length of the cathode potential drop $d_c$ in the PBD under investigation can be much smaller than that in an abnormal glow discharge, and the cathode layer is a source of accelerated electrons.

It has been shown in [6] that, under conditions similar to our experiments, the spatial charge of ions rapidly shields the outer field across the largest part of the discharge gap in the initial phase of the discharge, leading to the formation of a cathode layer. As a result, a CPD region with a length of $d_c$ is rapidly formed – a region where electrons are accelerated.

In the discharge with a slot cathode, when the value $d_c$ is small, as in the case of the abnormal glow discharge, about 60% of the applied voltage falls on the cathode layer.

$$U_c \approx 3E_0d_c/5 \quad (3)$$

In order to evaluate $U_c$ using the formula (3), the value $E_0d_c$ can be taken equal to that of the burning voltage.

The estimations of the mean free paths of electrons in terms of inelastic processes in neon give the following values: $\lambda = 1(N\sigma) = 0.4$ cm under $p=1$ Torr, where $\sigma(\epsilon) = 8 \times 10^{-17}$ cm$^2$ is the maximum value of ionization cross section [15]. The obtained estimations show that $\lambda > d_c$; therefore, electrons emitted from the plasma cathode pass through the CPD area without collisions acquiring the energy $\epsilon = eU_c$. The energies that electrons acquire when passing through the CPD under different values of applied voltage are presented in table 2. Let us evaluate the mean free paths of electrons accelerated in plasma using the formula

$$\Lambda = \frac{\epsilon\lambda}{\epsilon_i}$$

where $\epsilon$ is the energy of accelerated electrons, $\epsilon_i = 37$ eV is the energy of formation of an ion pair in neon. These values are also given in table 2. It should be noted that the relaxation of accelerated electrons in terms of impulse was not taken into account, since at $\epsilon > 75$ eV the electron distribution is strongly anisotropic, practically hindering their relaxation by direction [16].

| $U_{br}$, V | $\lambda$, cm | $d_c$, cm | $\epsilon$, eV | $\Lambda$, cm |
|------------|--------------|---------|-------------|------------|
| 1350       | 810          | 9       |
| 1700       | 0.4          | 0.26    | 1020        | 11         |
| 3000       | 1800         | 19      |
| 3250       | 1950         | 21      |

For a stable and efficient operation of accelerated electron plasma sources, high values of the electric field and the potential drop near the cathode should be ensured, along with the conditions for maintaining the discharge stability with regard to spark formation and contraction. The electrode system made of a slot cathode and a plane-parallel anode makes it possible to obtain the volumetric form of a dense glow discharge under the values of working gas pressure and applied voltage varying from tenths to 100 Torr and from 0.1 to 5 kV, respectively. High reduced field values in the discharge (table 1) ensure the fulfilment of the criterion of continuous electron acceleration at working gas pressures in the chamber of up to 10 Torr [17].

In order to generate ribbon electron beams behind the anode, a plasma electron source based on a discharge with a slot cathode and a mesh anode was used. Figure 3 provides a schematic representation of the electrode system of such an electron source. In the flat anode, an emission window with a size of 0.5×5 cm covered with a fine-structure tungsten mesh had been made.
The size of the unit grid cell was 0.5×0.5 mm, with its geometric transparency of 70%. The extraction of electrons from the discharge plasma and the formation of a ribbon electron beam with an initial rectangular cross section of 0.5×5 cm were accomplished by applying accelerating voltage between the anode and the extractor $U_a$ (figure 3). The resulting ribbon electron beam was transported and received by the collector located 3 cm from the blocking anode. Eventually, a plasma sheet with an area of 5×3 cm and a thickness of 0.5 cm was formed.

Preliminary studies of the effect of accelerating voltage and gas pressure on the dimensions and uniformity of the as-formed plasma sheet were carried out. Figure 4 presents the optical images of the plasma sheet at the accelerating voltage and gas pressure (neon) in the chamber of 1.5 kV and 0.5 Torr, respectively. According to the optical images, the radiation is uniformly distributed across the entire surface of the sheet, which indicates the uniform distribution of charged and excited particles.

For examination of the spatial structure of the discharge using diaphragms, the optical discharge radiation was measured in the cathode cavity, at the exit of the accelerating anode and at various points of the plasma sheet surface, with the collected data being subsequently sent to the PMT input window. The values of the optical radiation intensity measured at various points of the plasma sheet surface were shown to be identical. These measurements show that the length of the optical radiation impulse at the half-height is approximately 70 ns. For our experimental conditions, the estimation of the mean free paths of accelerated electrons in the cathode layer gives an approximate value of 20 cm, thus indicating the possibility for the plasma sheet area to be further expanded.
4. Conclusion
Therefore, our results show that, for a nanosecond discharge with a slot cathode in neon, the similarity ratio $J/p^2 = f(E/p)$, is fulfilled within a wide range of $U_{br}$ and $p$ values. The approximating formula (2) has been obtained for this relation. The values of the main discharge parameters ($j$, $E/N$, $n_e$) have been obtained, along with the energies of accelerated electrons. Under certain conditions, the discharge under investigation becomes a plasma source of accelerated electrons, generating ribbon electron beams with an electron energy of about 1 keV. Preliminary experimental results presented in this paper show the feasibility of forming a plasma sheet using a plasma source of ribbon electron beams on the basis of a nanosecond discharge with an extended slot cathode.

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