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INFLUENCE OF THE ANODE OF A NON-SELF-SUSTAINED GLOW DISCHARGE WITH A HOLLOW CATHODE ON THE SPATIAL DISTRIBUTION OF PLASMA CONCENTRATION

V. V. Denisov, N. N. Koval, Yu. A. Denisova, I. V. Lopatin, and E. V. Ostroverkhov

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The results of investigation of the influence of geometrical dimensions, shape and position of the anode of a high-current non-self-sustained glow discharge with a hollow cathode at low (≈1 Pa) pressure with the current up to 100 A on the degree of inhomogeneity of azimuthal plasma-concentration distributions are presented. The azimuthal measurements demonstrate that upon injection of an electron flow with the current exceeding that of the electrons, formed as a result of the secondary ion-electron emission, the value of the average path length L of electrons before their escape to the anode is much lower than that in a self-sustained discharge burning mode. It is determined that in the case of injection of an electron flow into the hollow-cathode glow discharge the anode position considerably affects the degree of plasma concentration inhomogeneity. It is shown that placing the annular anode in the site preventing the line-of-site between the electron injection and anode surface directions allows achieving the minimum inhomogeneity coefficient value.

Keywords: hollow-cathode glow discharge, discharge anode, plasma concentration distribution, inhomogeneity coefficient, electron flow.

INTRODUCTION

Thermo-chemical treatment, which allows saturating the surface layers of machine parts and mechanisms with the atoms of such elements as nitrogen (nitriding), carbon (carbonization), and boron (boriding) is one of the principal methods for industrial surface hardening [1]. Nitriding of steels in a low-pressure (≈1 Pa) discharge plasma is less time-consuming than that in a glow discharge plasma at the pressures within 100–1000 Pa [2]. Despite this advantage, low-pressure arc discharges [3, 4] have not been widely introduced into industrial practices. The major reason is a relatively high cost of ensuring a homogeneous plasma concentration distribution in large (>0.1 m^3) vacuum volumes. A hollow-cathode glow discharge in its self-sustained burning mode makes it possible to form homogeneous plasma in the chamber, whose internal walls represent a cathode, at the lower threshold gas pressure in the cathode plane on the order of about 10^{-2} Pa [5]. In a non-self-sustained mode, a hollow-cathode glow discharge, sustained by an external injection of electrons, is stably ignited and burns at the working pressures up to $5\cdot10^{-3}$ Pa [6]. By changing the current of the electrons injected into the hollow cathode, accelerated in the near-cathode potential drop and oscillating in the discharge volume until the moment of their thermalization or escape to the anode, it is possible to independently adjust the major working parameters – glow discharge working pressure, burning voltage, and current, as well as to considerably (by two orders of magnitude) increase the glow discharge current and hence plasma concentration. For instance, the authors of [7] reported a glow discharge current of about 370 A at the injected electron current about 50 A, and the value of the nitrogen plasma concentration was found to be about 10^{12} cm^{-3} at the working pressure 1 Pa. The injection of electrons

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Institute of High Current Electronics of the Siberian Branch of the Russian Academy of Sciences, Tomsk, Russia, e-mail: volodyadenisov@yandex.ru; koval@hcei.tsc.ru; yudenisova81@yandex.ru; lopatin@opee.hcei.tsc.ru; evgeniy86evgeniy@mail.ru. Translated from Izvestiya Vysshikh Uchebnykh Zavedenii, Fizika, No. 7, pp. 47–52, July, 2019. Original article submitted June 14, 2019.

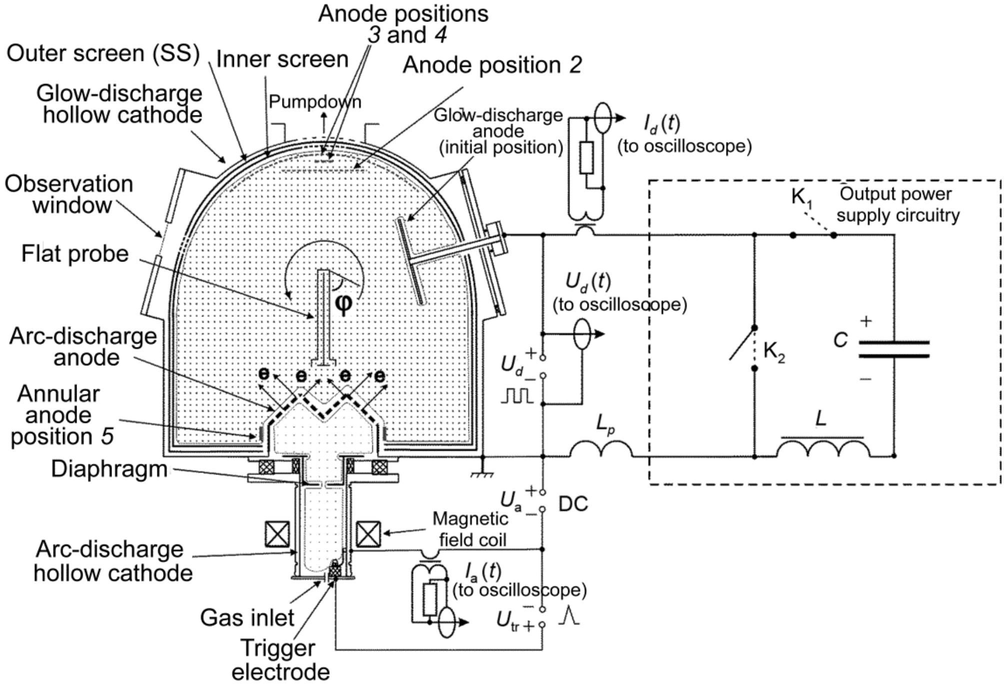

Fig. 1. Schematics of the experimental bench (top view of the chamber).

into the hollow cathode generates a considerable plasma-concentration gradient, caused by an elevated probability of gas ionization by a scattered electron beam near the output aperture of the electron source. This problem is partially solved via the use of a special shape of the emission electrode, deflecting the electron injection direction [8]. The plasma concentration near the anode also decreases; the measurements with an azimuthal probe [9] have demonstrated that a decrease in the ion current density is found to be a few tens of percent and more compared to its average value. In other words, the anode location can affect the plasma parameters near the processed parts and, hence, influence the results of the ion-plasma treatment. Furthermore, as it was shown in [5] for a self-sustained glow discharge, wherein the discharge was sustained by the ion-electron emission processes, in order to ensure a highly efficient hollow-cathode operation it is necessary to reduce the anode-to-cathode area ratio S_a/S_c. This decreases the probability of the escape of fast electrons to the anode, i.e., increases their average path length in the hollow cathode. This fact gives rise to improved plasma generation homogeneity. The purpose of this study is to determine the influence of such factors as the anode-to-hollow cathode area ratio, with the cathode placed behind the anode, and the shape of the latter on the distribution homogeneity of the plasma generated in a non-self-sustained glow discharge with the current approximately 100 A and plasma concentration about 10^{12} cm^{-3}.

EXPERIMENTAL SETUP

The experimental setup, using which the investigations were performed, was assembled on the basis of an NNV-6.6-I1 facility. The walls of a vacuum chamber with the dimensions 600×600×600 mm formed a hollow cathode of the principal (glow) discharge whose volume is 0.21 m^3 and total area $S_c \approx 1.8$ m^2 (Fig. 1). The chamber was pumped down with a TMN-500 turbo-molecular pump to the ultimate pressure $5 \cdot 10^{-3}$ Pa, and the working pressure was varied within the range 0.4–1.2 Pa during the regulated inlet of the working gas – extra pure nitrogen.

A non-self-sustained discharge was ignited between the glow-discharge hollow cathode represented by an inner stainless steel screen 1 mm in thickness and a flat anode introduced via the side flange of the chamber (initial experimental mode). To ensure a stable ignition of the glow discharge in a pulsed burning mode, the value of S_a in the experiments on the influence of the anode shape and location was taken to be 300 cm^2 and $S_a/S_c \approx 0.016$, which is approximately twice higher than the optimal ratio determined as $(2m_e / M)^{1/2}$, where m_e and M are the electron and ion masses, respectively.

The electrical power to the glow discharge was supplied from a pulsed voltage source ensuring an output voltage value U_d up to 300 V and a pulse current I_d up to 550 A at the maximum average output $I_{d\ \mathrm{av}}$ up to 120 A, a pulse repetition frequency f = 1–1000 Hz, and a pulse filling coefficient γ_i = 1–100%. The output circuit of the power supply contained two switches, S1 and S2, and an output inductance coil L in-series connected to the load, which formed an output LC-filter with the output capacitance bank C. The parasitic inductance L_p of the lead wires was up to 3 μH. When a DC voltage is supplied to the load, S1 is closed and S2 is open. In the pulsed burning mode S1 switches at the predetermined frequency f and pulse duration $t_\mathrm{p} = \gamma_i \cdot T = \gamma_i / f$. In the voltage interpulse time S1 is open and S2 is closed, connecting the anode and cathode of the glow discharge. The power supply makes it possible to prevent microarcing on the cathode surface. When the glow discharge current $I_d(t)$ changes, the signal from the Hall sensor is supplied to the oscilloscope, and the voltage $U_d(t)$ is measured by a 1:100 oscillographic probe between the anode and cathode of the glow discharge. To rule out plasma penetration into the vacuum system units, a fine-structure diaphragm was used.

Burning of a steady-state low-pressure glow discharge and its ignition in a pulsed mode were stabilized using an electron source based on an arc discharge with an integrally cold hollow cathode, which was detailed elsewhere [10]. Upon puffing nitrogen through the gas inlet and supplying a high-voltage pulse, an arc was initiated between the trigger electrode and the hollow cylindrical cathode by a discharge across the dielectric surface. The cathode spot was displaced across the inner surface of the cylindrical hollow cathode in the maximum of the tangential component of the magnetic field generated by the coil. An auxiliary discharge was burning in a steady-state mode through the hole in the diaphragm that, being under the floating potential, prevented the cathode spot from moving to the plasma-generator butt end and the arc from transferring from the diffuse-burning mode in the anode region into a constriction mode followed by the formation of an anode spot on the closely-lying area of the anode. The anode of the auxiliary arc discharge, being under the potential of the glow-discharge hollow cathode, represented a truncated cone with a convex central part, whose conical and central parts were covered with a fine-structure mesh. On the upper base of the truncated cone, the mesh represented an in-bent cone with an apex angle close to 90°. The mesh had a geometrical transparency of 45% (mesh cell size – 0.4×0.4 mm). This conical shape was used to deflect the injection directions of the electrons emitted into the main discharge from the axis of the electron source and due to this to improve the parameter distribution homogeneity of the plasma generated by the glow discharge in the hollow cathode.

The arc-discharge electron source with the integrally cold hollow cathode was fed from a stabilized-current source. The induction B of the magnetic field on the electron source axis, generated by a magnetic coil, in all major experimental modes was B = 3.8 mT.

In order to determine the influence of the anode-to-cathode area ratio $S_\mathrm{a}/S_\mathrm{c}$ on the azimuthal distribution of the ion current density from the plasma, three anode area values were used – 200, 300 and 600 cm^2. The investigation of the role of the anode location of a non-self-sustained hollow-cathode glow discharge with respect to the electron injection center on the inhomogeneity degree of the azimuthal distribution of the ion current density from the plasma were performed for several anode locations (Fig. 1). The initial anode position, with which the comparison was performed, was identified based on the data reported in [7–9]. Other anode positions were selected based on the conditions of a lower probability of the electron incidence on the anode compared to the initial position. Given this shape of the emission mesh electrode, the anode location into which the injected electrons cannot get without any intermediate interaction with the plasma particles or the hollow cathode walls in the case of acceleration along the normal to the emission mesh surface, is the anode position in a point lying on the electron source axis near the wall of the cathode plane (anode positions *2–4*). The longest path of the injected electrons to the anode would be attained in the case where the anode is located in the region of the geometrical shadow with respect to the initial electron flow. This is anode position *5* (Fig. 1). In order to determine the influence of the emission electrode shape, we used a flat anode, whose shape approximated a square, and an elongated anode in vertical and horizontal positions. In position *5* the anode represented a cylinder 300 mm in diameter and 16 mm in height.

In order to determine the plasma parameter distribution homogeneity in the chamber volume we measured the azimuthal distribution of the ion current density from the plasma. The character of the azimuthal distribution of the ion current density was determined using a flat probe 5.5 mm in diameter with a guard ring, which is under the potential of

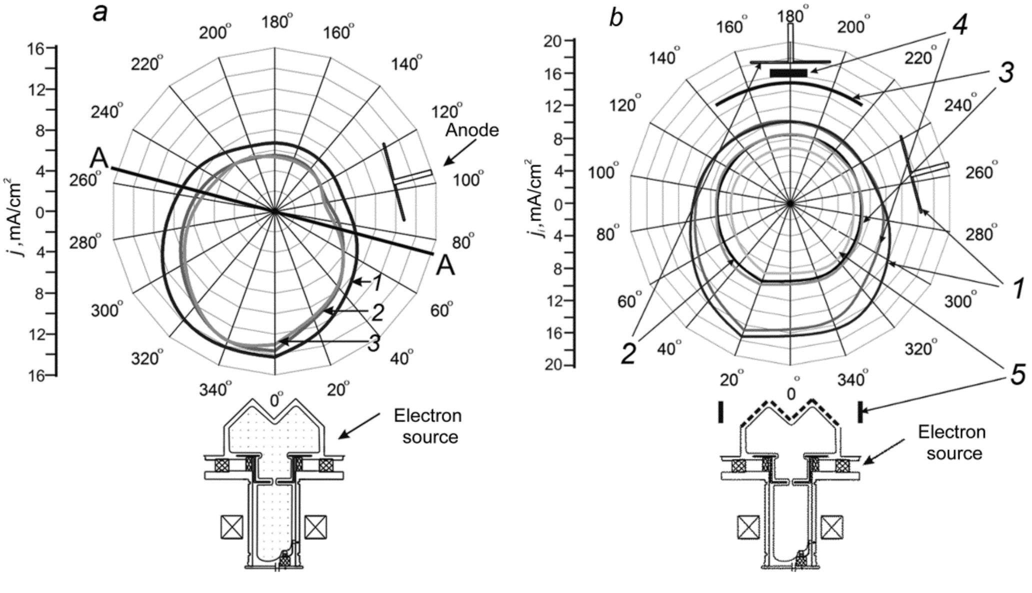

Fig. 2. Azimuthal distributions of the ion current density to the probe at: $p(N_2)$ = 0.65 Pa, U_d = 180 V, I_d = 90 A: *1* – S_a = 200 cm^2, *2* – S_a = 300 cm^2, *3* – S_a = 600 cm^2 (*a*) and at the distance 300 mm from the base of the stainless steel hollow cathode at: $p(N_2)$ = 0.65 Pa, I_d = 100 A, U_d = 180 V (*b*).

the glow-discharge hollow cathode. During the measurement of the azimuthal distribution of the ion current density the probe was rotated around the center of the chamber at a distance of 18 cm from its axis. The probe was fixed in the flange with a rotation vacuum feed-through placed on the chamber bottom. An inhomogeneity coefficient value was introduced, which characterizes the inhomogeneity degree of the azimuthal ion-current density distribution and is equal to the ratio of the maximum deviation of the density of the saturation ion current from the plasma to the average ion current density, i.e., $k_i = | j_{i\,\max} - j_{i\,\mathrm{av}}|\cdot 100\% / j_{i\,\mathrm{av}}$, where $| j_{i\,\max} - j_{i\,\mathrm{av}}|$ – the maximum deviation of the density of the saturation ion current from plasma from the average value, and $j_{i\,\mathrm{av}}$ – the average ion current density. The number of angular positions in the course of the azimuthal probe rotation from 0 to 360° was 18. Knowing the coefficient k_i allows evaluating a possible deviation of the modified layer thickness from its average value during processing of a large-size part in the glow discharge plasma.

The measurement of the azimuthal distributions was performed in a quasi-steady-state discharge burning mode at the third millisecond of the discharge pulse at the pulse repetition frequency 40 Hz and fixed values of the glow discharge burning voltage (180 V), glow discharge current (100 A), and nitrogen working pressure 0.65 Pa.

EXPERIMENTAL RESULTS AND DISCUSSION

In these investigations we evaluated how the azimuthal distribution was affected by such factor as the anode-to-cathode area ratio S_a/S_c. To this end the measurements were performed of the azimuthal distributions of the saturation ion current density to the probe and their inhomogeneity coefficients for the following anode areas: S_a = 200 cm^2 (k_i = 48%), S_a = 300 cm^2 (k_i = 54%) and S_a = 600 cm^2 (k_i = 54%), which are presented in Fig. 2*a*.

For the case of the minimum anode area (S_a = 200 cm^2), whose value is close to the optimal one ($2m_e / M^{1/2}$) according to [5], one can note a slight (a few percent) improvement of the distribution homogeneity of the saturation ion current density compared to the two large-area anodes. However, for the case of S_a = 200 cm^2 periodic failures of triggering the discharge pulses were observed, so the subsequent experiments were performed for the anode area 300 cm^2.

TABLE 1. Parameters of Azimuthal Distribution of Ion Current Density for Different Shapes and Locations of Anode with Respect to the Electron Injection Center

Anode position, shape and size	Average ion current density to probe $j_{i\,\mathrm{av}}$, mA/cm^2	Maximum deviation from average value ($\lvert j_{i\,\max}\rvert - j_{i\,\mathrm{av}}$), mA/cm^2	Inhomogeneity coefficient k_i, %
Initial position, flat anode 140×110 mm	12.8	2.5	37
Position *2*, flat anode 140×110 mm	9.3	1.6	17
Position *3*, elongated anode 470×32 mm, horizontal location	10.6	1.5	15
Position *4*, elongated anode 470×32 mm, vertical location	12.3	2.3	35
Position *5*, annular anode L300 mm × W16 mm, in geometrical shadow	8	1	12

The azimuthal distributions for different anode positions (Fig. 2*b*) demonstrate that the anode location considerably affects the degree of plasma concentration inhomogeneity. A lateral position (with respect to the injected electron flow) of the anode gives rise to the maximum inhomogeneity 37% (Table 1). Its location on the electron source axis on the wall, opposite to the electron injection center (Position *2*), allows reducing the plasma concentration inhomogeneity coefficient to 17%.

The use of a flat elongated anode of the same area placed vertically (Position *3*) makes it possibly to somewhat reduce the degree of plasma concentration inhomogeneity compared to that for the anode shapes *1* and *2*; and the vertical placement of the elongated anode (Position *4*) gives an azimuthal distribution form close to the initial one and with the same inhomogeneity coefficient. Since the injected electron current by about an order of magnitude exceeds that of the electrons formed due to the secondary ion-electron emission processes [7], it is the direction of electron motion which exerts the major influence on the degree of plasma concentration inhomogeneity in a hollow cathode. A considerable (more than twofold) difference in the degree of inhomogeneity for the anode positions *3* and *4* can be accounted for by the chamber unsymmetry along the electron source axis, i.e., by the influence of the hollow cathode geometry on the injected electron flow. It is likely that for the anode position *4* the number of the injected electrons, which have not spent their energy before their departure to the anode, is much larger than that for the anode position *3*.

By placing an annular anode in the site ruling out the line-of-sight between the direction of the electron injection and the anode surface (Position *5*) we managed to achieve the minimum inhomogeneity coefficient (12%). It is in this case that the maximum electron path *L* seems to be achieved before the electrons escape to the anode or thermalize, which favors a distribution with the minimum inhomogeneity.

In the case of a self-sustained hollow-cathode glow discharge, where the burning is ensured by the secondary ion-electron emission of electrons from the hollow cathode walls, the electron current density over the entire area of the hollow cathode is approximately equal. Due to acceleration in the near-cathode space and multiple oscillations, the plasma in the hollow cathode becomes comparatively isotropic. For the sake of calculations of the average path *L* of an electron before its escape to the anode, it was assumed in [5] that the formation of the first electron as a result of the secondary ion-electron emission is equally probable over the entire hollow cathode, in other words, there is no high-density electron flow and it is not probable that a large number of electrons would lose their energy on the anode. In this case the average electron path *L* would be equal to $4V/S_\mathrm{a}$, where V is the hollow cathode volume and S_a is the anode area. According to this expression, for the experimental conditions used in this study, the hollow cathode volume 0.21 m^3, and the anode area 300 cm^2, the average path *L* of the primary electron motion would be 28 m. The electron relaxation path Λ, on which they are supposed to spend their energy on ionization, is estimated from the expression $\Lambda = (eU_c/E_i)\lambda$, where e is the electron charge, U_c is the near-cathode potential drop, E_i is the ionization potential, and λ is the electron free path. For the nitrogen working pressure 0.65 Pa and the near-cathode potential drop 180 V, the electron relaxation path is about 3m, which is approximately an order of magnitude shorter than the average mean electron path. This suggests that the injected electrons accelerated in the near-cathode potential drop would manage to relax. On the other hand, a differing character of azimuthal distributions for different anode positions indicates different values of the average mean paths. The reason for this is the following: since the electron current density from the emission electrode surface by a few factors exceeds that of the current of electrons formed as a result of the secondary ion-electron emission, a considerable role in the discharge burning process now belongs to the probability of closing the electron flow on the anode. The expression used for evaluating L is not in this case quite correct, and the real value of L is very likely much lower.

From the data obtained a conclusion can be drawn that the most important factor in ensuring the lowest inhomogeneity degree is the geometrical factor, in other words, the shape of the glow-discharge hollow cathode and the geometry of the glow-discharge anode and its location with respect to the electron injection center. An optimal location of the latter is in the region of the geometrical shadow for the trajectories of the primary electrons injected from the auxiliary discharge plasma.

SUMMARY

As a result of the investigations of the influence of the geometrical dimensions, shapes and positions of the anode of a high-current (up to 100 A) hollow-cathode glow discharge at a low (≈1 Pa) pressure sustained by an external injection of electrons the following conclusions can be made:

1. Upon injection of an electron flow with the current by a few factors exceeding that of electrons formed via the secondary ion-electron emission, the real value of the average path length L of electrons before their departure to the anode is much lower than that estimated from the expression $4V/S_a$, obtained for the case where the production of primary electrons as a result of the secondary ion-electron emission is equally probable over the entire hollow cathode area. The reason for this is a high probability for the electrons that have not spent their energy on plasma generation to hit the anode.

2. Upon injection of an electron flow into a hollow-cathode glow discharge, the anode location considerably affects the degree of plasma concentration inhomogeneity. A lateral, with respect to the injected electron flow, position of the anode leads to the maximum inhomogeneity degree; it is due to the departure of part of the non-relaxed electron flow to the anode. By locating the anode on the electron source axis, on the wall opposite relative to the electron injection center, we can reduce the plasma concentration inhomogeneity coefficient by a factor of 2. Placing an annular anode in the point ruling out the line-of-sight between the electron injection direction and the anode surface we can reach the minimum value of the inhomogeneity coefficient, which is likely to be due to the maximum path length value L of the electrons before their departure to the anode.

3. In a pulsed non-self-sustained hollow-cathode glow discharge, a two-threefold increase in the anode area, compared to the value close to the optimum area ($2m_e/M^{1/2}$), results in an increase of the inhomogeneity coefficient of a few percent only, while this leads to a more stable discharge triggering and burning.

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