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ABNORMAL GLOW DISCHARGE IN A LONG COAXIAL SYSTEM OF ELECTRODES IN THE MAGNETIC FIELD OF THE INTERNAL ANODE

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A numerical simulation of the influence of the azimuthal magnetic field formed by the passage of current along the internal anode in a coaxial system of electrodes on the characteristics of an abnormal glow discharge in nitrogen was carried out. A strong influence of magnetic blowing on the redistribution of the discharge current density along the electrodes was revealed. A discharge with such an effect can be used for ion treatment of the internal surfaces of long metal pipes of small diameter and in various physical devices including sensor technics and MEMS.

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INTRODUCTION

Surface modification of metals using low-pressure plasma discharges is widely used in industry to strengthen the surface and apply protective or dielectric layers. An example is ion nitriding using a glow discharge for thermal diffusion saturation of the surface with nitrogen in its medium [1]. An abnormal form of glow discharge (AGD) is often used, since it provides sufficient ion current density on the cathode surface for processing [2]. Magnetic scanning of the discharge ("magnetic blowing") can be used to improve the homogeneity of surface processing and to prevent arc breakdowns on it [3]. Since AGD plasma in magnetic field (MF) is very sensitive to various factors, it may be used in sensor technics that makes AGD atractive for study from such point of view.

The literature describes many examples of AGD in different electrode systems, but there is a few information on the characteristics of the AGD supported within tubular metal parts with a diameter of $D \sim 0.5…2.0$ cm and less, its length $L >> D$ at gas pressure p of the order of 0.1…0.5 kPa [4]. Although ion treatments under such conditions are extremely necessary in the production of parts for mechanical engineering, medical applications, sensorics and so on. The simplest way to create a uniform AGD inside tubes under the specified conditions are coaxial electrode systems with an internal anode. It is impossible to use the tubes as a hollow cathode with an external anode, since a uniform discharge is not created in such long cathode.

The effect of MF on glow discharges at the above-mentioned p was studied in plane-parallel electrode systems: in [5] for a MF parallel to the electric field, and in [6] for a transverse MF. In [7], the study was performed of the effect of an azimuthal MF on the behavior of a low-current normal glow discharge with localized plasma in a coaxial system. The MF was formed by passing current along the internal anode from an external source. In this case, the MF was crossed with an electric field, and the plasma region of the discharge was shifted under the action of the MF to one of the ends of the system. When an alternating current passed along the anode, the effect of localized plasma movement along the cathode from one end to the other was observed.

In this paper, the effect of the azimuthal MF formed by passing current along the internal anode in the coaxial system of electrodes with dimensions $L >> D$ on the high-current AGD in nitrogen is investigated. A numerical computer modeling method is chosen, since it allows one to study the main parameters of the discharge and the nature of its behavior under the influence of the very non-uniform azimuthal MF of the anode without performing a complex physical experiment.

1. OBJECT AND METHOD OF RESEARCH

To simulate the AGD in the coaxial system of electrodes, a device with a tubular cathode was used, it is shown in Fig. 1. The length of the electrode system L was 33 cm and 1 m, the anode diameter and the inner diameter of the cathode were 5 and 23 mm, respectively, i.e. the interelectrode radial distance d was 9 mm. The ends of the system were dielectric disks.

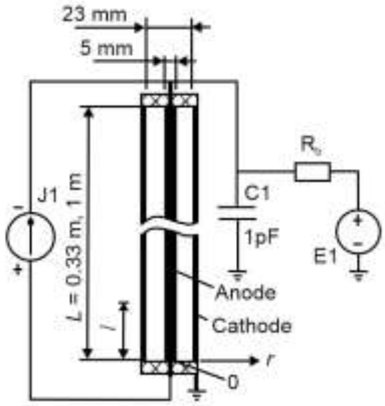

Fig. 1. Experimental device

E1 is a constant current source with a voltage of 350 V. The constant current source J1 was used to form the azimuthal MF. The capacitor C1 displays the total parasitic capacitance of the system and was used for a smoother voltage build-up on the discharge, which simplifies the calculation. The value of the discharge current (the operating point on the volt-ampere characteristic of the discharge) was set by the ballast resistor R1.

The working gas was nitrogen under pressure p = 133 Pa (1 Torr). The parameter *pd* was 1.2 Pa·m (0.9 Torr·cm), which corresponds to the minimum of the Paschen curve for nitrogen [2].

For the description of physical processes in the AGD at the above values of *pd*, the 3D hydrodynamic drift-diffusion model is well suited and, accordingly, we selected it, allowing us to obtain physically correct data with simpler mathematics compared to models using kinetic equations. This was convincingly shown in [6, 8] for a glow discharge with a transverse MF. The choice of the drift-diffusion model was also supported by the fact that there is a standard solver for such a model in the COMSOL environment, which is usually used to solve such a problem [9].

In the simulation, three reactions of interaction of electrons with N_2 molecules in a nitrogen medium were taken into account, as shown in Table 1: elastic collisions, excitation of a neutral molecule to a metastable state, and ionization of a neutral molecule (Δε is the loss of electron energy during interaction). Table 2 presents the reactions taken into account on the surfaces of solid state electrodes (SS): neutralization of N_2^+ ions and quenching of metastable N_2^* particles with the return of neutral N_2 molecules to the gas medium with according sticking coefficient S_C, as well secondary ion-electron emission of the cathode with the coefficient γ = 0.1. Coefficient S_C determines the degree of surface coverage with adsorbed nitrogen; for the cathode, S_C was chosen at the level of 0.1, since the cathode is bombarded with energetic ions that knock down the adsorbate. Low-energy ions hit the other surfaces, so S_C was chosen at the level of 1.0.

Table 1

Reactions in gas

Reaction	Type	Δε, eV
$e + N_2 \rightarrow e + N_2$	Elastic	0
$e + N_2 \rightarrow e + N_2^*$	Excitation	13.0
$e + N_2 \rightarrow 2e + N_2^+$	Ionization	15.6

Table 2

Reactions on surfaces

Reaction	Surface	S_c	γ
$N_2^+ + SS \rightarrow N_2 + e$	Cathode	0.1	0.1
$N_2^+ + SS \rightarrow N_2$	Anode, dielectric ends	1	0
$N_2^* + SS \rightarrow N_2$	All	1	0

Our 3D model was based on equations for the balance of charged and neutral particles, charged particle flows taking into account the electric field and MF, and boundary conditions that are standard for the drift-diffusion model of glow discharges with metallic and dielectric walls [2, 6, 8]. The coefficients and other parameters for the above-described model reactions, including those for the mobility and diffusion of particles within the medium with MF, were obtained from [2, 6, 8] and the COMSOL database [9].

To calculate the electric field, the Poisson equation was used taking into account the spatial charge of ions and electrons. To calculate the MF, the Maxwell equation for a stationary magnetic field was used, which was taken into account due to its effect on the mobility of electrons. When calculating MF, it was assumed that the magnetic field from the discharge current was very small, and it was not taken into account. In the initial conditions, the initial density of electrons in the interelectrode space was set at the level of $n_{e0} = 10^{13}$ m^{-3}.

2. RESULTS AND DISCUSSION

Fig. 2 shows the calculated MF induction distribution along the radius of the discharge gap for different values of the current passing along the anode. The left branch of the graphs shows the distribution of induction inside the anode, the right – in the interelectrode space. The maximum value of induction at an anode current of 170 A is 13.45 mT (134.5 G). It can be seen that the azimuthal MF of the anode is very inhomogeneous with a negative gradient along the radius.

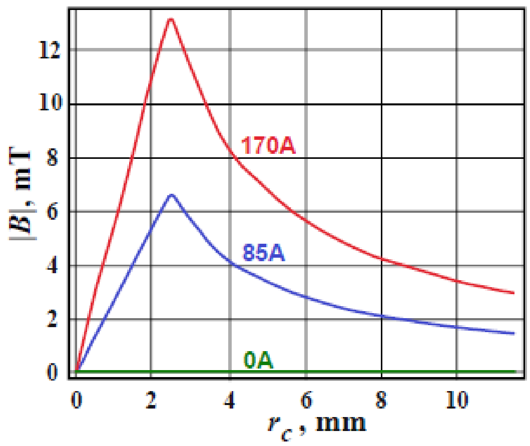

Fig. 2. Change of the induction of the azimuthal MF along the radius from the central axis at different currents along the anode

The simulation showed that the cathode surface is fully involved in the discharge without MF with a ballast resistance of less than 14 kΩ for a system with *L* = 33 cm. That is, in this case there was a transition from a normal to an abnormal glow discharge, which corresponds to a discharge current of 13.42 mA and its density of 56 μA/cm^2. In this regard, ballast resistance values of less than 14 kΩ were taken in the calculations.

Graphs in Fig. 3 show the distribution of the ion current density along the surface of the cathode at *L* = 33 cm.

In the absence of MF, the ion current density is distributed almost uniformly along the entire length of the cathode; This is typical for AGD [2].

In the presence of the azimuthal MF, the distribution becomes uneven with the formation of an “empty” interelectrode gap and the discharge zone, where ions are generated. An increase in the azimuthal magnetic field entails a displacement of the left edge of the discharge zone to the right end, i.e. in the direction of plasma particle drift in crossed fields [**EB**] (**E** and **B** are vectors of electric field strength and magnetic field induction) or according to the well-known Ampere law with a simultaneous increase in the ion current density. A nonlinear character of the influence of the azimuthal magnetic field on the distribution of the ion current on the cathode was revealed: with anode currents up to 85 A, the magnetic field impact is not very noticeable, especially at low ballast resistances.

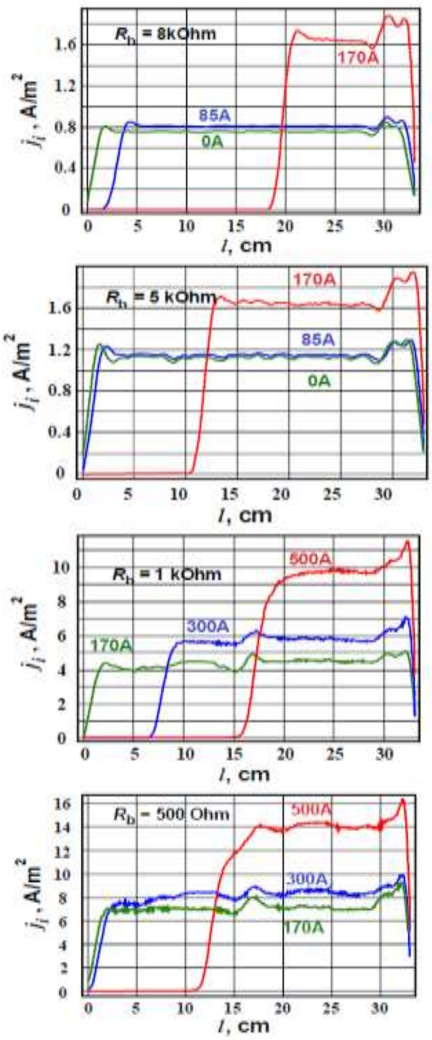

Fig. 3. Distribution of the ion current density along the cathode at L = 33 cm at different values of the ballast resistance

The graphs in Fig. 4 present the distribution of the ion current density along the cathode surface at L = 1 m. It is evident that the tendency of the AGD behavior has been preserved for this electrode length. However, in the latter case, when using the ballast resistance of 8 kΩ without MF, the distribution of the ion current density along the cathode surface is observed as in the normal glow discharge, i.e. with incomplete coverage of the cathode by the discharge plasma. Another difference in this case is that a strong shift of the left edge of the discharge zone already takes place at 85 A, which was not the case at L = 33 cm. Perhaps this follows from the fact that in the long system the ion current density on the cathode is less than in the short system, with the same values of the ballast resistance.

It is interesting to note two more features for both values of L: i) the distributions of the ion current density within the compressed plasma of the discharge zones is almost uniform along the cathode; ii) with a decrease in ballast resistance, the compression of the discharge zones decreases.

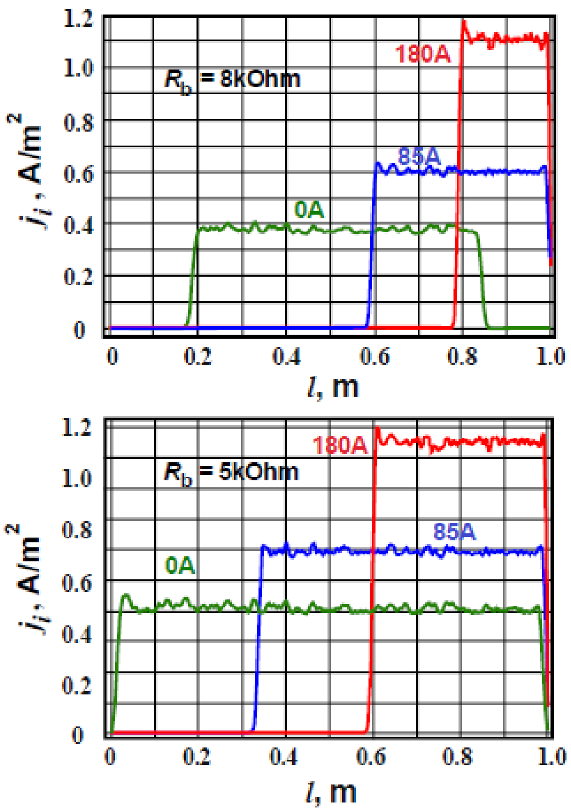

Fig. 4. Distribution of the ion current density along the cathode at L = 1 m at different values of the ballast resistance

Fig. 5 shows the distribution of the electron and ion concentration at different values of the ballast resistance and anode current along the radius in a system with L = 33 cm at a distance of l = 30 cm from the lower edge of the coaxial system (see Fig. 1). This coordinate is located in the plasma region of the discharge zone for all values of the anode current.

The obtained radial distributions of the charged particle concentration indicate the presence in the discharge of three layered zones, which are features of AGD, from the cathode to the anode (see from the right to the left in Fig. 5) [2]: the 1st is the near-cathode layer of the positive space charge of ions with voltage drop and high electric field strength; the 2nd is the layers of negative glow plasma with small voltage drop and low strength of the electric field, in which most of the charged particles are generated and located; the 3rd is the anode layer with negative voltage drop.

With an increase in the current along the anode and the generation of the higher MF, the concentration of charged particles in the negative glow plasma in the compressed discharge zone increases by several times and the zone expands toward the cathode due to a simultaneous decrease in the thickness of the cathode layer of the ion space charge. The latter is feature of the glow discharge [2].

Fig. 5 shows at the anode current of 700 A, the maximum concentration of charged particles in the compressed negative glow plasma was $1.9\cdot10^{17}$ m^{-3}, which is many times greater than the concentration in the absence of an azimuthal field.

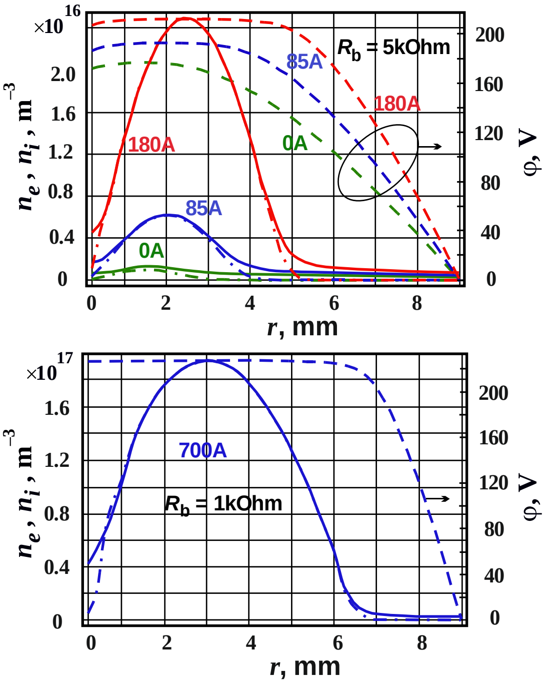

Fig. 5. Distributions of the electron concentration n_e (dashed lines) and ion concentration n_i (solid lines) and potential φ (dotted lines) by radius. L = 33 cm, l = 30 cm, r is reading from the anode surface (see Fig. 1)

The nature of the radial distribution of the concentrations of charged particles in the negative glow plasma layer resembles a half-sine wave or a Bessel function of the first kind-first order; this indicates that the distribution of plasma particles is mainly determined by the lowest diffusion mode, in which the concentrations are maximum in the middle part of the interelectrode gap and minimum at the cathode boundary of the negative glow plasma and near the anode. In this case, the electrode surfaces act as a drain for ions from the gaseous medium due to their transformation or absorption on the surfaces.

It should be noted here that the radial diffusion and drift of electrons occur across the MF lines. In this case, the presence of a radial negative gradient of the azimuthal MF should reduce its effect on the transverse diffusion of electrons in the cathode zone. The effect of the magnetic field on the motion of ions is not significant due to the large mass of the ions.

Fig. 6 shows a generalized volt-ampere characteristic of an AGD with an electrode length of L = 33 cm in the form of a zone in which individual characteristics intersect and overlap each other, when the anode current changes in the range from zero to 300 A.

As can be seen, the discharge voltage increases by 60…75 V when the discharge current increases by 200 mA as a result of reduction in the ballast resistence from 8 to 0.5 kΩ. Switching on the source J1 to create the azimuthal MF and increase the current along the anode in the range up to 300 A leads to a change in the voltage on the compressed discharge only by several volts.

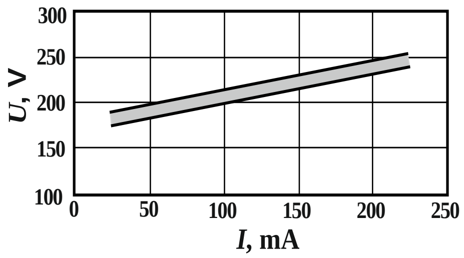

Fig. 6. Generalized volt-ampere characteristic of the AGD with electrode length L = 33 cm in the range of anode current from 0 to 300 A

CONCLUSIONS

The effect of an azimuthal magnetic field, created by passing current along the anode in the long coaxial electrode system of small diameter (cathode diameter was 23 mm, anode diameter was 5 mm, electrode length was 33 cm and 1 m), on the abnormal glow discharge in nitrogen at low pressure p = 133 Pa (1 Torr), pd = 1.2 Pa·m (0.9 Torr·cm), has been studied. The computer simulation within the framework of the hydrodynamic drift-diffusion approximation has been performed. The nature of the distribution of current and concentration of charged particles in the electrode system under different discharge conditions and azimuthal magnetic field has been determined.

The results of the calculations showed that the presence of an azimuthal magnetic field created by a current of certain values along the anode causes compression, that is, compaction and displacement of the plasma discharge zone to the end of the electrode system in the direction of the drift of charged particles in crossed fields [**EB**] and the action of Ampere's force. The compression effect took place at lengths of the electrode system of both 33 cm and 1 m. The width of the compressed discharge zone decreases, and the concentration of charged particles increases when a stronger azimuthal magnetic field is generated. Under our conditions, with an anode current of up to 700 A, the width of the discharge zone was several times smaller than the length of the electrode system, and the maximum concentration of charged particles in the compressed plasma was several times greater than the concentration in the absence of the azimuthal field.

The effect of the plasma discharge zone shifting to the end (this can be called as magnetic blowing effect) becomes noticeable at a certain threshold induction of the azimuthal magnetic field. At a higher discharge current, the compression process begins at a higher current along the anode, i.e. at a higher magnetic induction. In this case, the magnetic field of the discharge itself hardly plays any role due to the very small value of the discharge current relative to the current along the anode from the external source.azimuthal magnetic field is required to shift the discharge zone, but changing the length of the electrode system from 33 cm to 1 m did not show significant differences in the behavior of the discharge under the action of the azimuthal magnetic field of the anode.

The distributions of the concentrations of charged particles and the electric potential along the radius in the discharge interelectrode gap correspond to the same characteristics of the usual abnormal glow discharge between flat electrodes. That is, there are layers of the near-cathode voltage drop with a predominance of positive space charge of ions, the plasma region of negative glow, and the near-anode negative voltage drop. The character of the radial distribution of the concentration is dome-shaped with a predominance of the lower diffusion mode. The maximum concentration of charged particles is $1.9 \cdot 10^{17}$ m^{-3} at the source voltage E1 = 350 V, the ballast resistance of 1 kΩ, the anode current of 700 A, and the electrode of 33 cm. The discharge current density is from units up to 10 A/m^2.

The obtained results of the study of the effect of magnetic blowing can be used for the development of such processes as ion nitriding and other ion treatment of the inner surface of metal tubes of small diameter. since the movement of the discharge zone along the cathode under the action of the azimuthal magnetic field should increase the uniformity of the ion treatment on the surface of the cathode and prevent arc breakdowns on its surface. Thus, the obtained results create approaches to improving the technology of ion processing, including for the manufacture of MEMS. In addition, AGD in azimuthal MF can be used in plasma generators, injectors and accelerators as well as in ion microengines. The use of AGD in MF as a sensitive part of sensors of physical factors, including infrasound, is promising.

For further study, we can recommend the study of dynamic characteristics of the given AGD on mathematical models and experimental studies of gas-discharge microsystems, MEMS and sensors, too.

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АНОМАЛЬНИЙ ТЛІЮЧИЙ РОЗРЯД У ДОВГІЙ КОАКСІАЛЬНІЙ СИСТЕМІ ЕЛЕКТРОДІВ У МАГНІТНОМУ ПОЛІ ВНУТРІШНЬОГО АНОДА

А.І. Кузьмичев, І.В. Бережний, С.Б. Сидоренко, Ю.В. Прокопенко

Проведено числове моделювання впливу азимутального магнітного поля, утвореного проходженням струму по внутрішньому аноду в коаксіальній системі електродів, на характеристики аномального тліючого розряду в азоті. Виявлено сильний вплив магнітного продування на перерозподіл густини струму розряду вздовж електродів. Розряд з таким ефектом може використовуватися для іонної обробки внутрішніх поверхонь довгих металевих труб малого діаметра і в різних фізичних пристроях, включаючи сенсорну техніку і МЕМС.