SPECTROSCOPY AND PROBE DIAGNOSTICS OF DC SPHERICAL GLOW DISCHARGE

V.A. Zhovtyansky, V.G. Nazarenko, R.P. Syrotyuk

The Gas Institute of the National Academy of Sciences of Ukraine, Kiev, Ukraine

E-mail: zhovt@ukr.net

Probe and spectroscopic investigations of a spherical glow discharge (GD) were done in nitrogen and argon plasma. There were obtained the distributions of electron temperature and electron density in a discharge gap as well as plasma potential distribution. These results were compared with theoretical ones and the conclusion about their convergence was done in the present study. Particular attention was paid to the anode processes role in the formation of self-organized structure in a spherical glow discharge. It was shown the necessity of taking into account the possibility of the anode potential drop forming in this discharge region.

PACS: 52.80 Hc

INTRODUCTION

The theory of the gas-filled diodes is one of the fundamental in the physics of GD and low-temperature plasmas. At the same time, GD are widely used in technological processes of a metal surface nitriding. One of their advantages is maximal localization of the technological action on the treated surface – even if it has a complicate geometry shape with concave parts. The importance of its study and correct modeling is the ability to increase the energy efficiency of the modification processes in the industry.

The numerical modeling of a spherical GD plasma with using of the hydrodynamic model was done in the recent studies [1, 2]. There were used next balance equations and Poisson equation for the GD specification:

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2 J_e\right)-\alpha(E)J_e=0,\ J_e=-\mu_e N_e E-D_e\frac{dN_e}{dr}, \qquad (1)$$

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2 J_i\right)+\alpha(E)J_e=0,\ J_i=-\mu_i N_i E-D_i\frac{dN_i}{dr}, \qquad (2)$$

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{d\varphi}{dr}\right)=\frac{e}{\varepsilon_0}(N_e-N_i), E=-\frac{d\varphi}{dr},\ , \qquad (3)$$

where J_e and J_i are absolute values of electron and ion flows densities (respectively, density of current is $j = e(J_i + J_e)$; E is electric field strength; α(E) is the first Townsend coefficient; D_e, μ_e, D_i, μ_i are the diffusion and mobility coefficients of electrons and ions, respectively.

Boundary conditions for so-called short GD (without the positive column) were used [3]:

$$J_e=\gamma J_i, eJ_e=\gamma j_K/(1+\gamma), \phi=0, \text{ for the cathode,} \qquad (4)$$

$$N_i=0, eJ_e=j_A, dN_e/dr-0, \text{ for the anode.} \qquad (5)$$

Here J_K and J_A are current densities at the cathode and the anode, γ is the coefficient of electron secondary emission from the cathode, r is the spatial coordinate, N_e and N_i are the densities of electrons and ions.

The potential radial distribution was defined as a result of numerical solution. It demonstrates high potential drop in the discharge gap outside the cathode area. Its value can be up to half of the total voltage drop U_d across the discharge gap depending on the GD mode maintenance. Such potential behavior must provide a charge particles generation in the whole volume for space charge compensation in plasma. However, it did not correspond to reality, since such discharge voltage U_d increasing was not observed experimentally [5]. Therefore another model was proposed in [6], where the charged particles generation occurs in a narrow anode area (so-called anode potential drop (APD)) to compensate the space charge.

In this study, authors consider that taking into account the possibility of APD formation in GD explains the charged particles generation in the anode layer. An ions injection from this layer to an interelectrode gap provides the space charge compensation and eliminates the need for a large electric field here.

With this in mind, the variable value of electric field strength E_A on the anode played the boundary condition role. The efficiency of numerical calculations was provided with the method of the parameter continuation solution (so-called quasi-linearization) and allows determining the main discharge parameters distributions along the interelectrode gap [7].

The calculations were carried out for the spherical GD in molecular nitrogen at a pressure p = 1.1 Torr. The radii of the cathode and anode were r_K =1.5 cm and r_A = 20 cm, respectively. Electric current was (10…250) mA, that corresponds to the current density at the cathode (0.3…8.2) mA/cm^2. One of the obtained modeling results was the anode electric field dependence on the discharge voltage value U_d (Fig. 1).

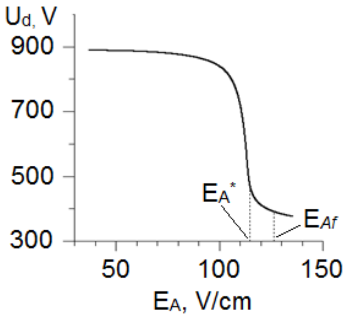

Fig. 1. Discharge voltage U_d as function of the field at the anode E_A. Discharge current I=100 mA

Two values E_A were chosen as the characteristic ones: E_A* that corresponds to d^2E_A/dr^2, and E_{Af} as the solution of the next expression:

$$E_{Af} = \frac{B}{\ln\left(\frac{2D_e}{\mu_i}\frac{A}{B}\right)} p, \qquad (6)$$

where A = 12 (cm·Torr)$^{-1}$, B = 342 V/(cm·Torr).

With this E_A values, a space distributions of charged particles density, potential U (Fig. 2), and electric field strength were obtained in this study.

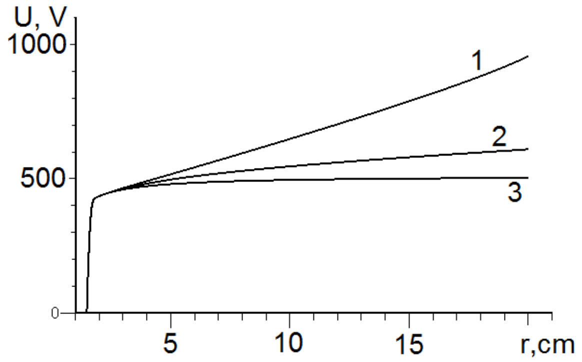

Fig. 2. Spatial distribution of potential in the spherical GD: 1 – solution without the APD; 2, 3 – $E_A = E_A$ and $E_A = E_{Af}$, respectively. Discharge current is I = 100 mA*

However, these results did not carry any restrictions on the electric field value at the anode and it can be very high at low voltages. Therefore, there was a need in the experimental determination of the absolute values of the potential drop near the anode.

1. THE EXPERIMENT

1.1. PROBE MEASUREMENTS

The experimental installation consists of a vacuum chamber (V=0.1 m^3), power system, electrodes and observational windows placed on the chamber walls (Fig. 3).

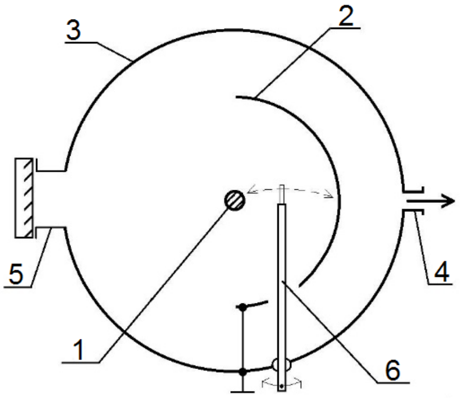

Fig. 3. The scheme of the probe measurements: 1 – cathode; 2 – half sphere anode; 3 – vacuum chamber; 4 – moveable probe; 5 – window; 6 – pump

The measurements were carried out in argon and nitrogen plasma at pressures of 5…150 Pa. A copper bowl with a diameter of 3 cm was used as a cathode, and a copper hemisphere with a diameter of 32 cm was used as an anode. The anode was separated from the grounded chamber. Single and double Langmuir probes were used for probe measurements. Material of a single probe was stainless steel while a double probe was tungsten one. Probes were set into the chamber through a spherical input, which allows to move the probe in 3 dimensions. A single probe was used for argon plasma diagnostic while a double probe was used for nitrogen plasma. It was due to high thermal and electrical conductivity of nitrogen, so the probe played an electrode role with misrepresenting of probe characteristics. A double probe ruled out this effect, but a disadvantage of its using was a limit of sensitivity at low electron densities. This led to the fact that a double probe was applicable in the cathode region only.

1.2. SPECTROSCOPIC MEASUREMENTS OF A SPHERICAL GD

Spectroscopic measurements were done in argon and nitrogen plasma with the coronary model using. This model allows plasma parameters determining using the intensity ratio of emission lines of excited atoms in plasma [8].

The experimental setup includes the monochromator, detector and PC. The emission spectrum was determined at pressures up to 100 Pa. A spherical molybdenum cathode was used in this experiment.

The data was processed with considering of the noise presence.

RESULTS

Probe electron current measurements in argon and nitrogen plasma were done with a single probe in order to estimate their spatial distributions (Fig. 4).

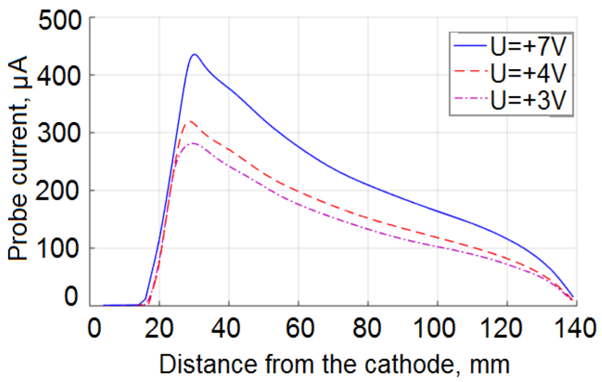

Fig. 4. Typical spatial distributions of probe electron current in the spherical GD in argon at different probe voltages. P=15 Pa

A slow probe current rise was experienced in the cathode region. The current growth rate sharply increased in a region where intensive luminosity took place (up to 22 mm). This is a negative glow region. The probe current maximum values took place in the area where luminosity absents. There was slowly decreasing of probe current with distance increasing from the cathode. In the approximation of a constant electron temperature T_e it is possible to observe a simply estimation of the N_e distribution.

A series of probe measurements were made in argon and nitrogen plasma at pressures of 5…150 Pa for T_e and N_e determining. Contributions of electron and ion component in total probe current were taken into account to determine plasma parameters. With this in mind, ion current values were accounted for each of probe characteristics for all probe voltages.

The temperature and density of electrons were obtained with resulting data processing. Contributions of ion current were taken into account for each of probe characteristics in accordance with the Laframboise theory. Fig. 5 demonstrates N_e (a) and T_e (b) spatial distribution in argon plasma at pressures of 50…150 Pa. The electron temperature in the cathode region is slightly higher than in the dark Faraday’s space and than increase at the anode area. This can be explained by nonuniformity of a glow discharge structure and the distribution of the electric field in an interelectrode gap. Experimentally and numerically determined electron density are shown on Fig. 6.

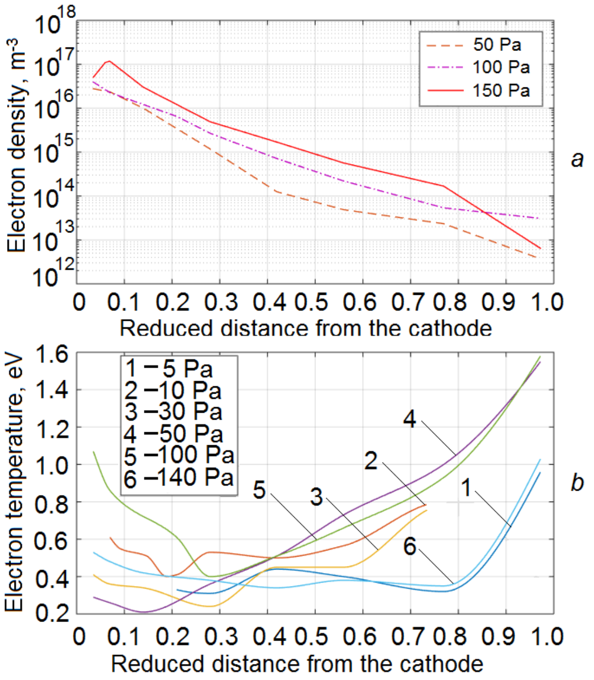

Fig. 5. N_e (a) and T_e (b) spatial distributions in argon plasma at pressures of 50…150 Pa. Supply characteristics: voltage U_G=500 V, current I_G=30…40 mA

Plasma potential χ_{pl} (with regard to anode) distributions were measured to establish the conclusions adequacy in numerical calculations [6, 7] regarding to APD role. For example, Fig. 7 shows potential distribution in argon plasma at pressures of 140 Pa.

As can be seen from the figure, there is non-uniform distribution of the potential in the gap, and similar behavior is consistently reproduced.

For practical purposes, the influence of downtime of the vacuum chamber effect at plasma characteristics was determined. It turned out that their little sediment can significantly change N_e and T_e which is an important factor in the nitriding technology.

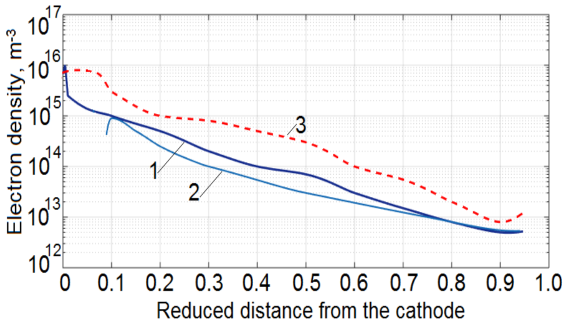

Fig. 6. Spatial distributions of electron density in nitrogen plasma obtained: 1 – numerically, p=150 Pa, r_K=1.5 cm, I=130 mA; 2 – numerically, p=150 Pa, r_K=1.5 cm, I=100 mA; 3 – experimental study, p=150 Pa, r_K=3 cm, I=35 mA

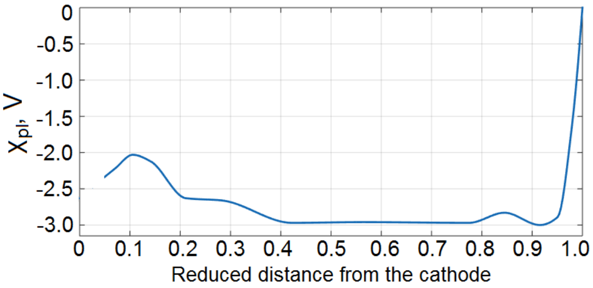

Fig. 7. Plasma potential χ_{pl} spatial distribution in argon plasma at pressures of 140 Pa. Supply characteristics: voltage U_G=500 V, current I_G=35 mA

Fig. 8 shows the results of spectral measurements in a GD plasma: N_e (a) and T_e (b) values at different pressures.

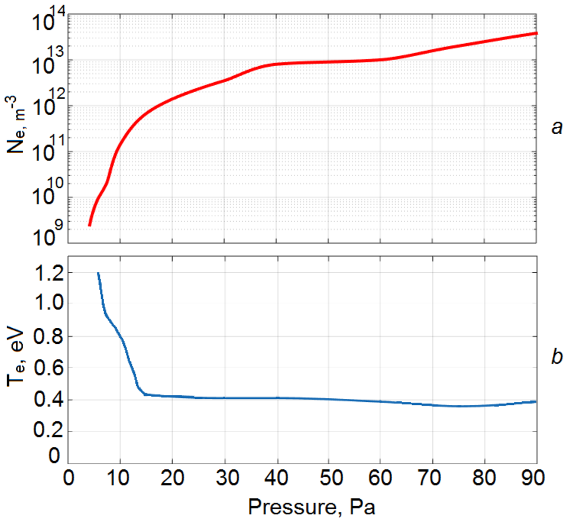

Fig. 8. N_e (a) and T_e (b) values at pressures of 5…90 Pa obtained with the coronary model

CONCLUSIONS

Thus, experimental studies of a glow discharge in a spherical geometry were done with using the probe and spectroscopic methods. The APD presence was experimentally verified and determined its value. The resulting distributions of the plasma parameters at different pressures are in a good agreement with the theoretical researches. The advantages of probe methods are the relative simplicity of the theoretical apparatus and low cost devices. The advantages of spectral methods are their speed, ability of working with a discharge gap at once, a minimal impact on the system and the possibility of using spectral methods to study a difficult accessible objects.

ACKNOWLEDGEMENTS

This work was supported by the National Academy of Sciences of Ukraine, program «Prospective study of plasma physics, controlled thermonuclear fusion and plasma technology».

REFERENCES

1. Yu.I. Lelyukh. Numerical Simulation of the Structure of a Spherical Glow Discharge // *Ukr. J. Phys.* 2010, v. 55, № 11, p. 165-1171.
2. V.A. Zhovtyansky, Yu.I. Lelyukh, O.V. Anisimova. Determination of Parameters of Stationary Spherical Glow Discharge // *Ibid.* 2009, p. 75-76.
3. Yu.P. Raizer, S.T. Surzhikov. Two-dimensional structure in a normal glow-discharge and diffusion effects in cathode and anode spot formation // *TVT.* 1988, v. 26, № 3, p.428-435.
4. V.A. Zhovtyansky, Yu.I. Lelyukh. Numerical Simulation of Stationary Processes in Glow Discharge Plasma // *Tech. Phys. Lett.* 2009, v. 35, № 8, p. 725-729.
5. V. Zhovtyansky, V. Khomych, Yu. Lelyukh, et al. // *VI Int. Conf. "Plasma Physics and Plasma Technology".* (Minsk, Belarus, 2009, v. 1, p. 163.
6. V.A. Zhovtyansky, O.V. Anisimova. Role of anode processes in glow discharge energetics // *Ukr. J. Phys.* 2016, v. 61, № 2, p. 98-106.
7. Yu.I. Lelukh. Numerical Modelling of Spherical Glow Discharge Structure // *Ukr. J. Phys.* 2010, v. 55, p. 1165-106.
8. Xi-Ming Zhu, Yi-Kang Pu. Optical emission spectroscopy in low-temperature plasmas containing argon and nitrogen: determination of the electron temperature and density by the line-ratio method // *J. Phys. D: Appl. Phys.* 2010, v. 43, p. 403001.

Article received 25.10.2016

СПЕКТРАЛЬНАЯ И ЗОНДОВАЯ ДИАГНОСТИКИ СФЕРИЧЕСКОГО ТЛЕЮЩЕГО РАЗРЯДА ПОСТОЯННОГО ТОКА

В.А. Жовтянский, В.Г. Назаренко, Р.П. Сыротюк

Проведены зондовые и спектроскопические исследования сферического тлеющего разряда в аргоновой и азотной плазме. Получены распределения электронной температуры и концентрации электронов в разрядном промежутке, а также распределение потенциала плазмы. Полученные в данной работе результаты сравнивались с теоретическими и сделаны выводы об их сходимости. Особенное внимание было уделено роли прианодных процессов в формировании самоорганизованной структуры тлеющего разряда. Показана необходимость принимать во внимание возможность формирования анодного падения потенциала в этой области разряда.

СПЕКТРАЛЬНА І ЗОНДОВА ДІАГНОСТИКИ СФЕРИЧНОГО ЖЕВРІЮЧОГО РОЗРЯДУ ПОСТІЙНОГО СТРУМУ

В.А. Жовтянський, В.Г. Назаренко, Р.П. Сиротюк

Проведено зондові і спектроскопічні дослідження сферичного жевріючого розряду в аргоновій та азотній плазмі. Отримано розподіли електронної температури і концентрації електронів у розрядному проміжку, а також розподіл потенціалу плазми. Отримані в даній роботі результати порівнювалися з теоретичними і зроблені висновки про їх збіжність. Особливу увагу було приділено ролі прианодних процесів у формуванні самоорганізованої структури жевріючого розряду. Показана необхідність брати до уваги можливість формування анодного падіння потенціалу в цій області розряду.