GAS DISCHARGE, PLASMA-BEAM DISCHARGE AND THEIR APPLICATIONS

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SOME CHARACTERISTICS OF PULSED DISCHARGE WITH HOLLOW CATHODE IN LOW-PRESSURE ARGON INITIATED BY INJECTION OF PLASMA BUNCH

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It has been established that the electric field in the plasma of a high-voltage, low-pressure discharge in argon with a hollow cathode, which is ignited by injection of a plasma bunch, can reach ≈ 10^5 Td. The dependence of the radial electric field on the argon pressure has been found. The fact of the presence of a group of electrons with an energy of more than 80 eV in the near-axial region of the cathode has been established.

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INTRODUCTION

Reducing the content of microdroplets in the flows of “metal” plasma from vacuum-arc discharges used to create various coatings allows significant quality improvement of these coatings. Although the removal of microdroplets larger than ≈ 1…2 μm from plasma flows is achieved by fairly simple methods, the removal of microdroplets of smaller sizes is a rather complicated task. One of the approaches to reducing the number of microdroplets with sizes ≈ (0.1…1.0) μm is their evaporation when passing through an additionally created gas discharge plasma. It was shown in [1] that the use of pulsed hollow cathode (HC) discharge plasma in argon allows to reduce the number of Ti microdroplets with sizes ≈ (0.1…0.6) μm by several times. The studies conducted in [2] allowed us to establish the dependence of plasma parameters (density, electron temperature) on the type of power source used (voltage source or current source) and argon pressure. In particular, it was found that at the same specific power in the discharge the temperature of plasma electrons of the discharge, which was powered by a voltage source, was several times higher than in the case of using a high-impedance power supply, and could reach ≈ (40…50) eV.

The purpose of the presented research is a further study of such kind of HC discharge, particularly, establishing of spatial-temporal dependences of electric field strength in the discharge plasma by probe methods and determining dependences of the EEDF on the discharge parameters by means of optical emission spectroscopy.

1. EXPERIMENTAL DEVICE AND MEASUREMENT METHODS

Fig. 1 shows the block diagram of the experimental device. Cylindrical hollow cathode (HC) with an inner diameter of D = 120 mm and a length of L = 220 mm was placed inside a quartz cylinder. The ends of the HC were closed with diaphragms under a floating potential – on the side of the vacuum-arc discharge an input metal one under a floating potential with a 30 mm hole, and on the other side – an output glass one with a hole with a diameter of 50 mm.

This entire device was located inside a grounded vacuum chamber. The anode of the hollow cathode discharge was both the grounded anode of the arc discharge and the wall of the metal chamber.

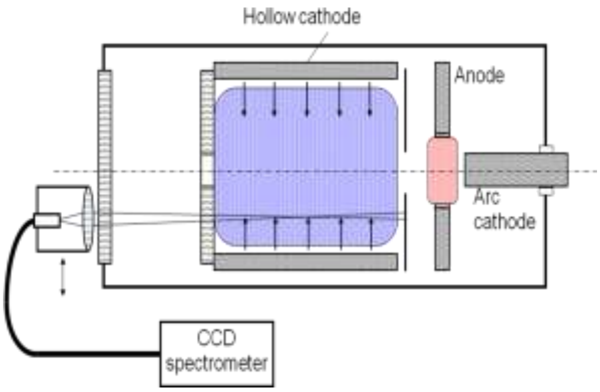

Fig. 1. Scheme of the experimental device

During the research, the pressure of argon P in the cathode varied within (3…12)·10^{-2} Pa.

Low impedance pulse DC power supply with repetition rate 0.2…10 Hz of voltage/current pulses with a duration of 5 ms with maximum values of voltage and current of 10 kV and 5 A, respectively, was used. The diagrams of discharge current and voltage are shown in Fig. 2.

The device worked as follows. At the moment of time t ≈ 0, a vacuum-arc discharge was ignited with a current of 120 A and a peak duration of about 0.1 ms (the frequency of current pulses was 1 Hz) and the flow of Ti plasma with an energy of ≈ 20…30 eV began to be injected into the cathode cavity. The voltages on the arc and HC were synchronized in such a way that the arc discharge with its back front ignited the HC discharge. The HC discharge ignition voltage was about 1.5…2.0 kV depending on the argon pressure in the chamber.

Plasma parameters were measured using three pairs of single Langmuir probes located at a radius of 10 and 40 mm at distances of 40, 110, and 180 mm from the input metal diaphragm (these probes were also shifted by an angle of 120° from each other). The probes were made of tungsten wire with a diameter of 190 μm, and the length of the receiving part was 5 mm. A Siglent SDS 1104X-E oscilloscope was used to obtain the time dependences of the probes floating potential at different argon pressure and discharge current.

Plasma emission spectra were studied using a CCD spectrometer SL40-2-2048 in the wavelength range of 400…900 nm with a resolution of about 0.5 nm. The design of the optical system provided spatial scanning of the emission detection zone along the radius of cylindrically symmetric plasma device (see Fig. 1) by radial move of the optical waveguide assembly used for delivery of the radiation to the spectrometer input. The waveguide had an effective input diameter of about 0.4 mm. The projection of the radiation reception zone onto the entrance of the waveguide was carried out using a lens with a focal length of 105 mm and a relative aperture of 1:4.5. Note that the effective value of the later was limited to about 1:8 due to the angular aperture of the waveguide. The length of the optical path from the lens to the center of the discharge system was about 1000 mm, which provided an effective diameter of the perception zone of about 5 mm with its effective length of about 200 mm for the correct measurement of transverse distributions inside the discharge area. The data for each point of the spatial distribution were acquired for 5 consequent discharge pulses so that the effective exposure time for the plasma emission was about 15 ms. The whole spatial distribution consisted of 200 points recorded with a step of about 0.5 mm so that an overall registration duration was about 15 minutes. Obtained set of the emission spectrum data was stored in a file using the spectrometer software for further processing.

2. EXPERIMENTAL RESULTS

Probe measurements at radii R = 10, 40 mm and distances L = 40, 110, 180 mm showed that the value of the floating potential U_f at different points in space depends in a complex way on the discharge duration t and the argon pressure. This is especially true for the temporal behavior of U_f at distances L = 40 and 180 mm, i.e. near the holes in the diaphragms that limit the volume of the hollow cathode. Not least, this is due to the fact that namely through these holes the fast ($\varepsilon_f \sim eU_d$) electrons accelerated in the cathode layer flow out of the HC volume.

For illustration, Fig. 2 presents typical diagrams of discharge current I_d and voltage U_d and time dependences U_f of two probes in the middle plane of the hollow cathode. As can be seen, the discharge voltage U_d during discharge glow remains practically constant, and the time dependences U_f on both probes generally repeat the time dependences of the discharge current. Both I_d and U_f reach their maximum values at t ≈ 1.25 ms. Approximately at the same time point of discharge glow, the values of U_f of the probes reach their maximum values at other distances L and argon pressures. An increase in argon pressure leads to a decrease of U_f value. It should be noted that it is at this time point t that the temperature of the electrons of the discharge plasma reaches its maximum values, in particular, at a pressure $P = 4{\cdot}10^{-2}$ Pa the value T_e is ≈ 40 eV [2].

The values of the floating potential of different probes U_f at an argon pressure of $5.5{\cdot}10^{-2}$ Pa for the time t ≈ 1.25 ms are presented in Fig. 3. As can be seen from this figure, as one moves from the entrance to the inner volume of the HC (i.e., from L = 40 mm to L = 180 mm), the difference in the floating potentials of the probes at radii of 10 and 40 mm decreases and, accordingly, the radial electric field in the plasma E_R in the spatial gap between these probes from ≈ 35 to 10 V/cm (or E_r/N from ≈ $3{\cdot}10^5$ to ≈ $1{\cdot}10^5$ Td). In addition, as can be seen from this figure, the radial electric field E_R in different sections of the HC not only has a different magnitude, but also changes its direction.

The measurements also showed that the magnitude of the longitudinal electric field E_{II} is approximately the same as E_R.

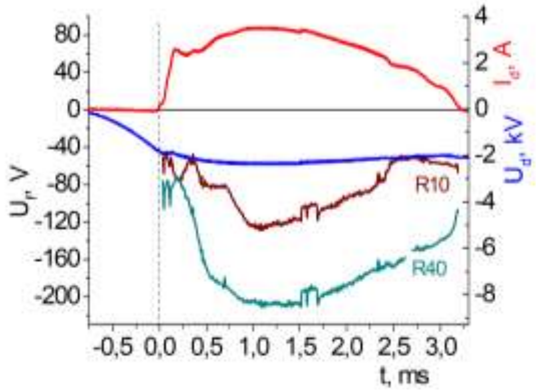

Fig. 2. Diagrams of HC discharge current and voltage; time dependences of floating potential U_f at different radii R = 10 and 40 mm at distance L = 110 mm. $P = 5.5{\cdot}10^{-2}$ Pa

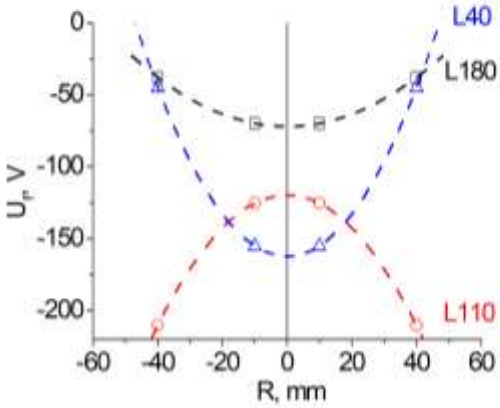

Fig. 3. Floating potential values U_f for the probes at a time point t ≈1.25 ms at different distances L. $P = 5.5{\cdot}10^{-2}$ Pa

Such a high value of the reduced electric field E/N ≈ 10^5 Td in the plasma of the studied discharge with HC is a very interesting fact, since in a conventional discharge with a hollow cathode the reduced electric field E/N is ≈ (1…10) Td with a much lower average electron energy, which varies within ≈ (2…4) eV [3 - 6]. That is, if in a conventional discharge with HC the main role in heating the plasma electrons is played by fast electrons e_f accelerated in the cathode layer, and the electric field has a negligible effect, then in the case of the studied discharge the situation is much more complicated. Most likely, the electron distribution function has a local character and is in equilibrium with the electric field. This question can only be answered correctly by conducting detailed measurements of the spatial distributions of both the electric field in the plasma and the EEDF form (or at least T_e). But the first step in this direction can be a rough estimate of the spatial behavior of the EEDF form by optical emission diagnostics methods. For this purpose, the approach used in [7] was used. With this approach, the spatial behavior of the radiation intensity of individual ArI and ArII lines is investigated, for which it is possible to estimate the range of electron energies participating in the excitation of the corresponding levels. In this article, we will limit ourselves to only some ArII lines that can give us information about the behavior of the group of fast electrons with energies above 35…37 eV. For this purpose, the behavior of the intensity of the Ar II lines λ = 487.98 nm (transition 4s ^{2}P3/2 – 4p $^2D^0_{5/2}$, Eth = 35.44 eV) and λ = 413.17 nm (transition 4s' $D_{3/2}$ – 4p' $^2P^0_{1/2}$, Eth = 37.17 eV) was considered (data for these lines are taken from [8]).

For a more complete understanding of the electron energy range that makes the main contribution to the population of the ArII 4p $^2D^0_{5/2}$ 487.99 nm and ArII 4p' $^2P^0_{1/2}$ 413.17 nm levels, their excitation rates $Q_e(\varepsilon) f_e(\varepsilon)\varepsilon^{0.5}$ were estimated, where $Q_e(\varepsilon)$ is the excitation cross section of the corresponding level, $f_e(\varepsilon)$ is the electron energy distribution function. The estimates were made for the electron temperature T_e = 40 eV assuming the Maxwellian EEDF $f(\varepsilon)$

$$f_e(\varepsilon) = \frac{2}{\sqrt{\pi}} T_e^{-3/2} \sqrt{\varepsilon} e^{-\varepsilon/T_e},$$

which is normalized such that

$$\int_0^\infty f_e(\varepsilon) d\varepsilon = 1.$$

The obtained dependences of $Q_e(\varepsilon) f_e(\varepsilon)\varepsilon^{0.5}$ on the electron energy ε are presented in Fig. 4.

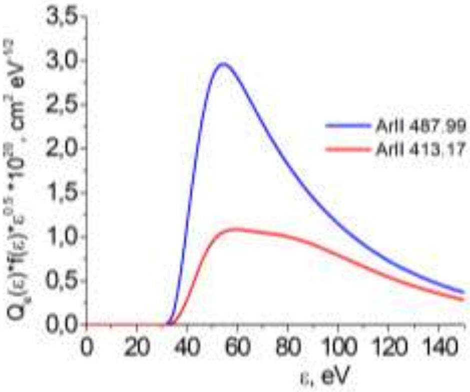

Fig. 4. Excitation rates $Q_e(\varepsilon) f_e(\varepsilon)\varepsilon^{0.5}$ for ArII 4p $^2D^0_{5/2}$ 487.99 nm and ArII 4p' $^2P^0_{1/2}$ 413.17 nm levels for T_e = 40 eV

As can be seen from this figure, the energies of the electron groups that make the main contribution to the excitation of these levels are somewhat different. If the main contribution to the excitation of the ArII 4p $^2D^0_{5/2}$ 487.99 nm level is made by a group of electrons with energy in the range ε ≈ (40…80 eV), then in the case of the ArII 4p' $^2P^0_{1/2}$ 413.17 nm level – a group of more energetic electrons with energy in the range ε ≈ (50…120 eV).

Let us now consider the radial dependences of the radiation intensity of the ArII 4p 4p $^2D^0_{5/2}$ 487.99 nm and ArII 4p' $^2P^0_{1/2}$ 413.17 nm lines obtained at different argon pressures (Fig. 5,a,b). (When considering the obtained radial dependences of line intensities, it should be borne in mind that the obtained spectra are averaged not only over time, but also over the thickness of the discharge plasma L ≈ 220 mm).

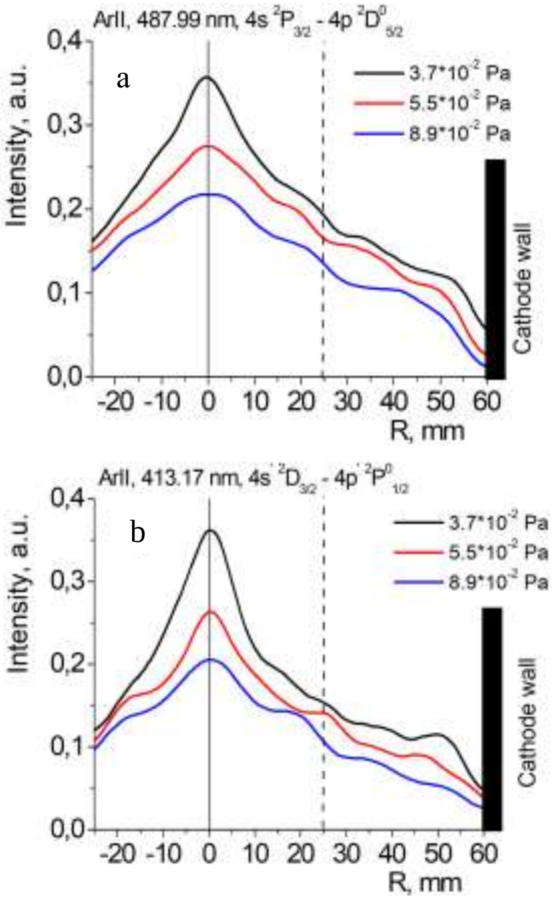

Fig. 5. Averaged over time and observation line radial dependences of intensities of the emission lines for ArII 487.99 nm (a) and ArII 413.17 nm (b) at different Ar pressure

The first thing that catches the eye when comparing the dependences in Fig. 5,a,b is the different nature of the change in the shape of the radial distribution of radiation intensities with a change in pressure. (A sharp drop in intensity at R > 50 mm in both cases is associated with the dark cathode space). The radial dependence of the ArII 487.99 nm radiation intensity at all pressures has practically the same triangular shape and a change in pressure leads only to a change in the intensity value. At the same time, in the case of ArII 413.17 nm radiation, the shape of the radial dependence of the radiation intensity also changes when the argon pressure changes. At a pressure of $3.7\cdot10^{-2}$ Pa, two sections can be distinguished in the dependence – a sharp drop in the radiation intensity with an increase in the radius R from 0 mm to ≈ 10 mm and a much slower drop in the intensity at R > 10 mm. Increasing the pressure first leads to a “blurring” of the bend at R ≈ 10 mm, then to its disappearance at a pressure of $8.9\cdot10^{-2}$ Pa. The most likely reason for such a difference in the behavior of the radial dependences of the radiation intensity of these lines may be related to the dependence of the shape of the EEDF on both R and the argon pressure.

At a low pressure of $3.7 \cdot 10^{-2}$ Pa, radial dependence of the radiation intensity of the ArII 413.17 nm line with a bend at R ≈ 10 mm may indicate the presence of an "excess" of electrons with an energy of more than ≈ 80 eV in the EEDF in the near-axial region compared to the EEDF at larger values of R. Increasing the argon pressure leads to "cooling" of the EEDF, i.e., to a decrease in the content of the most high-energy electrons. That is, such "cooling" will primarily affect the EEDF in the near-axial region of the cathode. Thus, the dependence of the EEDF shape on the radius weakens, which leads to a smoothing of the shape of the radial dependence of the ArII 413.17 nm line.

Since in the case of ArII 413.17 nm line radiation, electrons with energy less than ≈ 80 eV play the main role in excitation, the shape of radial dependence of the intensity will practically not change with increasing pressure.

CONCLUSIONS

Some features of the low-pressure discharge plasma in argon with a hollow cathode, which is ignited by injection of a plasma clot, have been established. In particular, it has been established that the electric field in the plasma can reach ≈ 10^5 Td. The fact of the presence of a group of electrons with an energy of more than 80 eV in the axial region of the cathode has also been established.

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REFERENCES

1. A. Ryabtsev, V. Bazhenov, A. Goncharov, V. Maslov, V. Tsiolko. About possibility application a hollow cathode discharge for evaporation and filtration micro-droplets from erosion plasma source // *Proceedings of 10th International Conference on "Nanomaterials: Applications & Properties" (NAP-2021)* Odesa, Ukraine, 5-11 Sept. 2021, p. MTFC-A-03.
2. V.Yu. Bazhenov, V.V. Tsiolko, V.M. Piun. Influence of power source type on time dependence of the plasma parameters of a pulse discharge with a hollow cathode // *Problems of Atomic Science and Technology. Series "Plasma Physics".* 2022, № 6, p. 95-98. DOI:10.46813/2022-142-095.
3. V.Yu. Bazhenov, A.V. Ryabtsev, I.A. Soloshenko, A.G. Terent'eva, V.A. Khomich, V.V. Tsiolko, and A.I. Shchedrin. Investigation of the Electron Energy Distribution Function in Hollow-Cathode Glow Discharges in Nitrogen and Oxygen // *Plasma Physics Reports*. 2001, v. 27, № 9, p. 813-818.
4. S.V. Matsevich, A.V. Ryabtsev, V.Yu. Bazhenov, V.V. Tsiolko, V.M. Piun. Bi-Maxwellian form of EEDF in hollow cathode discharge plasma as a results of the competing action of electric field and excitation from the metastable statesAr($1s_{3,5}$) // *Book of proceeding of the 18 International conference on electronics and applied physics APHYS 2022*, 18-22 October 2022, Kyiv, Ukraine, p. 96-97.
5. V.Yu. Bazhenov, S.V. Matsevich, V.M. Piun, A.V. Ryabtsev, V.V. Tsiolko. Kinetic of argon plasma negative glow in presence metastable atoms // *Problems of Atomic Science and Technology. Series "Plasma Physics".* 2013, № 1, p. 216-218.
6. S.N. Andreev, A.V. Bernatskiy, V.N. Ochkin. Spatial Variations of Plasma Parameters in a Hollow Cathode Discharge // *Plasma Chemistry and Plasma Processing.* 2021, v. 41, p. 659-672. DOI: 10.1007/s11090-020-10137-4.
7. V.Yu. Bazhenov, A.M. Dobrovolskii, V.V. Tsiolko, V.M. Piun. Two stage Hall type source: discharge characteristics and electron energy distribution function // *Problems of Atomic Science and Technology*. 2024, № 6, p. 72-77. DOI:10.46813/2023-146-121.
8. John B. Boffard, B. Chiaro, Tobin Webwr, Cnun C. Lin. Electron impact excitation of argon: Optical emission cross section in the range of 300…2500 nm // *Atomic Data and Nuclear Data Tables.* 2007, v. 93, p. 831-863. DOI:10.1016/j.adt.2007.06.004.

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ДЕЯКІ ХАРАКТЕРИСТИКИ ІМПУЛЬСНОГО РОЗРЯДУ З ПОРОЖНИСТИМ КАТОДОМ В АРГОНІ НИЗЬКОГО ТИСКУ, ЗБУДЖУВАНОГО ІНЖЕКЦІЄЮ ПЛАЗМОВОГО ЗГУСТКУ

В.Ю. Баженов, В.В. Ціолко, В.М. Піун

Встановлено, що електричне поле в плазмі високовольтного розряду низького тиску в аргоні з порожнистим катодом, який запалюється інжекцією плазмового згустку, може сягати ≈ 10^5 Td. Знайдено залежності величини радіального електричного поля від тиску аргону. Встановлено факт наявності групи електронів з енергією більше 80 еВ у приосьовій ділянці катода.