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STUDY OF PLASMA ELECTRON SOURCE WITH MULTI-CELL HOLLOW CATHODE

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The characteristics of a pulsed high-current plasma electron source with a cold hollow cathode in magnetic field and ion-electron emission are investigated. To reduce the cathode current density, eliminate arcing and minimize the dimensions of the cathode unit, a multi-cell structure of nested hollow cylinders with the formation of coaxial ring cavities and a discharge initiation system in them were used. The electron current on the collector was hundreds of amperes at a plasma-generating discharge voltage of hundreds of volts and a hydrogen pressure of 10…50 Pa.

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INTRODUCTION

Hollow-cathode discharges are well known as a simple and effective way to obtain plasma of various substances, and various designs of plasma sources of electrons and ions for various applications have been created on its basis [1 - 3]. In hollow-cathode systems, a very high discharge current density (up to 50 A/cm^2) has been achieved at low gas pressure, not reaching it in a conventional glow discharge with flat electrodes [2]. Efficient ionization of gas in the cathode cavity occurs due to the fact that the electrons, emitted by the cathode, oscillate continuously, like a pendulum, between opposite sections of the cathode surface until they have spent their energy on interaction with the gas. The electrons receive their initial energy during acceleration in the near-cathode sheath of the positive space charge of ions. The configuration of the electric field in the cathode cavity should facilitate the pendulum motion of the cathode electrons. This condition is met when the negative glow plasma is formed in the cathode cavity, then plasma serves as a source of ions that bombard the cathode surface and cause secondary electron emission. The plasma also acts as a transparent anode for the cathode electrons, which are successively accelerated in the near-cathode ion sheath, pass through the plasma, ionizing the gas, slow down in the sheath at the opposite part of the cathode surface, and then accelerate again, but in the opposite direction. External injection of plasma into the cathode cavity or maintaining a starting (preparatory) discharge in it is to stabilize the occurrence of a powerful discharge in the cathode. To increase the efficiency of plasma generation in a hollow cathode, it was proposed to introduce a magnetic field, which additionally lengthens the trajectories of electrons in the cathode cavity and enhances probability of electron collision with gas moleculars [4, 5].

At the same time, for a hollow cathode discharge, as for any glow discharge, the glow-to-arc transitions (arcing) are typical at high discharge current density. Therefore, to obtain a large discharge current, for example, 200 A, as in [6], it is necessary to use a large cathode, but this is not always acceptable.

In this paper, it is proposed to reduce the cathode current density for eliminating the arcing and minimize the dimensions of the cathode unit by use of a multi-cell cathode structure. It is created by nesting hollow cylinders inside each other, like a "matryoshka doll", to form coaxial ring cavities. In this case, the total area of the cathode surface will be much larger than the surface area of one cylinder with the largest diameter. To stably initiate discharge in narrower cavities of cathode cells without increasing the gas pressure, it is proposed to create an axial magnetic field in the cells and to use an additional system for initiating the discharge in them. Such approach to the design of a hollow cathode electron source will be investigated and its results will be presented.

1. EXPERIMENTAL

The electrode structure of the plasma electron source is shown in Fig. 1, it contains a multi-cell hollow cathode module, which consists of two coaxial parts: a hollow cylindrical cathode 1 and several coaxial cylindrical cathode cells 2. The cathode cylinders of part 2 are equipped with side openings for connecting all the cathode cavities. The external diameter of the cathode module is 44 mm, and its height is 45 mm. The radial distance *d* between the walls of the cathode cells was from 4 to 43 mm depending on the number of cells.

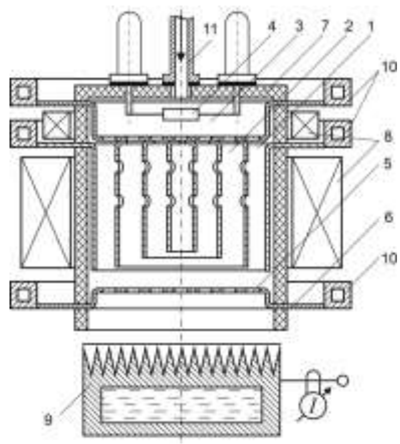

Fig. 1. The electron source diagram

The electrode material is molybdenum; the outer water-cooled cathode outputs are made of copper. The presence of separate outputs from both parts of the cathode module allows us determining the current distribution between these parts or use the electrode 1 as a control one, however in this work the outputs of the both parts were connected to each other.

Above the cathode module, under the upper ceramic roof, there is an igniter module 3, which contains a spark semiconductor igniter 4 equipped with electrical outputs through the ceramic roof to the outside. The cavities of the cylinder cells of the cathode part 2 and the cavity of the igniter module 3 are connected by openings on the upper plate of the cathode part 2.

Under the cathode module there is a flat mesh copper anode 5. The outer annular water-cooled anode output 6 is used as a flange for attaching the plasma electron source to the vacuum chamber of the experimental setup. The entire electrode structure is surrounded by a ceramic envelope 7, which serves as an isolator and electrode holder, and also seals the electrode system. The longitudinal (axial) magnetic field in the discharge volume is created with electro- or permanent magnets 8 for stable ignition and maintenance of a low-pressure gas discharge in the igniter and cathode modules.

Under the anode 5 there is a water-cooled copper electron collector 9. The upper surfaces of the anode 5 and collector 9 are covered with molybdenum coating. The external outputs of cathodes and anode are provided by water-cooling systems 10. The gas inlet 11 serves to supply the device with a working gas, in our experiments with hydrogen. The gas pressure was in the range of 10…50 Pa.

In the initial state, positive potentials of 1…2 kV, relatively to the cathode module, are applied to one of the electrical outputs of the spark semiconductor igniter 4 and the mesh anode 5 through ballast resistors of 10…20 kΩ. The supply of pulses with an amplitude of 2 kV and a duration of about 10 μs to the igniter 4 initiates an auxiliary glow discharge in the crossed fields inside the igniter module 3 between the igniter 4, as the anode, and the side wall of the output of the cathode part 2. Then the plasma of this glow discharge initiates, thanks to the openings on the upper plate of the cathode part 2, a glow discharge inside the cavities of the cathode cells with the anode 5. This discharge serves to stabilize the subsequent ignition of the working discharge to the electron collector 9.

The electron collector 9 is used for determination of the current of electrons extracted from cathode plasma. To determine the magnitude of the current of the extracted electrons, positive pulse voltage U are supplied to the electron collector 9 from a pulse modulator with L-C-R forming network and thyratron as a switch device. The modulator generated pulses with amplitude of up to 15 kV and duration of 10 μs at load current I of up to 1600 A. The value of I is considered as a value of the current of extracted electrons. The average current ~ 100 mA was set up by pulse rate regulation to reduce temperature effects.

One of the problems is the transition of high current glow discharge with cold hollow cathode in an arc discharge mode with sparking on the cathode surface. Cleaning that surface by ion bombardment and using refined cathode materials allows reducing probability of such transition. On this reason treatment of experimental devices by pulsed discharge with I = 400 A preceded to measurements.

2. RESULTS AND DISCUSSION

The volt-ampere characteristics ($U – I$) of the electron collector are presented in Fig. 2 for various d. B is induction of axial magnetic field within cylindrical cathode cells 2. At low currents (I < 200 A) the characteristics are rising, then after the extremum they are falling and when I > 800 A the current weakly influences on the discharge voltage. The behavior of the volt-ampere characteristics depends upon the cathode cell width d (see Figs. 2, 3). In Fig. 3, the parameter U_1 is the discharge voltage for d = 43 mm, that is for the hollow cathode with one cavity.

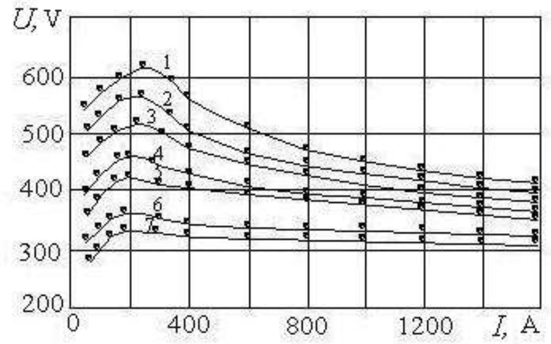

Fig. 2. The volt-ampere characteristics of the electron collector. B = 3 mT, p = 28 Pa; d, mm: 1 – 43, 2 – 14, 3 – 8.5, 4 – 6, 5 – 2, 6 – 3, 7 – 4

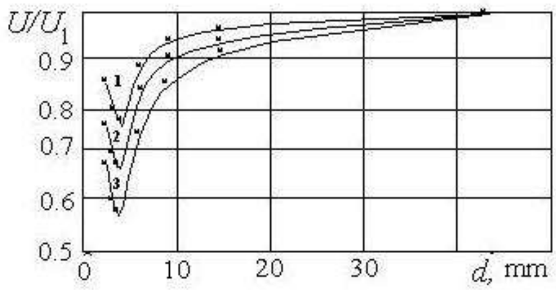

Fig. 3. Dependence of discharge voltage on the electron collector on the cathode cell width d. B = 30 mT, p = 28 Pa; I, A: 1 – 1500, 2 – 600, 3 – 200

As we see, the discharge voltage powerfully depends upon d when d < 14 mm and there is optimum $d \approx 4$ mm when the discharge voltage is minimum and has a practically constant value at different currents. It is reasonably to suppose these data reveal the great role of pendulum electrons and presence of the common negative glow for the two side cathode surfaces in the each cathode cavity. In our conditions, the near-cathode ion sheaths are collisionless and free paths of electrons are much more than d, therefore, gas ionization occurs mainly in the negative glow with participation of the oscillating cathode electrons. When d is small, fast hydrogen atoms (a part of the ions neutralized at the cathode and backscattered from opposite cathode surfaces) can enhance the secondary electron emission of cathode [7].

The axial magnetic field also influences on characteristics of the discharge. First of all, it is important to avoid a radial magnetic field preventing from igniting a discharge in the cathode cavities since the radial field lines prevent the diffusion of plasma particles downwards towards the anode. For this reason, the poles of the upper magnet create a magnetic field that is not counter to the magnetic field of the lower magnet. Fig. 4 shows the effect of the axial magnetic field upon the discharge voltage for various *d*: when $B < 10$ mT, igniting the discharge is impossible; when $10 < B < 30$ mT, increasing the magnetic field leads to decreasing *U*. At greater *B* the discharge voltage does not practically depend on *B*. The influence of the axial magnetic field is more when the width of cathode cavity *d* is larger.

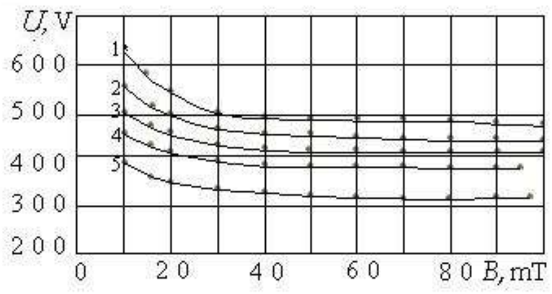

Fig. 4. Dependence of discharge voltage on the electron collector on the magnetic field induction B, I = 600 A, p = 28 Pa; d, mm: 1 – 43, 2 – 14, 3 – 8.5, 4 – 6, 5 – 4

The influence of gas pressure is shown in Fig. 5. The character of this influence depends upon the magnitude of the axial magnetic field.

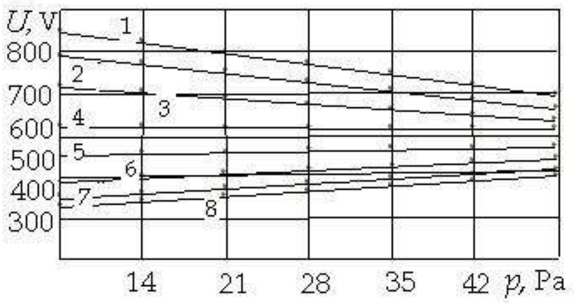

Fig. 5. Dependence of discharge voltage on the electron collector on hydrogen pressure, I = 200 A, d = 14 mm; B, mT: 1 – 10, 2 – 12, 3 – 18, 4 – 25, 5 – 30, 6 – 50, 7 – 65, 8 – 80

In the weak field the discharge voltage decreases with the gas pressure but in the stronger magnetic field the voltage increases with the pressure. Accordingly the effect of magnetic field is greater at low pressures, that is the gas pressure reduces the acting of the axial magnetic field, most likely due to more frequent collisions of electrons with gas molecules at higher pressures.

CONCLUSIONS

Studies have shown that the use of the pulsed plasma-generating discharge with a hollow cathode in the form of coaxial ring (toroidal) cells in axial magnetic field in the electron source allows for a stable collector current of up to 1600 A in an arc-free discharge in hydrogen at discharge voltages of hundreds of volts with relatively small dimensions of the cathode assembly. At a certain width of the cavity of the cathode cells (about 4 mm), the discharge voltage is minimal, and the current-voltage characteristic is weakly dependent on the current. Regulation of the discharge voltage can be carried out by changing the induction of the magnetic field.

The electron source can be used for energy switching in pulse techniques and in devices for high-current electronic processing of materials.

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ДОСЛІДЖЕННЯ ПЛАЗМОВОГО ДЖЕРЕЛА ЕЛЕКТРОНІВ З БАГАТОКОМІРКОВИМ ПОРОЖНИСТИМ КАТОДОМ

А.І. Кузьмичєв, І.В. Смирнов, Л.Ю. Цибульський

Досліджено характеристики імпульсного сильнострумового плазмового джерела електронів з холодним порожнистим катодом у магнітному полі та іонно-електронної емісії. Для зменшення катодної густини струму, усунення дугоутворення та мінімізації габаритів катодного блока використано багатокоміркову конструкцію із вкладених один в одного порожнистих циліндрів з утворенням коаксіальних кільцевих порожнин і системою ініціювання розряду в них. Електронний струм на колекторі становив сотні ампер при напрузі плазмогенеруючого розряду в сотні вольт і тиску водню 10…50 Па.