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LOW-PRESSURE UNIFORM PLASMA GENERATOR BASED ON HOLLOW CATHODE FOR ION PLASMA TECHNOLOGIES

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The current paper describes the results of the improvement of a volumetric high-current low-pressure plasma generator. The device was made on the basis of a hollow cathode with a gas-magnetron ignition of the discharge and an auxiliary arc discharge for the cathode heating up to thermionic emission temperature. The device was operated at a working gas pressure of 0.1...1 Pa and had an electron concentration of $10^{10}…5·10^{11}$ cm^{-3}. It was shown that the addition of the auxiliary electrode after the emission hole of the canoed unit lead to the improvement of generated plasma characteristics. This plasma generator may be used in the processes of ion-plasma technologies (oxidation, nitration in non-hydrogen media), as well as in energy-saving technologies of combined ion-plasma processing of structural materials.

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INTRODUCTION

The most advanced methods for plasma modification of the surface of structural materials (nitriding and oxidation, for example) are based on autonomous plasma arc sources [1]. Devices based on such discharges, in contrast to glow discharges, provide more flexible management of the technological parameters for the nitriding (oxidation) process, as well as significantly less ion sputtering of the processed materials, and allow the treatment of products of complex shape with holes of different diameters. Energy efficiency is also an important feature of devices based on these discharges, they allow the generation of bulk plasma with parameters (electron concentration in the plasma $10^{10}…5·10^{11}$ cm^{-3}) that ensure acceptable rates of heating and surface cleaning in the process of ion-plasma processing of materials and products.

But existing plasma generators based on arc discharge, both with a cold [2] and with an incandescent cathode [3, 4], are not without drawbacks. In the first case, there is a large number of microdroplets of the cathode material in the plasma flow, the separation of which leads to a decrease in the efficiency of the process. In the second case, the incandescent cathode has a limited-service life, which is tens of hours in inert gas and tens of minutes in an atmosphere of active gases, due to oxidation, as well as sputtering by ions coming from the discharge gap. In this regard, the development of reliable energy-efficient plasma generators with a large resource does not cease to be relevant.

One of the most important elements of plasma devices that determine reliability and service life is the cathode assembly of gas discharge plasma sources. The requirements for it increase in the case of using active gases in the plasma treatment process. The plasma generators with an incandescent cathode placed in a separate chamber and connected to the working volume through a diaphragm are well-known [5]. Such systems are characterized by a number of disadvantages, namely, the heating of the cathode to thermal emission requires a significant current, which leads to a limitation of the service life (due to self-spraying) [6], especially when the cathode is operated with large discharge current (tens of amperes). The use of a hollow thermal emission cathode significantly increases the service life of the cathode assembly in the arc discharge mode and allows working not only in a high vacuum but also at medium pressure (up to 10 Pa).

The main difficulty when working with a thermo-emissive hollow cathode is to ensure reliable discharge initiation since the ignition voltage exceeds significantly the voltage at which the discharge operates stably in continuous mode. This forces to creation of a special device for igniting and heating the hollow cathode to the temperature of thermoemission. There are several methods of heating the hollow cathode to the thermoemission temperature. In our experience [7] the most reliable method is the one in which initiation of a discharge with a hollow cathode and heating to the temperature of thermoemission is ensured by gas magnetron discharge in crossed electric and magnetic fields [8]. In this work, the hollow cathode was heated to thermoemission temperatures due to a high-voltage glow discharge.

Another disadvantage of plasma devices based on low-pressure arc discharge is the significant nonuniformity of the generated plasma. This leads to uneven surface treatment and/or reduction of the area that can be processed. The main task of this work is to search for the possibility to improve the uniformity of the radial distribution of electron concentration in the plasma working volume.

DESIGN AND PRINCIPLE OF ACTION

Fig. 1 shows the scheme of the experimental setup of a plasma generator with a thermoemission hollow cathode for ion-plasma technologies. In the plasma generator, cathode 2 with emission hole 4 is connected to vacuum chamber 1 through a ceramic insulator. Structurally, it is a tantalum tube (with a diameter of 4 and a length of 35 mm) inserted into a molybdenum housing. The argon which is a plasma-forming gas is supplied through the hollow cathode. This construction provides protection of the cathode assembly from the reactive gas which is entered directly into the working chamber. Anode 3 is located on the opposite side of the vacuum chamber. This is a flat disc made of stainless steel with a diameter of about 150 cm. As resources have shown, the diameter of the anode in the range of 50 to 250 mm practically does not affect the uniformity of electron concentration along the radius of the vacuum chamber. In order to improve the plasma distribution, there was a possibility to install an auxiliary electrode 5 in front of the emission hole of the hollow cathode at a distance of 10 cm. In the experiments, different electrodes with a diameter of 25 mm of conical shape with different angles at the top and with the possibility of applying a negative electric potential U1 to it were used [9].

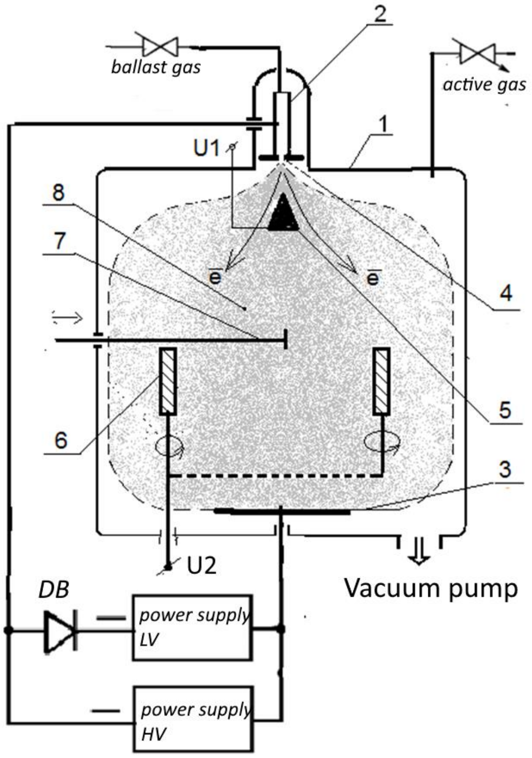

Fig. 1. Scheme of a gas discharge device for ion-plasma technologies: 1 – vacuum chamber; 2 – hollow cathode; 3 – anode; 4 – emission hole; 5 – reflective electrode; 6 – processed material holders; 7 – one-sided flat probe; 8 – plasma

Vacuuming the working chamber with a volume of 0.1 m^3 to a limit pressure of ~ 10^{-3} Pa was carried out by a steam-jet diffusion pump with a capacity of 1500 l/s. Gas supply of the installation and smooth adjustment of ballast and reactive gas pressure was carried out by needle injectors in the range of 10…10^{-1} Pa. A one-sided flat probe 7 with an area of 1 cm^2 was used for the continuous measurement of the saturation ion current. To form a homogeneous nitrided layer, sample holders 6 were installed around the perimeter of the working chamber and can rotate around their axis. The discharge is powered by high-voltage (starting stage) and low-voltage (working stage) power supply units. A blocking diode switch (DB) is installed to protect the low-voltage power supply unit.

When voltage was applied to the electrode system (hollow cathode – anode) and ballast gas (Ar) was injected into the hollow cathode, a high-voltage glow discharge ($U = 1000$ B, $I \leq 1$ A) was ignited and heating of the cathode began. The temperature of the hollow cathode raised up to the occurrence of thermionic emission, due to which the discharge switches to the low-voltage arc mode. As a result, the diode switch opened and the discharge was powered by a low-voltage power supply unit ($U = 35…80$ V, $I = 5…30$ A). By changing the discharge current, its power could be adjusted, reaching an electron concentration $n_e \approx 10^9…10^{11}$ cm^{-3} at the electron temperature of 1.4…3 eV. By applying a bias from a high-voltage power source ($U2 \leq 1300$ V), heating, degassing, and ion cleaning of parts were performed out in an inert gas plasma. When the working temperature of the samples was reached ($T = 450…550$ °C), the reactive gas (nitrogen) was injected into the chamber. Optimum nitriding conditions were achieved by adjusting the supply of reactive gas (nitrogen) [10].

RESULTS OF EXPERIMENTS

In the investigated installation, the hollow cathode forms a rather narrow stream of electrons with an energy of several tens of electron volts in the direction of the vertical axis of the device. Since the length of the electron's free path under such conditions is of the order of 10 cm, the electrons going out of the cathode experience only a few collisions on their way through the vacuum chamber, and therefore remain in the vicinity of the axial region. Thus, in such a device, the main volume of plasma is formed near the axis of the chamber and spreads to its edges with the help of ambipolar diffusion. This is visually confirmed by the presence of a bright glow of plasma in the center of the chamber, where the main processes of gas ionization and excitation take place.

If an auxiliary electrode at a negative potential to the cathode is installed at a distance of up to 10 cm in front of the emission hole of the hollow cathode, then in such a configuration one can be expected that a significant part of the electrons going out of the cathode will be deflected from the axis of the device. Thus, the presence of an additional electrode can lead to the fact that the majority of electrons will ionize the gas outside the central region of the discharge chamber, and therefore the uniformity of the plasma density in the chamber may be increased. Also, since the average length of the path of electrons from the cathode to the anode will become longer, we can expect an increase in the average number of ionization acts by one electron that leaves out of the cathode, and it will lead to an enlargement in the total amount of plasma generated in the chamber.

Fig. 2 shows the distribution of ion current density on the probe along the radius of the working chamber. Curve 1 corresponds to the case of no additional electrode present, curve 2 to an electrode with an angle at the top of 45°, curve 3 to an electrode with an angle to the top of 60°, and curve 4 to a flat electrode (which can be considered as a degenerate cone with an angle of 180°). In all cases of the presence of an additional electrode, it was located at a distance of 10 cm from the cathode, and its diameter consists of 25 mm. All curves were obtained with argon as the plasma-forming gas at a pressure in the vacuum chamber of 0.47 Pa. Discharge current was 27 A, and voltage was 52 V in all cases. The probe was located at a distance of 18 cm from the cathode.

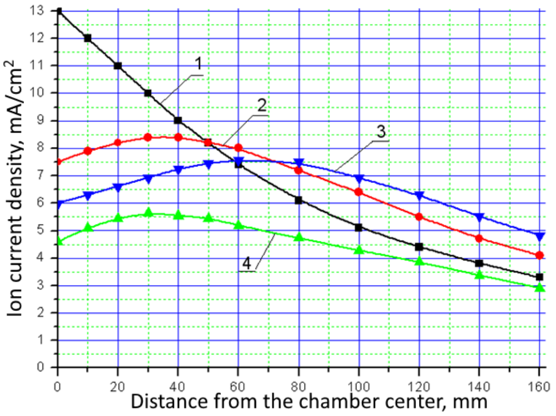

Fig. 2. Distribution of ion current density along the radius of the working chamber. 1 – without additional electrode; 2 – electrode with an angle of 45°; 3 – electrode with an angle of 60°; 4 – electrode with an angle of 180° (the flat one)

According to Bohm's formula [11], the concentration of ions in the plasma is directly proportional to the current density on the probe and has only a square root dependence on the plasma temperature. In addition, we do not expect significant changes in the plasma temperature depending on the radius in our case. Thus, it is more convenient to use direct measurements of the ion current density on the probe both for comparing the distribution of the plasma density along the radius and for the total amount of plasma generated in the working chamber.

Table shows the integral characteristics of the plasma when using different reflective electrodes. As the non-uniformity of the plasma density distribution, the ratio of the difference between the maximum and minimum of ion current density to the maximal value was taken. Taking into account their proportionality it is equal to the same ratio of plasma density:

$$\tau = \frac{n_{\max} - n_{\min}}{n_{\max}} = \frac{j_{\max} - j_{\min}}{j_{\max}}. \qquad (1)$$

The amount of plasma that was generated in the volume of the working chamber was estimated in arbitrary units according to the formula

$$N = C\int_0^R 2\pi r\, j(r)dr, \qquad (2)$$

where $j(r)$ is the current density depending on the radius, R is the radius to which the amount of plasma is estimated, and C is a common constant whose value is taken such that in the absence of an additional electrode, the value N would be equal to unity.

Integral characteristics of the plasma

N	Co-nangle	R = 16 cm		R = 12 cm	
		non-uniformity, τ	plasma amount, N	non-uniformity, τ	plasma amount, N
1	–	75%	1.00	66%	1.00
2	45°	51%	1.34	35%	1.38
3	60°	37%	1.29	20%	1.23
4	180°	48%	0.81	32%	0.78

As can be seen from the figure and table, the presence of a reflector leads to a significant reduction in the nonuniformity of the plasma density, as it was calculated by (1): from 75 to 50%, and even 40%. Also, with sharp angles of the cone of the additional electrode, the amount of plasma generated in the chamber increases by 30…35%. At the same time, the use of an electrode with large angles (as an extreme case – a flat electrode), although it may lead to a decrease in the nonuniformity of the plasma density, it significantly reduces the possibility of plasma forming in sufficient quantity. This is due to the fact that with reflective electrodes in the form of cones with obtuse angles, electrons begin to reflect back to the cathode, and thus make a smaller contribution to the plasma generation process in the main volume of the chamber.

The results look even better if we consider not the full radius of the working chamber, but only its central part with a radius of 12 cm, which is the most important for technological applications. This corresponds to a change in the upper limit of integration in (2) from $R = 16$ to 12 cm. In this case, even less density nonuniformity and/or a larger amount of plasma may be generated (see Table). Thus, by changing the angle at the top of the conical electrode and its distance to the emission hole of the hollow cathode, it is possible to obtain the necessary configurations of the radial distribution of the plasma concentration in the working volume of the chamber.

CONCLUSIONS

A plasma generator based on a low-pressure volumetric arc discharge with a thermoemissive hollow cathode has been developed. This allows someone to work with currents of tens of amperes in a plasma environment of reactive gases (O_2, N_2, H_2, etc.) with a long working life.

Installation of a conical electrode in front of the emission hole of the hollow cathode allows for reducing the nonuniformity of the radial distribution of plasma concentration in the working volume, as well as increasing the total amount of plasma generated in the chamber.

The volume plasma generator with high uniformity can be used in energy-saving technologies, for example, in nitriding, oxidation, coating, and other surface modification processes.

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ГЕНЕРАТОР ОДНОРІДНОЇ ПЛАЗМИ НИЗЬКОГО ТИСКУ НА ОСНОВІ ПОРОЖНИСТОГО КАТОДУ ДЛЯ ІОННО-ПЛАЗМОВИХ ТЕХНОЛОГІЙ

В.А. Хомич, А.В. Рябцев, В.Г. Назаренко

Описано результати удосконалення об'ємного сильнострумного генератора плазми низького тиску. Пристрій виготовлено на основі порожнистого катода з газомагнетронним запалюванням розряду та допоміжним дуговим розрядом для нагріву катода до температури термоелектронної емісії. Прилад працює при тиску робочого газу 0,1...1 Па і має концентрацію електронів $10^{10}…5·10^{11}$ см$^{-3}$. Показано, що додавання допоміжного електрода після емісійного отвору катодного вузла призводять до покращення характеристик генерованої плазми. Даний плазмогенератор може бути використаний в процесах іонно-плазмових технологій (окислення, нітрування в неводневих середовищах), а також у енергозберігаючих технологіях комбінованої іонно-плазмової обробки конструкційних матеріалів.