GENERATOR OF LOW PRESSURE VOLUME PLASMA WITH PLASMA ELECTRON SOURCE

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In the current paper the results of a study of a volumetric high-current low-pressure discharge with a plasma electron source are presented. The source 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 gas-discharge plasma was generated at a working gas pressure 0.1...1 Pa and hade an electron concentration of 10^{10}...(5×10^{11}) cm^{-3} in a volume of 0.1 m^3. Also the volt-ampere characteristics, the ion current density distribution in the working volume are presented for different discharge conditions. The 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. An improved electron plasma source with a hollow cathode will allow one to work in a wide range of discharge currents and also will be served for a large operating life of devices.

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INTRODUCTION

At present, methods of plasma modification of the structural materials surface (for example nitration and oxidation) are intensively developed using arc as plasma sources [1]. At the same time, unlike the glow discharge, the arc sources provided more flexible control of the technological parameters for the nitration (oxidation) process, such as less ion spraying of the processed materials and possibility to process items of complex shape with holes of different diameters. Being most energy-efficient, these methods allow generating volumetric plasma with parameters (electron concentration in plasma 10^{10}...(5×10^{11}) cm^{-3}) which ensure acceptable heating and surface cleaning rates during ion-plasma processing of materials.

Existing plasma generators based on an arc discharge with a cold [2] or incandescent cathode [3, 4], are not without shortcomings. In the first case, there are a large number of micro droplets of cathode material in the plasma stream. The separation of these droplets leads to a decrease in the total process efficiency. In the second case, the incandescent cathode has a limited lifetime which riche up to tens of hours in an inert gas environment and to tens of minutes in an atmosphere of active gases, as a result of oxidation, as well as sputtering by ions that come from the discharge gap. In connection with this, the development of reliable energy-efficient plasma generators with a long life resource does not cease to be relevant.

CONSTRUCTION AND PRINCIPLE OF ACTION

This paper presents the design and main characteristics of a plasma generator based on a non-self-sustaining low-pressure arc discharge with a plasma electron source on the basis of a hollow cathode with gas-magnetron ignition of the discharge and an auxiliary arc AC discharge for cathode heating to thermionic emission temperature. A volumetric (main) arc discharge was ignited between the plasma electron source and the anode located in the vacuum (working) chamber. In general, all plasma generators with continuous action based on an arc discharge at low pressure have considerable differences only in the design of their cathode assembly.

To create an arc discharge in plasma generators, cathodes are used that provide a current from a few to hundreds amperes. The choice of material and geometry of such cathodes have great influences on such important properties of the plasma generator as the service life, the time required for the source switching on, operation stability, input power and so on. The requirements become higher if there are active gases (O_2, N_2, H_2, CH_4, etc.) in the process of plasma treatment.

In the arc discharge mode, plasma sources of electrons based on a hollow thermionic emission cathode [5] are the most reliable and durable. They may operate not only in high but also in medium vacuum, at pressure up to 10 Pa. One may define the source of electrons with a plasma emitter as such electric discharge device that generates plasma from which electrons are injected into the working space, where in turn volumetric (technological) plasma is formed.

The main difficulty in working with a thermionic emission hollow cathode is ensuring of the discharge initiation reliable, since the ignition voltage is substantially higher than the voltage of the stable discharge operation in a continuous regime. To do this, it is necessary to create special devices for ignition and heating of the hollow cathode to thermionic emission temperature. There are several methods for heating the hollow cathode to such temperature. In one of the methods, a resistive heating of the hollow cathode is used. In this case a voltage is applied to the ends the cathode and while an electric current passes through it is heated up to the thermionic emission temperature [6].

This design is complex and insufficiently reliable, since it requires a large current (more than 100 A) to be supplied to the cathode. In another design, the hollow cathode is heated to thermionic emission temperatures due to an auxiliary high-frequency discharge [7]. This requires a separate high-frequency generator, which complicates the design of the cathode node and significantly increases its cost.

As it was shown in [8], the most reliable is the method in which the initiation of a hollow cathode discharge and heating to thermionic emission temperature is provided by a gas-magnetron discharge in crossed electric and magnetic fields [9]. But due to the fact that the working voltage of the magnetron discharge exceeds 250 V, the main drawback of this design is the intensive sputtering of the hollow cathode as a result of bombardment it by ions with energy greater than 200 eV. This reduces the lifetime of the electron source. To improve the plasma source of electrons with hollow cathode, its design was modernized [10], which allowed to work in a wide range of discharge currents and increased the operating life time of the device. In the plasma source of electrons, the hollow cathode is made of two electrically independent parts, each of which is connected to the AC power supply via an isolating transformer. This makes it possible to warm the hollow cathode to thermionic emission temperature due to the arc discharge of the alternating current.

Fig. 1 shows the experimental setup of a plasma generator with a plasma electron source for ion-plasma technologies. The plasma source of electrons was connected to the vacuum chamber 1 and consisted of a cylindrical anode 2 with a hollow cathode on its axis. The cathode was composed of two parts 3 and 4 (thin-walled tantalum tubes with a diameter of 4 mm and a total length of 60 mm), with a gap of 1...2 mm between them, and cathode reflectors 5, 6 attached to their ends. A magnetic system 7 consisted of permanent annular magnets, with a magnetic field on the B axis ≥ 0.07 T, and coaxially covered the anode. The upper reflector 5 hade a hole through which an inert gas (e.g. argon) was fed to the cathode. The aperture 8 in the bottom reflector 6 was used for extraction of the electron-plasma flow 9 into the vacuum chamber. To measure the plasma parameters (ion saturation current), a one-way flat probe 11 was introduced into the side opening of the vacuum chamber.

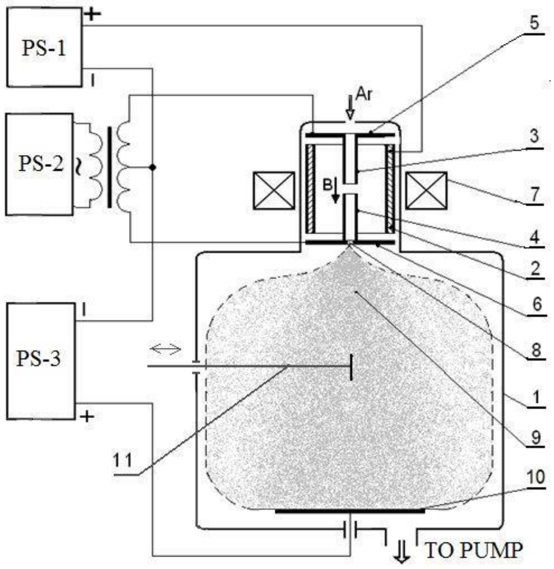

Fig. 1. The scheme of the experimental setup: 1 – vacuum chamber; 2 – anode of the plasma electron source; 3 and 4 – hollow cathode (consists of two parts); 5 and 6 – the cathode reflectors; 7 – magnetic system; 8 – emission aperture; 9 – plasma of the volumetric discharge; 10 – anode of the main discharge; 11 – probe

The gas-discharge device operated as follows. After evacuating the working chamber (the total volume 100 liters) to a pressure of 10^{-3} Pa, an inert gas (argon) was fed through a hollow cathode into the cylindrical anode. Smooth adjustment of the gas flow rate was realized by the leak valve in the range of 0.05...0.5 cm^3/s. The gas pressure in the volume of the working chamber was set within 0.1...1 Pa. The gas-magnetron discharge in the crossed electric and magnetic fields between the cylindrical anode and the parts of the hollow cathode was ignited by the PS-1 power supply unit. The ignition voltage of the gas-magnetron discharge did not exceed 800 V. Electrons under the action of crossed fields rotated around the cathode, which led to an increase in the probability of electron collisions with inert gas atoms, ionization of the gas and discharge combustion. Due to ion bombardment, parts of the hollow cathode were heated. The more the power of the magnetron discharge, the more the cathode was heated. The voltage and current of the magnetron discharge could be set within the limits of U_{dis} = 250…550 V and I_{dis} = 1…3 A respectively. Fig. 2 shows the calculated temperature of the hollow cathode (for our tantalum tube size), depending on the heating power. When the temperature of the hollow cathode reached 2300 K (dashed boundary in Fig. 2), a minimum thermionic emission (with current density 0.2 A/cm^2) was sufficient to provide ignition of the auxiliary arc discharge between the cathode parts. Due to the applied alternating voltage (an idle voltage was 160 V) from the power supply unit PS-2 through the

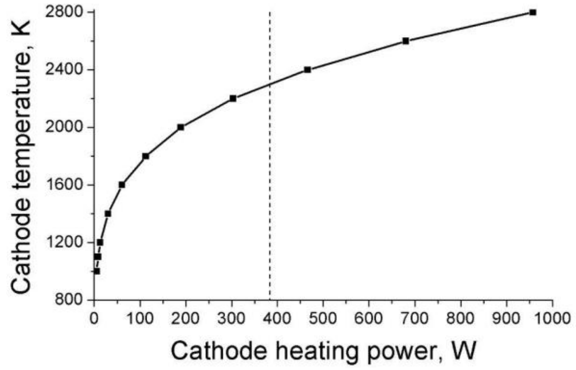

Fig. 2. Dependence of the temperature of the hollow cathode on the heating power

insolating transformer between the parts of the hollow cathode, an AC arc was ignited and as a result of its power both parts of the hollow cathode were heated up to higher temperature.

EXPERIMENTAL RESULTS

The current-voltage characteristic of the effective voltage and current for the auxiliary arc discharge (between two halves of the hollow cathode) and the dependence of the power introduced into the discharge on the current are shown in Fig. 3 (operating frequency of power supply was 50 Hz, argon consumption – 0.15 cm^2/s). In practice all AC discharge power went to heating parts of the hollow cathode. With a discharge voltage of 35...60 V and current in the range of 5...20 A, the parts of the cathode were heated up to a temperature of 2800 K. It provided the level of electron current emission from the cathode more than 10 A/cm^2. By injecting charged particles from the hollow cathode into the discharge gap, a reliable arc ignition and stable combustion of a volume arc discharge in the vacuum chamber between the anode of the main discharge 10 and parts of the hollow cathode from the discharge power supply unit PS-3 (see Fig. 1) was ensured. After this, the auxiliary magnetron discharge was turned off to prevent intensive sputtering of the hollow cathode. It is well known that the sputtering mainly occurs due to ion bombardment of the cathode material (self-sputtering). The cathode sputtering rate is proportional to the current strength and the square of the discharge voltage, and is practically independent of the kind of gas fed into the discharge gap [11]. In our cases the reduction of the discharge voltage below 100 V led to a sharp decrease in the cathode sputtering speed, which increased the durability of the cathode and significantly reduced the flow of pollutants. The combustion voltage of the auxiliary arc discharge between the parts of the hollow cathode was less than 55 V, and the magnetron discharge was more than 250 V. Thus, the intensity of sputtering in the arc discharge decreased, which considerably increased the durability of the plasma electron source. Fig. 4 shows the volt-ampere characteristics of a volume arc discharge with argon as plasma forming gas (flow rate 0.15 cm^3/s) for the case of the switched-off (curve 1) and activated (curve 2) auxiliary arc discharge for heating of the hollow cathode. In case when the auxiliary discharge was switched off, the volume arc discharge changed over to the mode of self-heating hollow cathode, where its heating was produced due to ion bombardment from the plasma situated inside the cathode cavity. In this case, the burning voltage of the discharge increased and the cathode sputtering also increased. In the case of an auxiliary arc discharge, the burning voltage of the main discharge was less, and the discharge itself had a high stability, especially at a high current (more than 30 A).

In Fig. 5 the spatial distributions of the density of the ion saturation current per probe are shown for two distances from the cathode. The probe was disposed in the cross section at a distance of 90 and 180 mm from the cathode. If the parts under treatment are not large in size and located along the perimeter of the working chamber, then the ion-plasma effect will not be inhomogeneous on them by more than 25 %. The heterogeneity of the parts can be reduced by using a planetary drive.

The plasma generator based on a non-self-sustaining low-pressure arc discharge was tested with argon and nitrogen as plasma-forming gases (the reactive gas was fed directly to the working chamber) with a discharge operating current in the range 5...50 A. The results of testing of the plasma generator with a plasma electron source showed high reliability, stable operation in all range of operating current and an increase in the service life of the device as a whole.

CONCLUSIONS

A plasma generator based on a volume low-pressure arc discharge with a plasma electron source made on the basis of a hollow cathode with a gas-magnetron ignition of the discharge and an auxiliary arc discharge for the

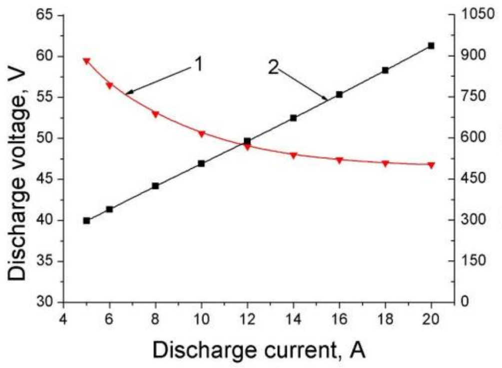

Fig. 3. 1 – Volt-ampere characteristic of the auxiliary arc discharge (between the two halves of the hollow cathode);

2 – the dependence of the power introduced into the discharge

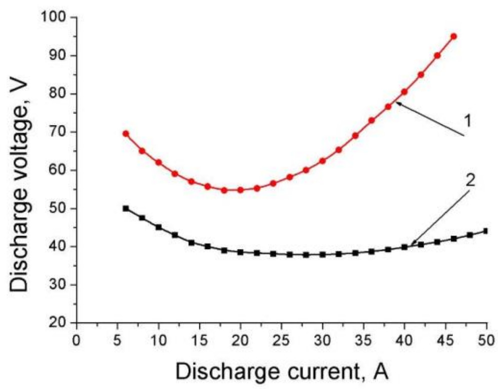

Fig. 4. Volt-ampere characteristics of volumetric arc discharge:
1 – auxiliary discharge is turned off; 2 – auxiliary discharge is switched on (discharge current is 12 A

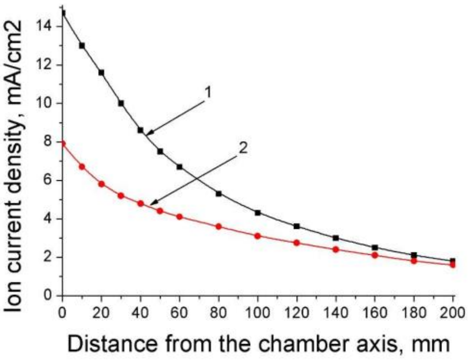

Fig. 5. Spatial dependences of the density of the ion saturation current on the probe for various distances from the cathode (argon gas, pressure in the working chamber – 0.4 Pa, volume (main) discharge current – 34 A, discharge voltage – 39 V, auxiliary discharge current – 12 A)

heating of the hollow cathode to thermionic emission temperature was developed. This device allows one to work with current up to tens of amperes in the plasma environment of reactive gases (O_2, N_2, H_2, etc.) with large service life duration. The volumetric plasma generator can be used in energy-saving technologies, for example, in nitration, oxidation, coating and other surface modification processes.

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ГЕНЕРАТОР ОБЪЕМНОЙ ПЛАЗМЫ НИЗКОГО ДАВЛЕНИЯ С ПЛАЗМЕННЫМ ИСТОЧНИКОМ ЭЛЕКТРОНОВ

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

Приведены результаты исследования объемного сильноточного разряда низкого давления с плазменным источником электронов, выполненным на основе полого катода с газомагнетронным зажиганием разряда и вспомогательным дуговым разрядом для разогрева катода до термоэмиссионных температур. Газоразрядная плазма, генерируемая при давлении рабочего газа 0,1…1 Па, имеет концентрацию электронов $10^{10}…(5·10^{11})$ см$^{-3}$ в объеме 0,1 м^3. Представлены вольт-амперные характеристики, зависимости распределения плотности ионного тока в рабочем объеме от условий разряда. Плазмогенератор может быть использован в процессах ионно-плазменных технологий (оксидирования, азотирования в безводородных средах), а также в энергосберегающих технологиях комбинированной ионно-плазменной обработки конструкционных материалов. Усовершенствованный плазменный источник электронов с полым катодом позволит работать в широком диапазоне разрядных токов и с большим рабочим ресурсом устройства.

ГЕНЕРАТОР ОБ'ЄМНОЇ ПЛАЗМИ НИЗЬКОГО ТИСКУ З ПЛАЗМОВИМ ДЖЕРЕЛОМ ЕЛЕКТРОНІВ

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Наведено результати дослідження об'ємного дугового розряду низького тиску з плазмовим джерелом електронів, виконаним на основі порожнистого катода з газомагнетронним запалюванням розряду і допоміжним дуговим розрядом для розігріву порожнистого катоду до термоемісійних температур. Газорозрядна плазма, утворювана при тисках робочого газу 0,1…1 Па, має концентрацію електронів $10^{10}…(5·10^{11})$ см$^{-3}$ в об'ємі 0,1 м^3. Надано вольт-амперні характеристики та залежності розподілу густини іонного струму в робочому об'ємі від умов розряду. Плазмогенератор може бути використаний в процесах іоно-плазмових технологій (оксидування, азотування в безводневих середовищах), а також в енергозберігаючих технологіях комбінованої іонно-плазмової обробки конструкційних матеріалів. Вдосконалене плазмове джерело електронів з порожнистим катодом дозволить працювати в широкому діапазоні розрядних струмів і з більшим робочим ресурсом пристрою.