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INFLUENCE OF POWER SOURCE TYPE ON TIME DEPENDENCE OF THE PLASMA PARAMETERS OF A PULSE DISCHARGE WITH A HOLLOW CATHODE

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Peculiarities of the time dependence of the plasma parameters of a pulsed discharge with a hollow cathode in low-pressure argon were experimentally determined when using two types of pulsed high-voltage power sources – voltage and current sources (pulse duration up to 10 ms, voltage up to 10 kV). It is shown that the use of pulsed current sources provides significantly more stable discharge glow in the working range of argon pressure variations $(2.5…10)\cdot10^{-4}$ Torr. At the same time, the temperature of plasma electrons of the discharge which was powered by a voltage source, was several times higher and could reach 40 eV.

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INTRODUCTION

Erosive metal plasma sources based on vacuum-arc discharges are widely used to create various coatings. However, the presence of microdroplets with a size of ~ (0.01…100) μm in the plasma flow leads to a significant deterioration of the functional characteristics of the coatings. Removal of microdroplets larger than ≈ (1…2) μm is achieved by fairly simple methods, while further cleaning of the plasma flow requires a significant complication of the existing “filters” and simultaneously leads to a decrease in the flow of metal plasma. At the same time, the presence of microdroplets with a size smaller than ≈ (0.1…0.2) μm is quite acceptable when creating a certain class of coatings. 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. Existing systems created on the basis of pulsed arc discharges have a number of significant drawbacks, in particular, the low energy of the ions that heat the microdroplets. In previous direct experiments [1-4] it was established that the use of a pulsed discharge plasma with a hollow cathode (HC) allows several times reducing the number of Ti microdroplets with a size of ≈ (0.1…0.6) μm. Preliminary calculations also showed that the rate of evaporation of Ti microdroplets with a size from 0.2 to 2 μm depends in a complex way on the density and temperature of plasma electrons, floating and plasma potentials. But, as is known, with the same discharge geometry and gas pressure, the plasma parameters are significantly affected by the type of discharge power source. Therefore, the purpose of the presented research was a detailed study of the dependence of plasma parameters when using two types of sources – a voltage source and a current source.

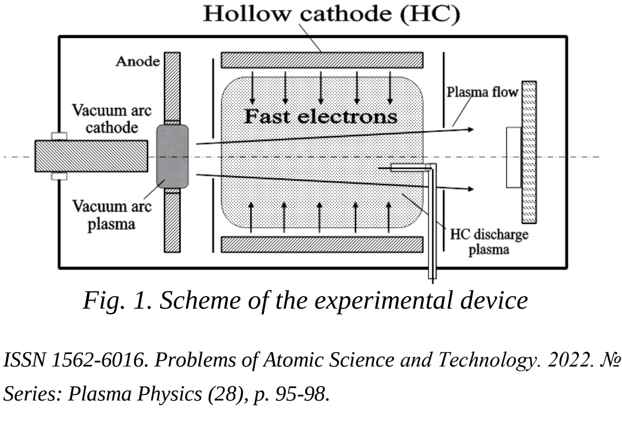

Fig. 1. Scheme of the experimental device

1. EXPERIMENTAL DEVICE AND MEASUREMENT METHODS

Fig. 1 shows the block diagram of the experimental device. Cylindrical hollow cathode 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 with a 30 mm hole, and on the side of the collector with substrates – an output with a hole with a diameter of 50 mm. This entire device was located inside a grounded vacuum chamber. The collector, which was located at a distance of 25 mm from the output diaphragm, could be at “ground” or floating potential. The grounded anode of the arc discharge simultaneously served as the second anode of the HC discharge. With a floating potential of the collector, the wall of the grounded vacuum chamber could also have a certain influence on the discharge glow mode due to the plasma leakage into it between the "floating" diaphragm and the collector.

Sources of two types were used to power the HC discharge. The output impedance of the first power source at a frequency of 1 kHz was ≈ 1.5 kΩ with an ohmic resistance of the discharge plasma of ≈ (1 … 3) kΩ. Therefore, in the zero approximation, this power source can be considered as a voltage source. The repetition rate 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 0.2…10 Hz.

The second power supply is built using a high-voltage transformer with a total inductance of 36 H. As is known, the dynamics of the current I in a circuit with an inductive limiter L satisfies the equation $dI/dt = U/L$, where U is the voltage on the inductor. At the same time, the voltage at the output of the source can take any values allowed by this source. The consequence of this is the shape of the graphs, significantly different from those previously obtained for powering the discharge from the voltage source. Namely, the discharge current rises and falls slowly, without any fluctuations.

The device worked as follows. At the moment of time $t \approx 0$, a vacuum-arc discharge was ignited with a current of 120 A and a peak duration of about 1 ms (the frequency of current pulses was 1…2 Hz) and the flow of Ti plasma together with microdroplets 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. This discharge goes through several phases or stages: a stage of non-self-sustained discharge, intermediate and self-sustained discharge with the effect of a hollow cathode. At the moment of self-discharge in the HC, plasma particles of the arc plasma have already left its volume, and microdroplets are just beginning to enter. These microdroplets are heated and vaporized due to interaction with particles (electrons and ions) of the hollow cathode discharge plasma.

During the research, the pressure of argon P in the cathode varied within $(2…10)\cdot10^{-4}$ Torr.

Plasma parameters were measured using three single Langmuir probes located at a radius of 30 mm and at distances of 40, 110, and 180 mm from the input aperture (these probes were also shifted by an angle of 120^0 from each other). A Hantek iDSO-107A oscilloscope was used to obtain the time dependences of the current of the probes at different voltages. The peculiarity of this oscilloscope was the absence of galvanic connection with the computer during measurements – the transmission of the useful signal was done via Wi-Fi.

2. EXPERIMENTAL RESULTS AND DISCUSSION

2.1. LOW IMPEDANCE SOURCE

The study of the I-V characteristics and the discharged plasma parameters was carried out at three values of argon pressure – $2.7\cdot10^{-4}$, $4\cdot10^{-4}$, and $8\cdot10^{-4}$ Torr. Typical plots of current, voltage and I-V characteristic of the discharge was obtained from these data, are presented in Fig. 2. (Zero on the time axis corresponds to the moment of arc discharge ignition).

During its glow, this HC discharge goes through several phases or stages:

I – the phase of a non-self-sustained discharge, which is supported due to the injection of plasma particles of the arc discharge into the volume of the cathode. The duration of this phase is determined by the duration of arc discharge operation (in the case presented in Fig. 2, this duration is ≈ 5 ms);

II – the phase of the intermediate discharge (that is, the transition process) that takes place during the transition from a non-self-sustained discharge to a self-sustained one with the effect of a hollow cathode. In fact, this process begins from the moment when charged particles enter the hollow cathode at back front of the arc and lasts from ≈ 0.5 to 0.8 ms of the glow;

III – self-sustained discharge phase with the effect of a hollow cathode - from 0.8 ms to 3.0 ms.

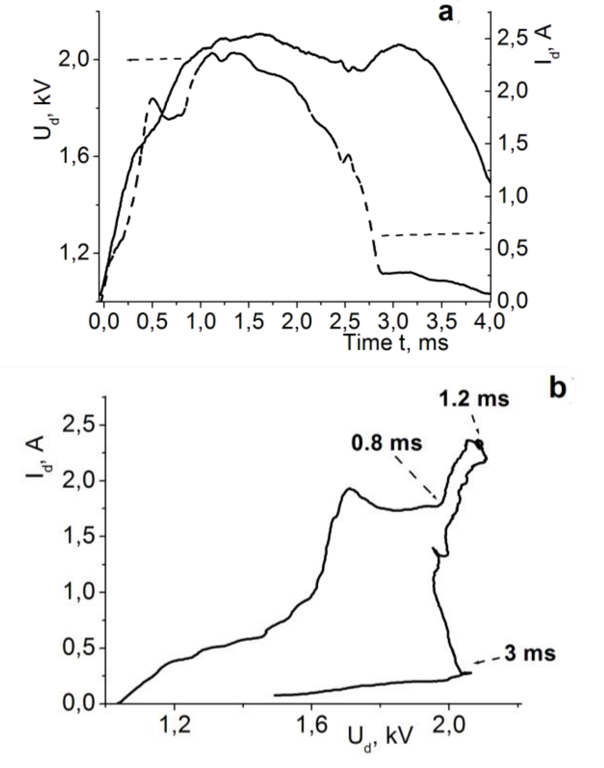

Fig. 2. Plots of discharge current and voltage (a) and I-V characteristics of the discharge (b) when using a voltage source. Argon pressure $4\cdot10^{-4}$ Torr

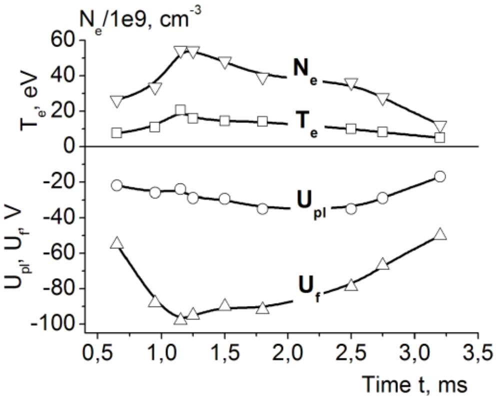

Fig. 3. Time dependences of plasma parameters of HC discharge when using a voltage source. Argon pressure $4\cdot10^{-4}$ Torr

Most measurements of plasma parameters were performed using a probe that was located at a distance of 110 mm from the input diaphragm (ie, in the middle plane of the HC). The results of measurements in the case of a discharge in argon at a pressure of $4\cdot10^{-4}$ Torr are presented in Fig. 3. As can be seen from the figure, the values of the temperature T_e, the density N_e of plasma electrons and the floating potential U_f initially increase sharply with time t, reaching their maximum values at t ≈ 1.2 ms (which coincides with the moment of the maximum value of the discharge current I_d), and then begin to decrease monotonically with t increase. In turn, the plasma potential U_p shows a monotonous increase up to t ≈ 2.5 ms.

At all the pressures used, the time dependences of the temperature values T_e show the same non-monotonic behavior in general, with maxima at t ≈ 1.2 ms (Fig. 4,a), although the shapes of the dependences are slightly different. Namely, while at Ar pressures $2.7\cdot10^{-4}$ and $4\cdot10^{-4}$ Torr after reaching the maximum values of t (≈ 40 and 20 eV, respectively), the temperature T_e decreases almost linearly down to the value of ≈ 8…10 eV at the end of the discharge glow, then the temporal behavior of Te in the case of the maximum used pressure of $8\cdot10^{-4}$ Torr is somewhat different. This time dependence has a bell-shaped appearance – T_e in the discharge also rapidly increases from ≈ 8 to ≈ 20…25 eV, but then decreases just as quickly, reaching ≈ 6 eV already at t ≈ 2 ms.

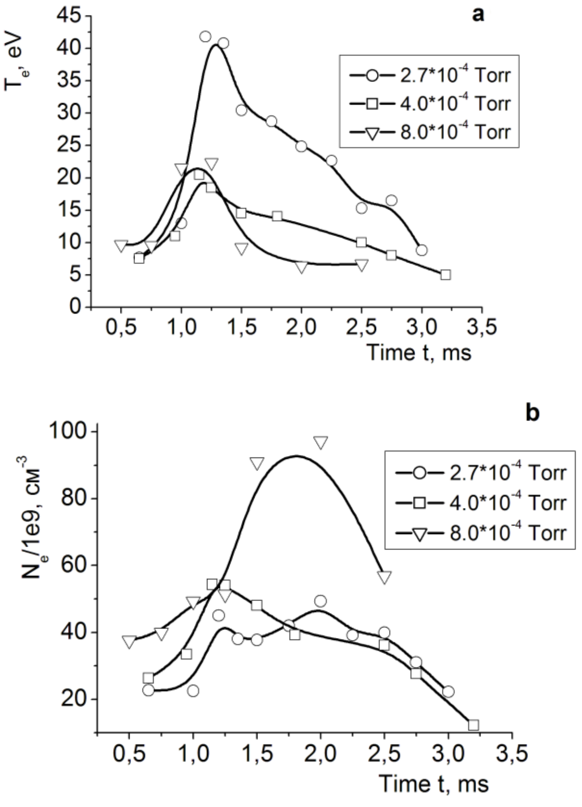

Fig. 4. Time dependences: temperature T_e (a) and plasma density N_e (b) of a HC discharge at different argon pressures in the case of using a voltage source

The temporal behavior of the plasma density N_e at an argon pressure of $8\cdot10^{-4}$ Torr is also significantly different from the cases of lower argon pressures. While at lower Ar pressures, the plasma density during the glow varies within ≈ $(30…50)\cdot10^9$ cm^{-3}, then in the case of $P = 8\cdot10^{-4}$ Torr, the density N_e shows significantly non-monotonic behavior. It rapidly increases from ≈ $40\cdot10^9$ at the beginning of discharge glow to ≈ $100\cdot10^9$ cm^{-3} at t ≈ 2 ms.

2.2. HIGH IMPEDANCE SOURCE

The study of the I-V characteristics and the discharge plasma parameters was also carried out at three argon pressures – $2.4\cdot10^{-4}$, $4\cdot10^{-4}$, and $9\cdot10^{-4}$ Torr. Typical plots of current, voltage and I-V of the discharge, which was obtained from these data, are presented in Fig. 5.

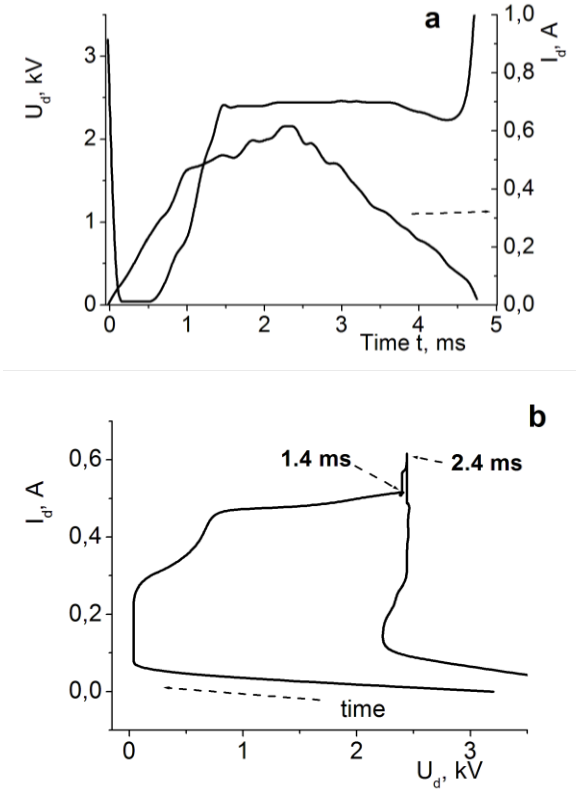

Fig. 5. Plots of discharge current and voltage (a) and discharge I-V characteristics (b) when using a source with a high output impedance. Argon pressure $2.4\cdot10^{-4}$ Torr

As can be seen from the comparison of these figures, at the transition from a non-self-sustained mode to a self-sustained one with the HC effect the discharge current does not exhibit any fluctuations, and the discharge voltage quickly reaches its quasi-stationary value. After the disappearance of the discharge current, there is a significant jump in the discharge voltage associated with the release of energy stored in the inductor. It should be noted that, in contrast to the case of a voltage source, when conducting research with a source with increased output impedance, the maximum discharge current was limited to ≈ 0.5…0.6 A.

Let us now consider the results of measuring plasma parameters. As in the case of using a voltage source, measurements were made using a probe at a distance of 110 mm from the input diaphragm. The results of measurements carried out at an argon pressure of $4\cdot10^{-4}$ Torr are presented in Fig. 6.

Comparison with Fig. 4 shows that the electron temperature T_e also reaches its maximum value at $t \approx 1.5$ ms and subsequently decreases with time. However, its value is approximately two times smaller, and is ≈ 10 eV.

Argon pressure variation does not significantly affect both the shape of the temporal behavior of temperature T_e and the density N_e of plasma electrons. It should only be noted that decreasing the Ar pressure to $2.4 \cdot 10^{-4}$ Torr leads to some increase in the maximum value of T_e – by approximately 20…30%.

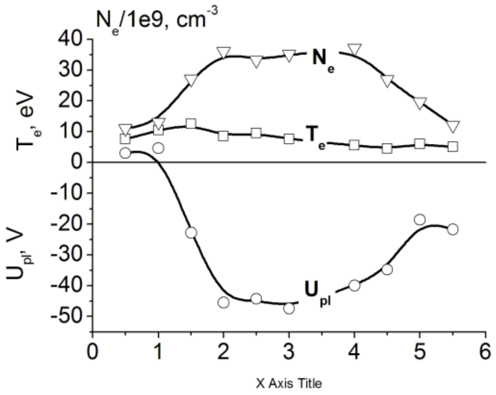

Fig. 6. Time dependences of plasma parameters of HC discharge when using a source with high output impedance. Argon pressure 4×10^{-4} Torr

CONCLUSIONS

The peculiarities of the time dependence of the plasma parameters of a pulsed discharge with a hollow cathode in low-pressure argon were experimentally studied when using two types of pulsed high-voltage power sources – voltage and current sources (pulse duration up to 10 ms, voltage up to 10 kV). It is shown that the use of pulsed current sources provides significantly more stable discharge glow in the working range of argon pressure variations ($(2.5…10) \cdot 10^{-4}$ Torr). At the same time, the temperature of plasma electrons of the discharge, which was powered by a voltage source, was several times higher and could reach 40 eV.

At present, it is not entirely clear what mechanism is responsible for the rise of the electronic temperature to ≈ 40 eV at the use of a voltage source. At the same time, previous measurements showed that exactly at this time interval $t \approx (1.0…1.5)$ ms, that the electric field in the plasma reaches its maximum values – up to ≈ 10 V/cm (or $\approx 10^5$ Td). It is possible that the existence of this electric field is the particular cause of the found increase in plasma temperature.

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ВПЛИВ ТИПА ДЖЕРЕЛА ЖИВЛЕННЯ НА ЧАСОВІ ЗАЛЕЖНОСТІ ПАРАМЕТРІВ ПЛАЗМИ ІМПУЛЬСНОГО РОЗРЯДУ З ПОРОЖНИСТИМ КАТОДОМ

В.Ю. Баженов, В.В. Ціолко, В.М. Піун

Експериментально знайдено особливості часових залежностей параметрів плазми імпульсного розряду з порожнистим катодом у аргоні низького тиску при використанні двох типів імпульсних високовольтних джерел живлення – джерел напруги та струму (тривалість імпульсів до 10 мс, напруга до 10 кВ). Показано, що використання імпульсних джерел струму забезпечує значно більш стабільне горіння розряду в робочому діапазоні змін тиску аргону $(2.5…10) \cdot 10^{-4}$ Торр. У той же час температура електронів плазми розряду, який живився джерелом напруги, була в кілька разів більшою і могла сягати 40 еВ.