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Characteristics of a quasi-stationary non-self-sustained pulsed gas discharge with a hot cathode

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Abstract. The paper presents the electrode system and main characteristics of a non-self-sustained pulsed discharge with a hot cathode operating in argon at a pulse repetition frequency of 5 kHz and pulse duration of 50 μs. It is found that during the operation at a pressure of 0.3 Pa, the discharge current can reach amplitudes of up to 300 A and more with a rather high average discharge current of ≈ 100 A and low average discharge operating voltage of less than 20 V. The ion current from the discharge plasma to a Langmuir probe oscillates at frequency of about 100 kHz.

1. Introduction

Increasing the quality and efficiency of vacuum plasma treatment requires new technologies and equipment. In particular, there is a need for efficient plasma sources which provide a plasma density as high as $10^{11}\div10^{12}$ cm^{-3} and allow, for example, high-quality surface cleaning dominated by impurity ion sputtering against adsorption [1]. In the 1990s, a bulk plasma generator based on a thermionic-cathode non-self-sustained arc was designed [2–4] and till now this type of generators, due to its design simplicity and plasma generation efficiency, is one of the most acceptable and reliable technological tools for cleaning, etching, nitriding, doping, and plasma-assisted coating deposition. The generator uses a thermionic or so-called hot cathode, making possible the generation of high-density ($\geq 10^{11}$ cm^{-3}) plasma controllable in a wide pressure range (0.1÷1 Pa). At the same time, the lifetime of a hot cathode is limited (tens of hours) and its use in a plasma generator limits the continuous operation of the source. As has been shown [4], the limiting wear of a hot cathode is defined by the operating voltage of a non-self-sustained arc discharge, and decreasing this voltage from 85 to 28 V in a plasma generator allows a seven-fold increase in the cathode lifetime. The present paper studies the operation of a hot-cathode plasma generator based on a quasi-stationary non-self-sustained pulsed discharge with the aim to decrease the average discharge operating voltage, reduce the loads on the hot cathode, and enhance the efficiency of attaining the desired discharge current and plasma density.

2. Experimental arrangement

An experimental arrangement of the hot-cathode plasma generator based on a quasi-stationary non-self-sustained arc discharge is shown in figure 1.

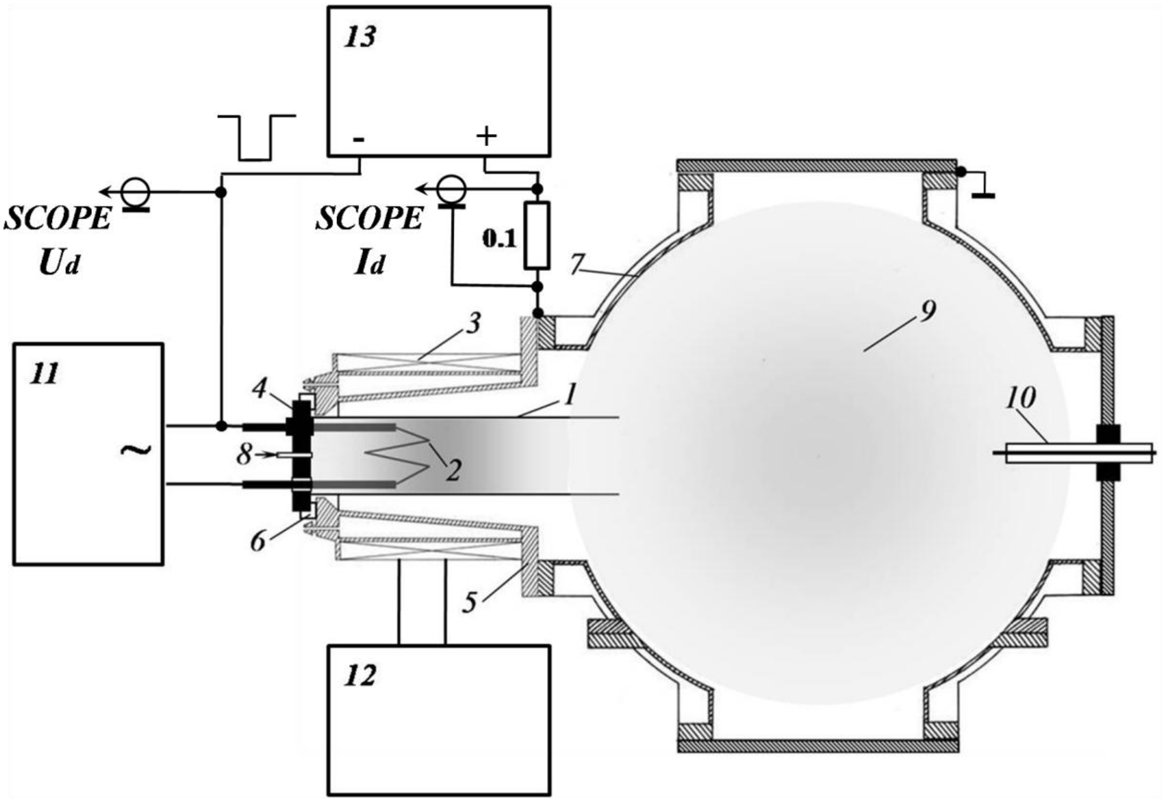

Figure 1. Hot-cathode plasma generator based on a quasi-stationary non-self-sustained pulsed arc.

The main element in the electrode system of the plasma generator is its composite cathode comprising cylindrical hollow stainless steel cathode *1* of diameter 86 mm and length 380 mm with hot tungsten cathode *2* in the form of a spiral (filament) on the inside. The composite cathode is mounted on the water-cooled flange of cathode assembly *4* insulated from water-cooled case *5* of the plasma generator via insulator *6* and is placed in a longitudinal magnetic field of 0.02 T produced by solenoid *3*. Case *5*, which is at anode potential, serves for mounting the plasma generator on vacuum chamber *7* (hollow anode) to produce gas discharge plasma in the chamber through ignition of an arc discharge. The arc is ignited as follows. Alternating voltage and current source *11* provides heating of the hot cathode to the desired thermionic emission current from its tungsten filament. Direct current source *12* powers the solenoid to produce a magnetic field of 0.02 T from the cathode cavity of the plasma generator. Discharge power supply *13* with a no-load voltage amplitude of 90 V produces a train of voltage pulses with a duration of 50 μs and repetition frequency of 5 kHz. As the pulses are applied between the vacuum chamber (anode) and composite cathode (electrically connected hollow and hot cathodes), the electrons emitted by the hot cathode are accelerated along the magnetic field lines toward the anode the role of which is played by the inner walls of the vacuum chamber. Gas supply *8* to the cathode cavity of the plasma generator creates a region of increased pressure near the hot cathode. The region of increased gas molecule concentration and the flow of accelerated electrons whose paths are lengthened by the magnetic field assist the initiation of ionization processes. The electrons reflected from the cathode cavity as a potential barrier execute an oscillatory motion in the cavity, efficiently ionize the working gas molecules, and provide the ignition of a non-self-sustained diffuse arc discharge the operation of which is ensured by thermal electron emission from the hot cathode. The discharge operates between the cathode (electrically connected hollow and hot cathodes) and the anode (inner walls of the vacuum chamber). Gas discharge plasma *9* rather uniformly fills the cavity of the vacuum chamber and provides a medium for surface treatment of objects. The discharge plasma density was estimated by measuring the ion current density from the plasma with Langmuir probe *10* at a distance of 330 mm from the exit aperture of the hollow cathode of the plasma generator.

The characteristics of the plasma generator were studied during its operation with argon. The cylindrical vacuum chamber was 600 mm in diameter and 500 mm in height and was pumped to a residual vacuum of 10^{-3} Pa by a cryogenic pump rated at 1000 l/s. The hot cathode in the experiments was a tungsten (VA) filament of diameter 0.8 mm and working length 150 mm. The filament heating power of the hot cathode P_f was calculated by multiplying the effective values of the alternating filament current I_f and voltage U_f; for example, P_f=56.3 A (I_f) × 16.5 V (U_f)≈ 929 W.

The pulse and average discharge currents I_d were calculated from oscillograms of discharge current signals taken with a shunt (0.1 Ω), as shown in figure 1. The pulse and average discharge voltages U_d were calculated in the same way through direct oscilloscope measurements.

3. Results and discussion

Figure 2 shows typical waveforms of the current I_d (a) and voltage U_d (b) of the quasi-stationary non-self-sustained pulsed arc discharge at an argon pressure of 0.3 Pa and filament power of 580 W. A signal of the saturation ion current density j_p from the argon plasma to the Langmuir probe at a constant negative bias of U_p=200 V with respect to the vacuum chamber (anode) is presented in figure 2 (c). The signal was taken by the oscilloscope in sync with the discharge current and voltage.

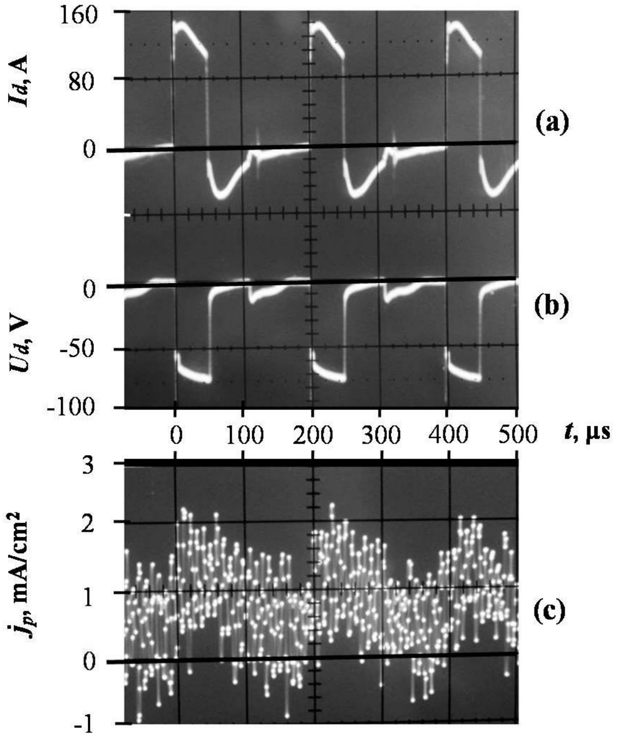

Figure 2. Typical waveforms of the current I_d (a) and voltage U_d (b) of the quasi-stationary pulsed discharge and saturation ion current density j_p (c) from the argon plasma to the Langmuir probe for the indicated discharge current and voltage at an argon pressure of 0.3 Pa and filament power of 580 W.

It is seen from figure 2 (c) that the ion current density from the discharge plasma reveals oscillations with a peak-to-peak amplitude of 1.4 mA/cm^2 which is higher than the average ion current density equal to about 1.2 mA/cm^2 for the indicated values of the discharge current and voltage. The ion current continues to oscillate with the same amplitude even after cessation of the voltage pulses and discharge current. The average ion current density, by estimates from figure 2 (c), can be taken equal to 0.8 mA/cm^2. The pulse discharge current I_d and voltage U_d calculated from the oscillograms in figure 2 (a) and (b) approximate 128 A and 70 V, respectively, and their average values measure about 32 A and 17.5 V. The average discharge current and voltage were determined through dividing the pulse discharge current and voltage by 4, because the discharge pulse duration is 1/4 of the pulse train period.

Figure 2 (c) suggests that during the pulse-to-pulse pause equal to 150 μs, the gas discharge plasma formed by the pulses does not actually decay (recombine) in full, the discharge gap remains filled with the plasma, and the density of the ion current arrived at the probe is about 0.5 mA/cm^2. Thus, it can be concluded that during the pulse-to-pulse interval, the plasma density decreases about 2.4 times due to deionization of the discharge gap in the absence of discharge voltage. During the pulses, the plasma density increases again such that the average ion current density from the plasma measures 1.2 mA/cm^2. This discharge allows maintenance of the quasi-stationary plasma in the vacuum volume with an average ion current density of 0.8 mA/cm^2 (at an average current of 32 A).

The rise of violent oscillations in the ion current to the probe can be due to excitation of plasma oscillations inherent in beam-plasma collective interactions [5]. Really, in our case, the electron beam emitted from the hot cathode of the plasma generator is injected into the gas discharge plasma of the vacuum volume under the action of pulse voltage.

Thus, in our case, it is the excitation of plasma oscillations at ~100 kHz and deep modulation from 0.6 to over 1 in the average ion current during the pulse train period (figure 2) which is responsible for the increase in the ion current density from the plasma if we consider the peak values of this density. The oscillatory character of the ion current density from the discharge plasma can play a positive role in terms of increasing the efficiency and quality of ion plasma treatment and applying the plasma of this type of discharge, similarly to high-frequency discharges, for surface treatment (cleaning, etching) of dielectric materials and products.

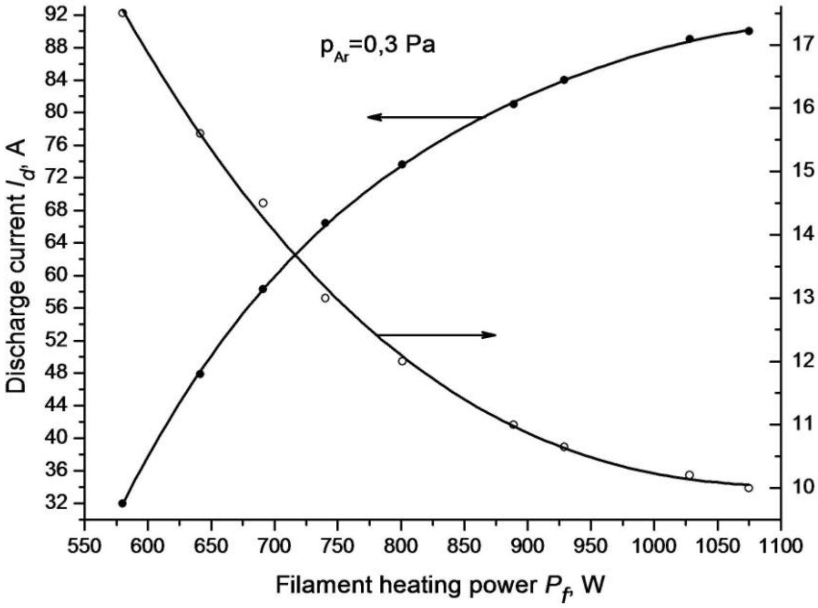

Figure 3. Average current and voltage of the quasi-stationary pulsed discharge vs the filament heating power of the hot cathode.

The discharge system and discharge power supply *13* (figure 1) with a fixed no-load voltage amplitude of 90 V admits control of the discharge current merely by varying the thermionic emission current from the hot cathode of the plasma generator through varying the filament power. Figure 3 shows the dependence of the average current and voltage of the quasi-stationary non-self-sustained pulsed arc discharge on the filament power of the hot cathode at an argon pressure in the vacuum chamber of 0.3 Pa. It is seen from the dependence that the discharge system makes it possible to attain rather high (up to ≈ 90 A) average discharge currents at extremely low (≈ 10 V) average discharge voltages. The average discharge current equal to 32 A for the oscillograms in figure 2 corresponds to the first left point on the dependence in figure 3 (at a filament power of P_f=580 W) and is the minimum value in the range of average discharge currents produced by the plasma generator with the hot cathode comprising a single tungsten filament.

For all discharge currents in the range studied, the ion current from the quasi-stationary argon plasma to the probe at a negative bias of U_p=200 V with respect to the anode (figure 3) also reveals high-frequency modulations like those in figure 2 (c). It should be noted that calculations similar to the calculation from the oscillograms in figure 2 (c) show that the average ion current density from the quasi-stationary pulsed discharge plasma is about three times higher than that from the argon plasma produced at the same argon pressure with the same electrode system, same vacuum chamber, and same positioning of the probe but in the continuous (direct current) mode of the plasma generator [4]. So, for example, for the pulsed operation of the plasma generator at an average current of 32 A (figure 2), the average ion current density to the probe was 1.2 mA/cm^2, whereas that for the continuous operation at 32 A was merely≈ 0.4 mA/cm^2 [4]. For producing the argon plasma with the above ion current density in the continuous mode of the plasma generator at 32 A, the discharge operated at a voltage of 60 V.

The first conclusion on the advantages of the quasi-stationary non-self-sustained pulsed arc discharge system based on a hot cathode is its high efficiency to generate discharge currents compared to the same electrode system but operating in the continuous mode [4]. So, for example, the average discharge current 32 A in the continuous mode is attained at a discharge operating voltage of 60 V, whereas the same current in the pulsed mode is ensured at an average discharge operating voltage of a mere 17.5 V, and this allows an about 3.4-fold decrease in the energy expended for attaining the same discharge current. Also, as shown above, the quasi-stationary pulsed discharge provides a high plasma generation efficiency which, according the estimates from the saturation ion current to the probe, is three times that in the continuous mode of the plasma generator at the same discharge current.

4. Conclusion

Thus, the designed gas discharge system based on a quasi-stationary non-self-sustained arc discharge with a hot cathode demonstrates a high plasma generation efficiency which is several times greater than the efficiency of a dc non-self-sustained arc discharge. The short discharge pulses (50 μs) with short rise times spaced by rather long intervals provide the formation and maintenance of the gas discharge plasma the density of which is about three times greater than that in the stationary discharge. The advantages of the plasma generator based on a quasi-stationary pulsed discharge provide much promise for its use in ion plasma treatment of various materials and products, including dielectrics and products with composite surfaces.

Acknowledgments

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