FORMING A UNIPOLAR PULSED DISCHARGE IN NITROGEN

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This paper reports the current and voltage oscillograms of the pulsed discharge in the wide frequency range (from 20 to 300 kHz) with the duty cycle from 15 to 85 % for two values of the nitrogen pressure 0.1 and 1 Torr. It has been demonstrated that the current oscillograms of the pulsed glow discharge possess a plasma phase and an afterglow phase. The following stages of the plasma phase have been observed: 1. A pulse of the capacitive current of about 0.5…1 μs in duration; 2. A stage of current growth which duration has depended on gas pressure; 3. Current decrease occurring during tens of microseconds down to the level corresponding to the constant voltage discharge.

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INTRODUCTION

Pulsed gas discharge devices are widely applied as light sources in lasers, plasma display panels as well as for plasma nitriding, reactive magnetron coating etc. [1-4]. But now the pulsed discharges of medium frequency range are studied much less than radio frequency [5-11] or direct current [12-18] discharges thus hampering the progress in this domain. Therefore the subject of this research has been to investigate the processes participating in the formation of a unipolar pulsed discharge of low pressure in various gases.

In her thesis Efimova [4] has reported the research into the formation of a pulsed discharge in argon and nitrogen in the pressure range from 2 to 7 Torr with the duty cycle of the applied voltage from 10 to 4000 μs. She has obtained that with the voltage growing the discharge current increases and at earlier stages of the discharge development this current is substantially higher than one observed when the dc voltage is applied. It has been revealed that the current signal is not constant during the pulse and the duty cycle duration is an important parameter.

The authors of paper [2] have performed a numerical study of the processes taking place during the breakdown in the dc pulsed discharge at low nitrogen pressure in the "plane-tip" design. They have demonstrated that the formation of the pulsed discharge undergoes 3 consequent stages. First, the gap is slowly filled with the ions produced near the anode, then during the second stage the ionization front is propagating from the anode to the cathode. At the same time the cathode sheath is being formed and secondary phenomena become to participate leading to the third stage, i.e. to the glow discharge formation.

The present paper deals with the studies of the formation stages of the pulsed discharge between flat electrodes in nitrogen in a wide range of frequencies and duty cycles.

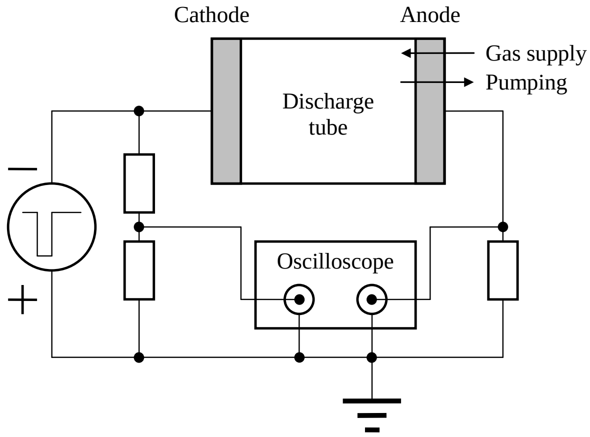

Fig. 1. Block-scheme of the experimental device

1. EXPERIMENTAL

Experiments in the present paper have been performed with the help of the device with the block-scheme depicted in Figure 1. Flat anode and cathode of stainless steel have been located in the discharge tube 56 mm of inner diameter with the inter-electrode distance of 20 mm. The cathode has been fed with a pulsed unipolar negative voltage from the generator in the frequency range of 20…300 kHz, duty cycle from 0.15 to 0.85 and the applied voltage values up to 1000 V. The anode potential was zero. The voltage between the electrodes and the current have been registered with the oscilloscope PCS500 (Velleman Instruments) with its signals fed to a computer. The range of the discharge current values registered did not exceed 100 mA. All experiments have been performed for two values of the nitrogen pressure, namely, 0.1 and 1 Torr. Gas pressure has been measured with the capacitive manometer-baratron with the maximum measured pressure value of 10 Torr.

2. EXPERIMENTAL RESULTS

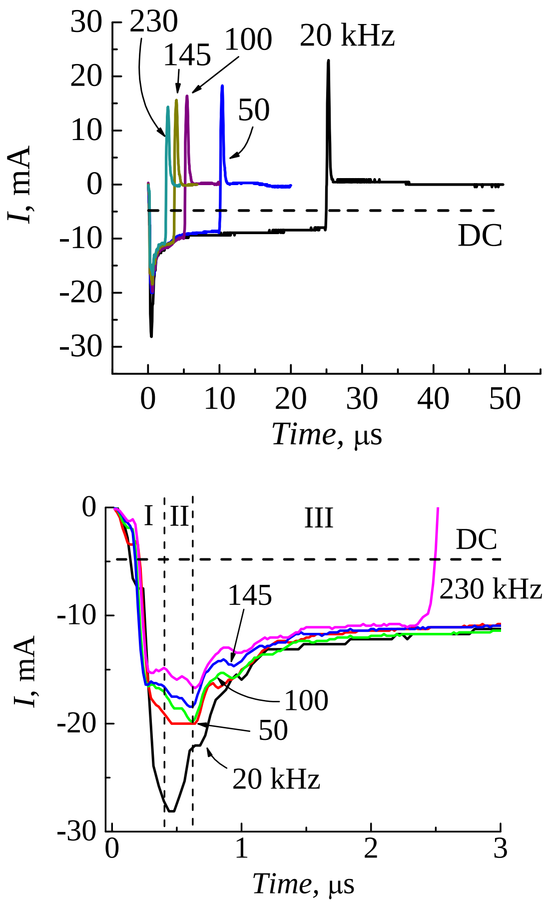

Fig. 2. Discharge current oscilloscope pictures and the stages of plasma formation (I, II and III) for the pulsed voltage of 700 V, the duty cycle of 0.5 and the nitrogen pressure of 0.1 Torr

The oscilloscope pictures measured clearly demonstrate two different phases: a plasma phase (when the negative voltage is fed to the electrode) and an afterglow phase (no voltage across the electrodes, the plasma is decaying).

Fig. 2 presents the current oscilloscope pictures for the pressure of 0.1 Torr, the duty cycle of 0.50 and the frequencies from 20 to 230 kHz. The pulsed voltage with the constant amplitude of 700 V was applied across the electrodes. It is clear from Fig. 2 that after an abrupt growth of the capacitive current in the plasma phase the discharge current first achieves the level of about -20 mA, and then it decreases uniformly. It approaches the value -4.8 mA marked by a horizontal line, i.e. the value of the discharge current at the constant (not pulsed) voltage but has no time to achieve it because the plasma time period is finished. For the discharge with the conditions presented in Fig. 2 the current approaches on the average the value of -10 mA.

Let us consider the stages of plasma formation in more detail. Fig. 2 also presents the oscilloscope pictures of the current pulses during the first 3 μs. One may define 3 stages of the discharge development in the plasma phase:

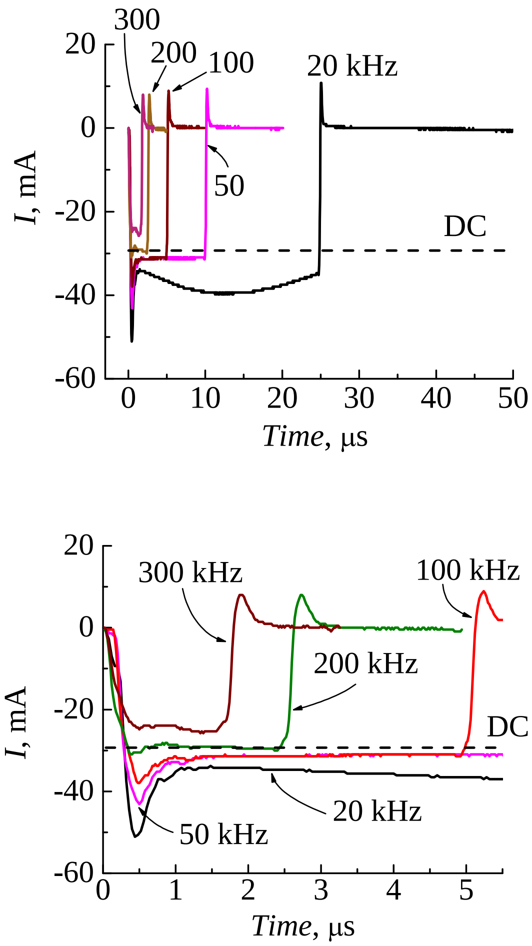

Fig. 3. Discharge current oscilloscope pictures for the pulsed voltage of 400 V, the duty cycle of 0.5 and the pressure of 1 Torr in N_2

I. A capacitive current pulse,
II. Discharge current growth,
III. Slow decrease of the discharge current.

The first stage is identical for all gas pressure values, this is the capacitive current pulse approaching–(10…30) mA. The duration of this stage is constant amounting about 0.5 μs, and it is associated with the time of voltage growth at the cathode to its maximum value. At the second stage there occurs the current growth under the discharge formation. At the pressure given the duration of the second stage amounts to about 0.2 μs. At the third stage of the plasma phase formation we observe the decrease of the discharge current in time with moderate oscillations, and the current is approaching the saturation at the level of -10 mA. However the duration of the discharge plasma phase at the low nitrogen pressure happens to be insufficient to approach the level corresponding to the glow discharge current.

It is clear in Fig. 2 that the current oscilloscope pictures for the frequencies above 50 kHz almost match, i.e. the discharge experiences almost identical stages of formation and development at different frequencies.

Let us further consider the pulsed discharge in N_2 with the same parameters (the duty cycle of 0.5, the frequency range from 20 to 300 kHz) but at higher pressure of 1 Torr. One clearly observes on the oscilloscope pictures for this case shown in Fig. 3 that similar to the pressure value of 0.1 Torr the capacitive current jumps are present under the transition between the plasma phase and the afterglow one. For high frequency pulses the capacitive current at the start of the plasma phase is less than that for the low frequency ones. This is associated with the properties of the generator of pulses because for high frequencies the front of the voltage pulse is not so steep as for low frequencies. Consequently, the derivative of the voltage over time is less and so respectively is the capacitive current.

The voltage at the cathode possesses several time periods with the different growth rate. During the first time period the growth rate of the voltage is maximum, the current also grows fast. The second time period is characterized by a slower growth of the voltage and the current, and at the end of this time period the current approaches maximum. During the third time period the voltage slowly saturates, and the current decreases. Such a behavior of the current indicates that this current is not purely capacitive but it is a sum of the capacitive current and the current of the discharge under formation.

Perhaps the charged particles remained after the first plasma phase play a considerable role at the initial time of the discharge formation. During the afterglow phase they fill the cathode and anode sheaths due to ambipolar diffusion, these sheaths possessing very low concentrations of electrons and ions in the burning discharge. At the beginning of a regular voltage pulse the ions and electrons escape to the cathode and anode, respectively, thus leading to the increase of the discharge current at the first and second stages. One may assume that after the second stage is completed the charged particles which arrived to the electrodes under afterglow are lost at their surfaces, and the forming cathode and anode sheaths are depleted of charged particles what leads to a decrease of the discharge current during the third stage.

Note that during the voltage saturation the discharge current ceases to decrease and starts to grow. The discharge current maximum is achieved in about 10–15 μs depending on the frequency of the pulses. Similar current behavior has also been observed at low nitrogen pressure of 0.1 Torr, however, the period of current growth amounted then to 0.2 μs that was approximately 50 times higher than at the gas pressure of 1 Torr. In the paper by Efimova [4] for the argon pressure of 4.5 Torr the current oscilloscope picture for the 500 V voltage also possesses a section with the discharge current growth with a duration of about 75…80 μs. Therefore one can draw a conclusion that increasing gas pressure involves the growth of the period duration associated with the growing discharge current.

The general formula for the coefficient D_a of the ambipolar diffusion in the plasma consisting of positive ions and electrons is written in the form [19, 20]:

$$D_a = \frac{D_+ \cdot \mu_e + D_e \cdot \mu_+}{\mu_e + \mu_+} \approx D_+ + D_e \cdot \frac{\mu_+}{\mu_e}, \qquad (1)$$

where D_+, D_e, μ_+, μ_e are the diffusion coefficients (D) and mobilities (μ) of ions and electrons, respectively. For nitrogen papers [21–23] report the values $D_+ = 39.7$ cm^2 Torr/s, $D_e = 9\cdot10^5$ cm^2 Torr/s, $\mu_+ = 1.54\cdot10^3$ cm^2 Torr/(V s), $\mu_e = 4.2\cdot10^5$ cm^2 Torr/(V s). At the pressure of 1 Torr we have $D_a = 3340$ cm^2/s. The rate of the charged particle loss due to the escape to the tube walls and electrodes is equal to $\nu_d = D_a / \Lambda^2$ where Λ is the diffusion length which for the tube of radius R with the inter-electrode distance L may be found according to the formula

$$\frac{1}{\Lambda^2} = \left(\frac{2.405}{R}\right)^2 + \left(\frac{\pi}{L}\right)^2. \qquad (2)$$

As the experiments in this paper have been performed in the tube of 2.8 cm in radius and the inter-electrode gap was 2 cm then

$$\frac{1}{\Lambda^2} = \left(\frac{2.405}{2.8}\right)^2 + \left(\frac{\pi}{2}\right)^2 = 4.19\ cm^{-2}. \qquad (3)$$

The rate of diffusion loss of charged particles will be

$$\nu_d = \frac{D_a}{\Lambda^2} = 3340 \cdot 4.19 = 1.38 \cdot 10^4\ s^{-1}, \qquad (4)$$

whereas the period of plasma decay at the pressure of 1 Torr amounts to $\tau_d = 7.2\cdot10^{-5}$ s = 72 μs, and at the pressure of 0.1 Torr it will be ten times less, $\tau_d = 7.2$ μs. It is clear from Fig. 2 that at the nitrogen pressure of 0.1 Torr and the frequency of 20 kHz the plasma has time to decay during the afterglow phase (of 25 μs in duration) and at the frequency of 100 kHz the afterglow phase has a duration of 5 μs what might lead to a substantial decrease in the charged particle concentration in the plasma volume up to the moment a regular voltage pulse arrives.

CONCLUSIONS

This paper has undertaken the study of the unipolar pulsed discharge in nitrogen for two values of pressure, 0.1 and 1 Torr. The current and voltage oscilloscope pictures have been registered in the frequency range from 20 to 300 kHz and of the duty cycle from 0.15 to 0.85. The pulsed discharge has been observed to transit through a plasma phase and an afterglow phase. The plasma phase has been separated into three stages: 1. A pulse of capacitive current of duration amounting to about 0.5…1 μs; 2. A stage of current growth with the duration depending on the nitrogen pressure; 3. Current decrease during tens of microseconds to the level corresponding to the discharge with the constant voltage. A conclusion has been drawn that charged particles being remained after the preceding plasma phase may play an important role at the initial period of the discharge formation. Ions and electrons fill in the cathode and anode sheaths during the afterglow phase due to the ambipolar diffusion, and at the start of a regular voltage pulse they escape to the electrodes leading to the increase of the discharge current at the first and second stages. Then the cathode and anode sheaths under formation are depleted of the charged particles what is the cause of the discharge current to decrease during the third stage.

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ФОРМИРОВАНИЕ ОДНОПОЛЯРНОГО ИМПУЛЬСНОГО РАЗРЯДА В АЗОТЕ

В.А. Лисовский, П.А. Оглоблина, С.В. Дудин, В.Д. Егоренков, А.Н. Дахов

Были измерены осциллограммы тока и напряжения импульсного разряда в широком диапазоне частот (от 20 до 300 кГц), коэффициентов заполнения от 15 до 85 % для двух значений давлений азота – 0,1 и 1 Торр. Было получено, что осциллограммы тока тлеющего импульсного разряда имеют плазменную фазу и фазу послесвечения. Наблюдались следующие этапы плазменной фазы: 1. Импульс емкостного тока длительностью примерно 0,5…1 мкс; 2. Этап роста тока, длительность которого зависела от давления газа; 3. Уменьшение тока, длившееся десятки микросекунд, до уровня, соответствующего разряду с постоянным напряжением.

ФОРМУВАННЯ ОДНОПОЛЯРНОГО ІМПУЛЬСНОГО РОЗРЯДУ В АЗОТІ

В.О. Лісовський, П.О. Оглобліна, С.В. Дудін, В.Д. Єгоренков, О.М. Дахов

Були виміряні осцилограми струму і напруги імпульсного розряду в широкому діапазоні частот (від 20 до 300 кГц), коефіцієнтів заповнення від 15 до 85 % для двох значень тиску азоту – 0,1 та 1 Торр. Було отримано, що осцилограми струму тліючого імпульсного розряду мають плазмову фазу і фазу післясвітіння. Спостерігалися наступні етапи плазмової фази: 1. Імпульс ємнісного струму тривалістю приблизно 0,5…1 мкс; 2. Етап зростання струму, тривалість якого залежала від тиску газу; 3. Зменшення струму, що тривало десятки мікросекунд, до рівня, відповідного розряду з постійною напругою.