INTER-ELECTRODE DISTANCE EFFECT ON DC DISCHARGE CHARACTERISTICS IN NITROGEN

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This paper studies the inter-electrode distance effect on voltage drop across it and cathode sheath thickness. The voltage across the electrodes and the sheath thickness are found to increase when the anode moves away from the cathode through the negative glow. The probe technique reveals that increasing the inter-electrode gap with the current fixed leads to the plasma concentration growth in the negative glow. The discharge current is transported through the negative glow by fast electrons accelerated in the cathode sheath; therefore one requires applying higher voltage across the electrodes to support the current in a longer gap. This is the reason for the increase of the plasma concentration in the negative glow and in the cathode sheath thickness.

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INTRODUCTION

Direct current glow discharge is widely applied in gas discharge lasers [1, 2], luminescent lamps [3], dc diode sputtering systems [4], in isotope separation [5]. Therefore studying the processes taking place in its parts and their characteristics is described in a large number of papers (see, e.g. [6 - 13]).

Already Güntherschulze [14 - 16] discovered that varying the inter-electrode distance keeping the discharge current constant (e.g. displacing the anode) affected not only the length (and the very existence) of the positive column, the dark Faraday space and the negative glow but also the voltage drop across the cathode sheath and its thickness. When one brought the anode nearer to the cathode sheath boundary through the negative glow the voltage drop across the electrodes might pass through a sharp minimum which after further nearing the anode to the cathode was replaced with abrupt rise of the voltage and the discharge transition to the obstructed mode. Güntherschulze himself attempted to explain the appearance of this minimum by fast primary electrons coming from the cathode and producing in the gas film located on the anode more positive ions than in the gas gap thus diminishing the cathode drop. However, Penning [17] demonstrated that this phenomenon might be observed with a clean degassed anode but not in all gases. Fischer [18] made a suggestion that this effect may be induced by gas concentration changes due to its cooling by the cold anode. Druyvesteyn [19] agreed that gas cooling near the anode may play a role but also put forward another explanation. Near the anode located in the negative glow a negative anode voltage drop is formed. Slow electrons would be reflected by this anode drop back into the plasma, the space charge in the negative glow would decrease, and the maximum potential would shift toward the anode resulting in the increase of the number of ions approaching the cathode and in the voltage drop decrease. A brief review of old papers may be found, e.g. in papers [20, 21]. Further, we know only two papers where such studies were continued. Guseva et al. [22] registered the voltage values across the electrodes against the gap values between them in the nitrogen pressure range below 0.5 Torr. They demonstrated that on increasing the gap the discharge experienced the transition from the obstructed mode to the glow one, the voltage across the electrodes after abrupt decrease approached saturation, and no minimum was observed. The authors of paper [23] studied the dependence of the voltage across the electrodes on the distance between them only for the discharge normal mode and there is also no minimum in their graphs.

The present paper aimed to find out under what conditions a minimum may be observed in the dependence of the voltage across the electrodes against the gap between them, to study this dependence in the broad range of inter-electrode gap values and to register the axial profiles of plasma parameters in narrow gaps with probe technique. We also suggested another explanation of the processes taking place in the glow discharge when one varied the inter-electrode distance.

For studying dc glow discharge we employed the chamber designed as shown in Fig. 1. The inner diameter of the discharge tube was 55 mm. The distance between flat electrodes varied from 8 to 385 mm using a movable anode. Studies were made in nitrogen in the pressure range $p = 0.05\ldots0.2$ Torr with the voltage values $U_{dc} \leq 1400$ V and the current values ranging up to 5 mA. Gas pressure was controlled with 1000 and 10 Torr baratrons. The 75 kOhm resistor was switched in series into the discharge circuit between the cathode and the dc supply to prevent the cathode spot formation.

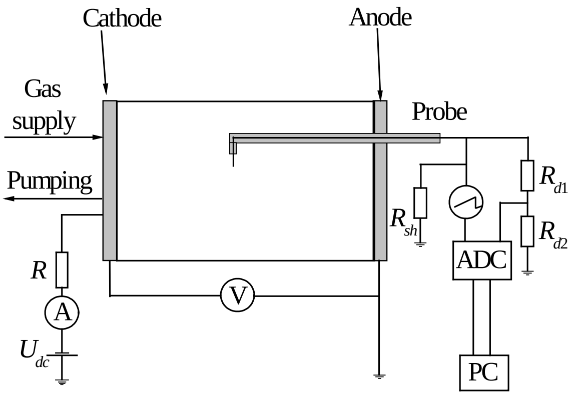

Fig. 1. Design of the discharge tube employed in the present paper

Axial profiles of plasma parameters were registered with a single cylinder Langmuir probe of 3.2 mm in length and 0.18 mm in diameter made of nichrome. The saw-like voltage was applied to the probe from the generator with the potential difference between the "saw" spikes height being about 300 V. This voltage was lowered with the resistive divider (containing R_{d1} and R_{d2} resistors) and fed to the 24-digit analog-to-digital convertor (ADC). The registered probe current was reduced with the shunt (the R_{sh} resistor) and was also fed to ADC. The ADC signal was fed to the computer for subsequent processing. Plasma concentration n_i was calculated from the ion branch of the probe current I_{pr} and electron temperature T_e was measured according to the technique described in papers [24, 25].

EXPERIMENTAL RESULTS

One may observe in papers [15, 16, 22] that the dependence of the voltage U across the electrodes on the distance L between them approaches the saturation after the abrupt decrease, and that a well-expressed minimum is absent in this dependence. Therefore we performed similar measurements of voltage across the electrodes at different discharge current values to find out the conditions for the appearance of a minimum or other characteristic features in the $U(L)$ patterns.

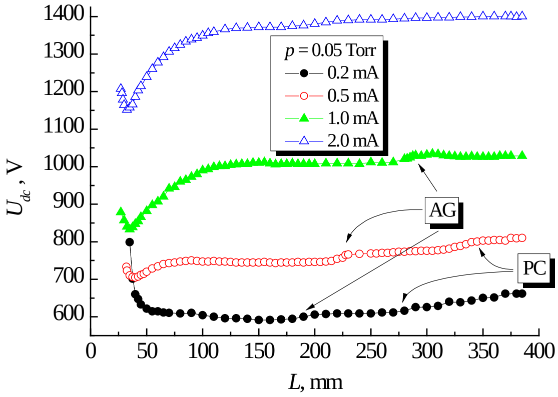

Fig. 2. Voltage across the electrodes against the distance between them for the nitrogen pressure of 0.05 Torr for different discharge current values

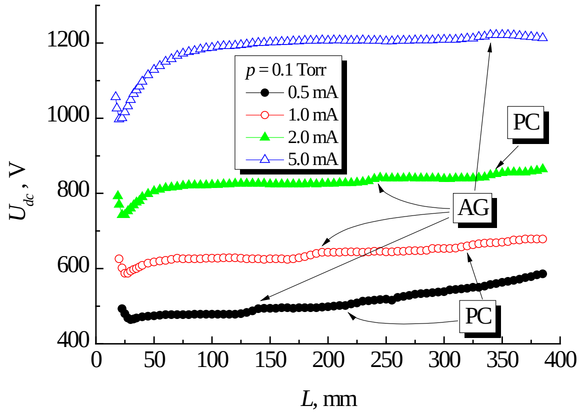

Fig. 3. Voltage across the electrodes against the distance between them for the nitrogen pressure of 0.1 Torr for different discharge current values

In Fig. 2 we present the $U(L)$ dependence for the nitrogen pressure value of 0.05 Torr and discharge current values of 0.2, 0.5, 1 and 2 mA. One observes that at the smallest current value of 0.2 mA there is indeed no well-expressed minimum in the $U(L)$ pattern. If the anode is moved away from the cathode, one first observes the obstructed mode with the abrupt decrease of voltage U when the anode is located in the cathode sheath or in the negative glow not far from its boundary. However, with the further gap L increase the voltage across the electrodes remains almost the same and even experiences a small decrease. When the anode approaches about the middle of the dark Faraday space, an anode glow appears near its surface (this moment is indicated in Figs. 2-4 with the arrows labeled AG), whereas the inter-electrode voltage increases by about 15…20 V (what corresponds to the ionization potential of nitrogen molecules of 15.6 eV). With the further increase of the inter-electrode distance and the anode located in the Faraday dark space the voltage across the electrodes remains unchanged and the anode glow continues to be observable. When the inter-electrode gap increases such that the positive column appears (see the PC label in the figures) the voltage starts to grow linearly with the anode moving away from the cathode.

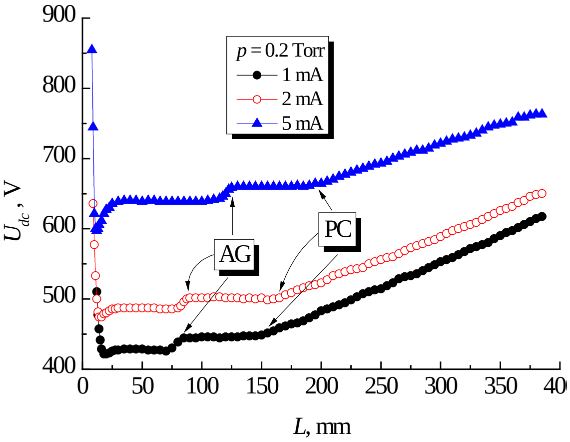

Fig. 4. Voltage across the electrodes against the gap between them for the nitrogen pressure of 0.2 Torr at different discharge current values

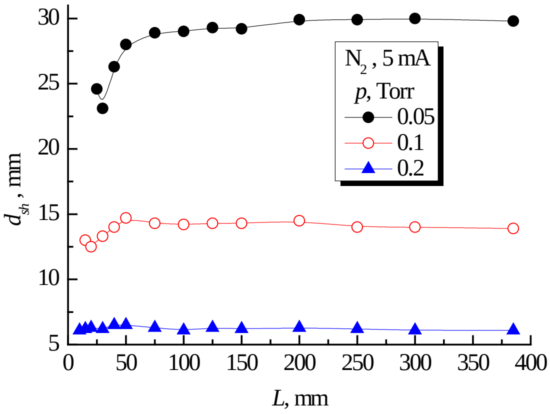

Fig. 5. Cathode sheath thickness against the inter-electrode gap at different nitrogen pressure values for the discharge current of 5 mA

At higher discharge current values (0.5 mA and larger) an abruptly expressed minimum appears on the dependence of the voltage across the electrodes against the gap between them, which was discussed in papers [14 - 21]. On decreasing the inter-electrode distance when the anode is traversing the negative glow, the voltage drop experiences a fast decrease, it approaches a minimum, and after the discharge transition to the obstructed mode the voltage across the electrodes grows abruptly. The depth of this minimum increases with the discharge current growing, but it decreases with gas pressure growing when the discharge current is kept fixed.

Figs. 3 and 4 demonstrate the dependence of the voltage across the electrodes on the distance between them for the nitrogen pressure values of 0.1 and 0.2 Torr, respectively. This dependence is qualitatively similar to that described above for the pressure value of 0.05 Torr. However, increasing the gas pressure involves the appearance of the anode glow and the positive column at lesser inter-electrode gap values. Besides, the electric field in the positive column grows therefore the voltage between the electrodes increases faster when the anode is moving through the positive column.

When the anode is moving through the negative glow to the cathode, the voltage drop across the electrodes as well as the cathode sheath thickness decrease as is shown in Fig. 5. The effect is most pronounced at low nitrogen pressure values. Thus for the pressure value of 0.05 Torr the sheath thickness decrease amounted to about 6 mm, whereas for 0.1 Torr it was about 3 mm. Earlier the authors of papers [14 - 17] also observed the simultaneous variation of the cathode sheath thickness and the voltage drop across it.

The single Langmuir probe technique was employed to measure the axial distributions of plasma parameters in the negative glow for two different values of the inter-electrode gap of 30 and 50 mm at the same discharge current value (probe measurements in the cathode sheath are impeded due to a weak electron concentration and the directed flows of charged particles, therefore we did not perform these studies there). Fig. 5 evidences the small electron temperature in both cases not exceeding 1 eV, whereas the plasma potential with respect to the anode was in the range of 2…3 V. We remark that with the gap of 30 mm the cathode sheath thickness was 22 mm, and the maximum plasma concentration approached $4\cdot10^9$ cm^{-3}. Increasing the distance to 50 mm led to the growth of the cathode sheath thickness to 28 mm and of the maximum plasma concentration to $6\cdot10^9$ cm^{-3}. I.e. one requires an enhanced concentration of charged particles to transport current through a longer gap.

We may suggest the following mechanism of increasing the voltage across the electrodes when the anode is moving away from the cathode through the negative glow. As the plasma is positively charged with respect to the grounded anode (negative anode voltage drop), only fast electrons accelerated in the cathode sheath may approach its surface [26]. When the discharge gap is short (e.g. 30 mm in Fig. 5) the anode is located almost at the boundary of the cathode sheath, fast electrons move through a narrow negative glow performing comparatively not large number of inelastic collisions with gas molecules. When the anode is moved away from the cathode without changing the generator emf, then the discharge current will be decreased as rather less number of fast electrons approach the anode surface because many of them have time to lose much energy due to collisions with gas molecules and be thermalized on their way from the cathode sheath. Therefore to transport a fixed current through a longer gap one has to apply higher voltage across the electrodes in order to increase the flow of fast electrons. Then (as we observed in Fig. 5) the cathode sheath thickness as well as the maximum plasma concentration in the negative glow experiences an increase.

CONCLUSIONS

Thus our present paper reports the results of studies we made into the dependence of the cathode sheath thickness and the voltage drop across the electrodes on the distance between them. We demonstrated that moving the anode away from the cathode through the negative glow is accompanied by the increase of the voltage drop across the electrodes and the sheath thickness. When moving the anode through the dark Faraday space and the positive column we observe that the cathode sheath thickness ceases to depend on the inter-electrode gap. The voltage across the electrodes first experiences a jump when the anode glow appears (this occurs when the anode is located approximately in the middle of the dark Faraday space). Then, when the anode is located in the positive column, the voltage varies linearly with the inter-electrode distance. We employed the probe technique to measure axial profiles of plasma parameters in short discharge gaps when only the cathode sheath and the negative glow can find their place inside the inter-electrode gap. We demonstrate that moving the anode away from the cathode keeping the current fixed leads to the increase of the plasma concentration in the negative glow. Perhaps the transport of the fixed current through the negative glow with a longer inter-electrode gap requires an enhanced flow of fast electrons from the cathode sheath for which higher voltage has to be applied across the electrodes. In its turn, it leads to the increase of the cathode sheath thickness as well as the plasma concentration in the negative glow.

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ВЛИЯНИЕ РАССТОЯНИЯ МЕЖДУ ЭЛЕКТРОДАМИ НА ХАРАКТЕРИСТИКИ ТЛЕЮЩЕГО РАЗРЯДА В АЗОТЕ

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Исследовано влияние расстояния между электродами на падение напряжения на них и толщину катодного слоя. Получено, что напряжение на электродах и толщина слоя возрастают, когда анод удаляется от катода через отрицательное свечение. Зондовым методом показано, что увеличение зазора между электродами при фиксированном токе приводит к повышению плотности плазмы в отрицательном свечении. Разрядный ток через отрицательное свечение переносится быстрыми электронами, ускорившимися в катодном слое, поэтому для поддержания фиксированного тока в более длинном зазоре нужно к электродам приложить более высокое напряжение. Это приводит к увеличению плотности плазмы в отрицательном свечении и толщины катодного слоя.

ВПЛИВ ВІДСТАНІ МІЖ ЕЛЕКТРОДАМИ НА ХАРАКТЕРИСТИКИ ТЛІЮЧОГО РОЗРЯДУ В АЗОТІ

В.О. Лісовський, К.П. Артюшенко, В.Д. Єгоренков

Досліджено вплив відстані між електродами на падіння напруги на них і товщину катодного шару. Отримано, що напруга на електродах і товщина шару зростають, коли анод віддаляється від катода крізь негативне світіння. Зондовим методом показано, що збільшення зазору між електродами при фіксованому струмі призводить до підвищення густини плазми в негативному світінні. Розрядний струм крізь негативне світіння переноситься швидкими електронами, які прискорюються в катодному шарі, тому для підтримки фіксованого струму в більш довгому зазорі потрібно до електродів прикласти вищу напругу. Це призводить до збільшення густини плазми в негативному світінні і товщини катодного шару.