BURNING MODES OF DC LOW PRESSURE DISCHARGE WITH A TRANSVERSE CONSTRICTION

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This paper reports the current-voltage characteristics (CVCs) of dc discharge in different modes of burning we registered for several values of the transverse constriction diameter in a broad nitrogen pressure range. Existence conditions for normal and abnormal modes are determined. The CVCs are shown to possess a hysteresis for discharge tubes with constrictions at nitrogen pressure of 0.05 and 0.1 Torr. At higher pressure of 0.3 Torr the constriction does not actually affect the discharge CVC. For the pressure of 5 Torr a positive column is observed in the anode part of the tube what enables one to support discharge burning at lower voltage values across the electrodes.

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INTRODUCTION

Glow discharge in a tube supplied with a transverse diaphragm or possessing a constriction in the transverse cross-section is widely applied in low pressure mercury lamps [1 - 5], for geometric compression in a plasmatron [6], as well as for double electric layer studies [7 - 9]. For correct application of discharges in tubes with a constriction or a transverse diaphragm one has to know its modes of burning and current-voltage characteristics for different orifice diameter values.

To study the glow dc discharge CVCs we employed a chamber with the design depicted in Fig. 1. Fused silica tube had the inner diameter of 56 mm. The flat electrodes were spaced 173 mm apart. A glass diaphragm 2 mm thick was installed at the central part of the tube with the orifice diameter values of 1, 3, 5 and 8 mm. We also registered the discharge parameters in the tube without a diaphragm.

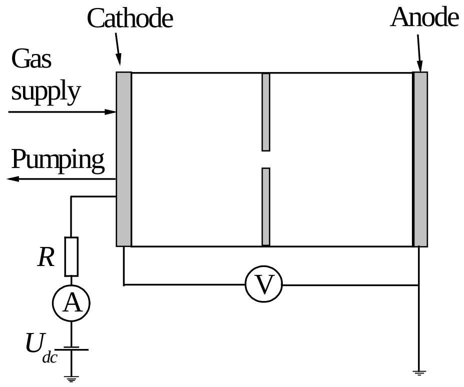

Fig. 1. Discharge tube design employed in this paper

Studies were performed in nitrogen within the pressure range p = 0.05…5 Torr with the dc voltage values $U_{dc} \leq 3000$ V and the current range up to 200 mA. Gas pressure was controlled by 1000 and 10 Torr baratrons. A resistor of 75 kOhm was included in series into the discharge circuit between the cathode and the dc supply.

EXPERIMENTAL RESULTS

Consider the data of studying discharge CVCs in different modes of burning for several diaphragm diameter values in a broad nitrogen pressure range. In Fig. 2 the CVCs are shown in the absence of a diaphragm. At low nitrogen pressure (0.05 Torr) and moderate current (below 1 mA) the discharge consists of a cathode sheath, a negative glow and a Faraday dark space approaching the anode surface. Increasing the discharge current leads to an increase in the negative glow length and for current values above 1 mA it approaches the anode whereas the dark Faraday space disappears. The CVCs presented in Fig. 2 demonstrate that in this pressure range the discharge was burning only in the abnormal mode with a cathode surface completely covered by the discharge. The current grew simultaneously with the voltage increase across the electrodes. At higher nitrogen pressure of 0.1 Torr an anode glow appears near the anode surface disappearing at currents above 1 mA.

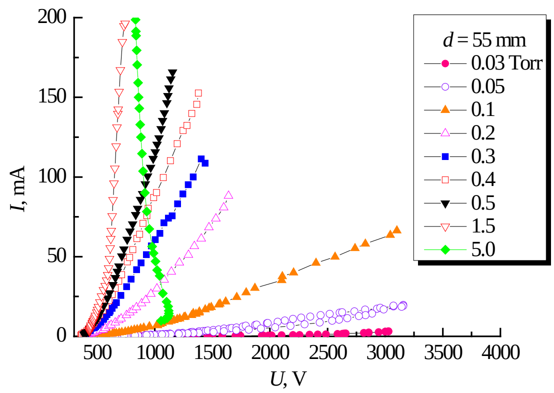

Fig. 2. Discharge current-voltage characteristics without a diaphragm at different nitrogen pressure values

The presence of the anode glow indicates that a potential drop in the anode sheath becomes positive accelerating electrons to the anode surface. Depending on the gas pressure, discharge current and inter-electrode gap values one may observe either a positive potential jump (several volts – tens of volts) or a negative one (several volts) [10]. The sign of the anode drop and its value are determined by a relation between the stochastic electron current density in plasma before the anode, its surface size and the discharge current supporting the concentration of charged particles before the anode to supply a discharge current to it.

Increasing gas pressure leads to a faster growth of the discharge current and to lowering a minimum voltage at which a discharge sustainment is possible. However, already at nitrogen pressure of 1.5 Torr the discharge may exist not only in the abnormal but also in the normal mode when the discharge spot (discharge column) occupies only a portion of the cathode surface. In the normal mode the discharge CVC is vertically growing or even falling, i.e. the discharge current increase is accompanied by the voltage fall across the electrodes [11, 12]. Current increase in the normal mode is caused by the increase of the discharge spot area with the current density in it remaining almost constant thus called a "normal one". This effect of normal current density is mostly pronounced in the CVC for the nitrogen pressure of 5 Torr (within the total range of discharge current density values we studied up to 200 mA).

As was already said above, in the abnormal mode the increase of the discharge current I is accompanied by the growth of voltage across the cathode sheath U_c (and the voltage across the electrodes U) and the decrease of the cathode sheath thickness d_c, all the cathode being covered with the discharge. The normal mode is characterized by a partial coverage of the cathode surface with a cathode glow. On decreasing the discharge current the cathode voltage drop and the cathode sheath thickness remain constant ($U_c = U_n$, $pd_c = (pd_c)_n$, where p is the gas pressure), the area occupied by the discharge on the cathode S decreases whereas the current density $j = I_{dc}/S$ also keeps constant ($j = j_n$).

Let a dc discharge burn in the normal mode and occupy only a portion of the cathode surface. If one increases the voltage drop across the electrodes a little (increasing the generator emf), then the voltage drop across the cathode sheath also grows thus increasing the ionization rate and plasma concentration at its boundary. Due to ambipolar diffusion the discharge column will begin to expand in the radial direction occupying a larger area on the cathode, the discharge current also increasing. Then according to Ohm's law for a closed circuit (with the external ballast resistor), the voltage across the electrodes will be decreased to the normal fall [13]. This will stop the discharge expansion over the cathode surface. If the discharge expansion described above did not lead to the complete coverage of the cathode surface, the discharge would continue its normal mode glow. As the normal voltage drop across the electrodes is below the breakdown voltage [14], then decaying plasma of afterglow with low concentration is observed outside the discharge column. If the discharge happened to cover the cathode completely, then for further current increase one requires to increase the ionization rate in the cathode sheath what is possible through the increase of voltage across the electrodes. The discharge experiences a transition to the abnormal mode with a growing CVC.

Note that even at high pressure in our discharge tube the positive column may be observed not in the total range of current values studied. For example, at the nitrogen pressure values below 1 Torr the positive column is not observed at all for a given inter-electrode gap. For the pressure value of 1 Torr the positive column is visually not observed up to discharge current values of 50 mA. However at higher current values a positive column starts to form near the anode which length then increases with the current increasing. Similar situation is also observed at the nitrogen pressure of 5 Torr, at which the positive column appears only at the current values above 15 mA.

Now consider the effect of the transverse diaphragm of different diameter on the burning modes of the discharge at various gas pressure values. Fig. 3 presents CVCs for the diaphragm of 8 mm in diameter. One and the same current has to flow in the wide portion of the discharge tube as well as in the narrow orifice of the diaphragm. Therefore a region of increased plasma concentration is formed near the orifice that affects the plasma properties at the cathode as well as the anode portions of the discharge.

First consider the CVC for the pressure values of 0.05 and 0.1 Torr. After the ignition the discharge in the cathode portion of the tube consisted of the cathode sheath and the negative glow approaching the transverse diaphragm. In the anode portion of the tube (between the diaphragm and the anode) a noticeable glow was absent excluding a small area near the diaphragm. Increasing the discharge current was accompanied by the growth of the voltage across the electrodes. However at the current values of about 30 and 40 mA for the nitrogen pressure values of 0.05 and 0.1 Torr, respectively, a brightly shining spot was formed near the anode surface and a further current increase was accompanied by the voltage decrease across the electrodes. After the maximum generator emf was achieved, a portion of the CVC was also registered on decreasing the discharge current. The anode spot intensity glow first diminished, then the spot left the anode surface and transformed into a stratum spreading with a further current lowering. One observes in Fig. 3 that the CVC branch registered with the current decreasing ran above that related to the growing current, i.e. a hysteresis is observed.

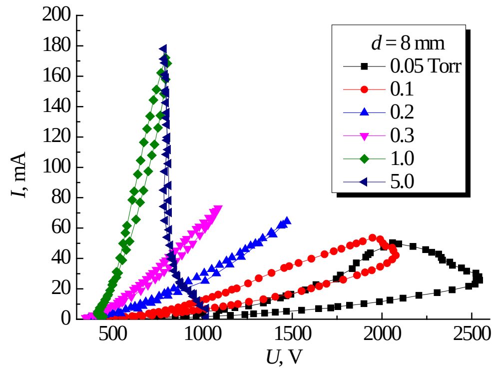

Fig. 3. Discharge current-voltage characteristics at different nitrogen pressure values and diaphragm diameter of 8 mm

At the pressure value of 0.2 Torr and higher the hysteresis disappears practically because the anode glow already exists at these pressure values. Perhaps the reasons for small divergence observed in the CVCs are the gas temperature growth, the accumulation of metastable molecules as well as the dissociation of a portion of nitrogen molecules into atoms. At the pressure of 5 Torr the discharge experiences a transition into the normal mode. Almost the total anode portion of the discharge tube is occupied by the positive column (excluding a small area near the diaphragm), and in the cathode portion a narrow cathode sheath, a negative glow and a dark Faraday space are observed. The positive column possesses a falling CVC, i.e. the voltage drop across it decreases with the discharge current increasing [15].

The voltage drop across the cathode sheath in the normal mode also decreases with the current increasing. As the electric field in the negative glow and the Faraday dark space are small, then also the voltage drop across these two discharge regions is not large. Therefore we observe the falling CVC of the complete discharge in Figs. 2-4 for large nitrogen pressure values.

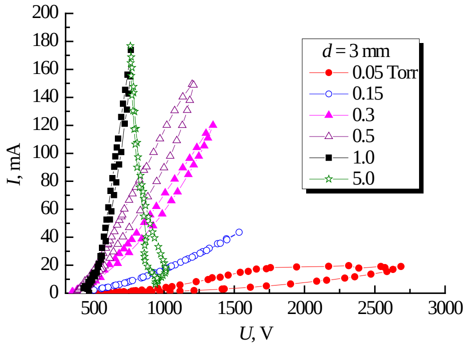

Fig. 4. Discharge current-voltage characteristics at different nitrogen pressure values and diaphragm diameter of 3 mm

Fig. 4 demonstrates the discharge CVCs for the diaphragm diameter of 3 mm. They are similar qualitatively to the discharge CVCs described above; therefore we will not describe them in more detail.

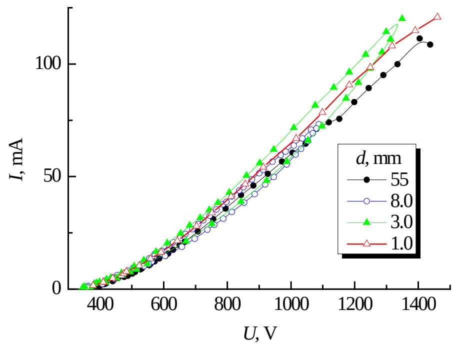

Fig. 5. Discharge current-voltage characteristics for the nitrogen pressure of 0.3 Torr and diaphragm diameter values of 55, 8, 3 and 1 mm

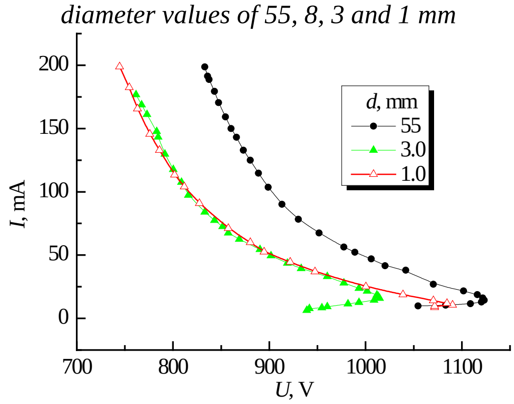

Fig. 6. Discharge current-voltage characteristics for nitrogen pressure value of 5 Torr and diaphragm diameter values of 55, 3 and 1 mm

Compare now the CVCs for two values of the nitrogen pressure of 0.3 and 5 Torr and different diaphragm diameter values shown in Figs. 5 and 6, respectively. We observe in Fig. 5 that at low pressure of 0.3 Torr the presence of the diaphragm does not have a noticeable effect on the discharge CVC. At this pressure value the discharge, with a diaphragm or without it, consisted of the cathode sheath, the negative glow (its length changing slightly with the current) the dark Faraday space (located in the anode as well as the cathode portions of the tube at both sides of the diaphragm), as well as the anode glow. The presence of the diaphragm caused a local disturbance of the plasma parameters in the dark Faraday space, in which the electric field strength and the ionization rate are usually small. Therefore we observe that the discharge CVCs almost coincide for different diaphragm diameter values.

However it follows from Fig. 6 for the nitrogen pressure of 5 Torr that to support the same discharge current in the presence of the diaphragm one requires noticeably lower voltage values. The discharge CVCs for the diaphragms of 1 and 3 mm with the discharge current values above 25 mm practically coincide. In the discharge tube without a transverse diaphragm the positive column appears only at sufficiently high current values (above 15 mA). At the same time in the anode portion of the tube with the diaphragm the positive column is also observed at lower discharge current values.

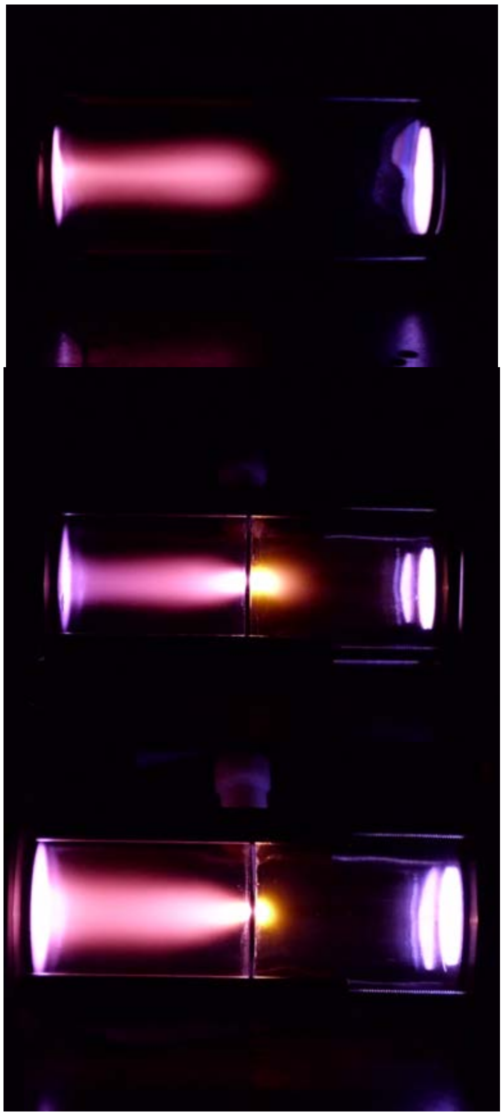

Fig. 7. Discharge photos at the pressure of 5 Torr and the current of 100 mA for the tube without a diaphragm and with diaphragms of 3 and 1 mm in diameter, respectively

Fig. 7 presents photos of the burning discharge at the nitrogen pressure of 5 Torr and the current of 100 mA for the tube without a diaphragm, and with the diaphragms of 3 and 1 mm in diameter, respectively. In the presence of the diaphragm almost all anode portion of the discharge tube is occupied by the positive column, whereas in the cathode portion one observes the narrow cathode sheath, the negative glow and the dark Faraday space. The transient region between the positive column and the diaphragm, as well as the region of transition to the dark Faraday space are characterized by a bright glow indicating the increase in the particle concentration in the orifice region. Let us estimate the current density in the diaphragm orifice. For the discharge current of 100 mA the current density in the tube without the diaphragm was 4.1 mA/cm^2. However in the tube with a diaphragm of 3 mm in diameter the current density was 1.4 A/cm^2, whereas with the diaphragm diameter of 1 mm it approaches 13 A/cm^2. The concentration and temperature of plasma in the orifice grow such that the diaphragm material sputtering occurs. Sodium is contained in the glass of the constriction, and a yellow glow indicates its presence.

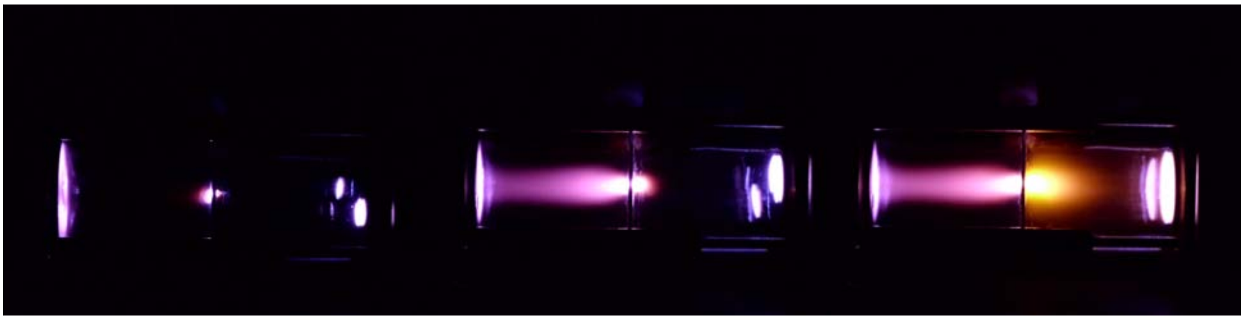

Fig. 8. Discharge photos for the diaphragm of 3 mm in diameter at the pressure of 5 Torr and the current of 10, 50 and 150 mA, respectively

Fig. 8 shows the photos for the pressure of 5 Torr and the diaphragms of 3 mm in diameter at different current values. One observes that at small current values there is no yellow glow because the temperature and current density are insufficient for sputtering the glass constriction. The sodium presence was supported through registering the radiation spectrum of plasma in the diaphragm vicinity, in which the lines 588.9950 and 589.5924 nm forming a sodium doublet are clearly observed.

CONCLUSIONS

This paper studies the normal and abnormal burning modes and current-voltage characteristics of the direct current discharge at different diameter values of the transverse diaphragm in the wide range of nitrogen pressure.

In the tube without a diaphragm at low pressure the discharge is burning only in the abnormal mode in which a voltage applied grows with the increase of current. At higher pressure values starting with 1.5 Torr, the discharge may exist not only in the abnormal but also in the normal mode.

In discharge tubes with a diaphragm at the pressure values of 0.05 and 0.1 Torr a brightly glowing anode spot is formed near the anode surface starting with a certain threshold current value after which the CVC acquires a negative tilt. A hysteresis is observed in the discharge CVC. At the same time after increasing pressure to 0.3 Torr the presence of a diaphragm does not actually affect the discharge CVC.

At the pressure of 5 Torr a positive column appeared in the discharge tube without the transverse diaphragm only at sufficiently high current values (above 15 mA). At the same time the presence of the diaphragm enables one to obtain a positive column in the anode portion of the tube even at low discharge current values. Therefore with a diaphragm one can support the discharge at lower voltage values across the electrodes and at lower current values.

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РЕЖИМЫ ГОРЕНИЯ РАЗРЯДА ПОСТОЯННОГО ТОКА НИЗКОГО ДАВЛЕНИЯ С ПОПЕРЕЧНОЙ ДИАФРАГМОЙ

В.А. Лисовский, П.А. Оглоблина, В.Д. Егоренков

Измерены вольт-амперные характеристики (ВАХ) разряда постоянного тока в различных режимах горения для нескольких диаметров поперечной диафрагмы в широком диапазоне давлений азота. Определены условия существования нормального и аномального режимов. Получено, что для разрядных трубок с сужениями при низких давлениях азота 0,05 и 0,1 Торр ВАХ имеют гистерезис. При более высоком давлении (0,3 Торр) наличие диафрагмы практически не оказывает заметного влияния на ВАХ разряда. Для давления 5 Торр в анодной части трубки с диафрагмой наблюдается положительный столб, что позволяет поддерживать горение разряда при более низких напряжениях на электродах.

РЕЖИМИ ГОРІННЯ РОЗРЯДУ ПОСТІЙНОГО СТРУМУ НИЗЬКОГО ТИСКУ З ПОПЕРЕЧНОЮ ДІАФРАГМОЮ

В.О. Лісовський, П.О. Оглобліна, В.Д. Єгоренков

Виміряно вольт-амперні характеристики (ВАХ) розряду постійного струму в різних режимах горіння для декількох діаметрів поперечної діафрагми в широкому діапазоні тиску азоту. Визначено умови існування нормального і аномального режимів. Отримано, що для розрядних трубок із звуженнями при низьких тисках азоту 0,05 і 0,1 Торр ВАХ мають гістерезис. При більш високому тиску (0,3 Торр) наявність діафрагми практично не робить помітного впливу на ВАХ розряду. Для тиску 5 Торр в анодній частині трубки з діафрагмою спостерігається позитивний стовп, що дозволяє підтримувати горіння розряду при більш низьких напругах на електродах.