AXIAL STRUCTURE OF HOLLOW CATHODE DC GLOW DISCHARGE IN DIFFERENT BURNING MODES

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The axial profiles of the electron temperature, plasma concentration and plasma potential in a DC glow discharge in nitrogen with a hollow cathode were registered with probe technique. At low pressure (0.05 Torr) the discharge is shown to burn in a high-voltage (electron-beam) mode when an electron beam is formed inside the cathode cavity. A potential barrier is found near the cathode sheath boundary. At gas pressure starting from 0.15 Torr at low discharge currents a glow mode is observed. At higher current the discharge is burning in the hollow mode in which the cavity is filled with high concentration plasma. A potential well up to 3 V deep is observed near the edge of the cathode cavity. On increasing the gas pressure the depth of the potential well in the cathode cavity decreases and the well disappears at 0.5 Torr.

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INTRODUCTION

The hollow cathode glow discharge is widely applied in many industrial ionic devices (stabilitrons and thyratrons), gas discharge lamps, spectral sources in atomic-absorption spectroscopy, for pumping gas discharge lasers, welding and melting materials with an electron gun, for modifying surfaces of solid bodies (etching, depositing thin films), in analytic and plasma chemistry [1, 2]. Recently a hollow-cathode discharge found broad application in correcting ion space thrusters [3].

In order to apply a hollow cathode glow discharge correctly, one has to know the conditions of its existence and quantitative data for different burning modes, therefore this problem is under study by a number of research groups for many years. They experimented mostly with a glow discharge due to a cylindrical hollow cathode as well as a segmented cathode. The available literature contains only several papers devoted to probe measurements of the plasma parameters in a hollow-cathode discharge. Thus the aim of this report was to register CVCs of a single Langmuir probe along the discharge axes in different burning modes and to determine the axial profiles of electron temperature, plasma concentration and plasma potential outside as well as inside the hollow cathode.

Measuring with Langmuir probes [4, 5] demonstrated that conventionally two groups of slow electrons were present in the negative glow of the hollow cathode discharge. The slowest of them (so called final electrons) possess the Maxwellian distribution with the temperature below 1 eV. They are contained in the potential well of the hollow cathode [6] and they form a plasma concentration profile. The second group consists of secondary electrons having the energy about 3 eV. These electrons were produced due to ionization at the very end of the cathode sheath and they are responsible for the transport of current from the hollow cathode to the anode. The presence of this potential well was discovered in experiment by Moskalev [6] via the Langmuir probe technique, its depth amounted to around 2…3 V. Obviously the slowest electrons are unable to leave it, whereas the fastest electrons from the second group may go out of the cavity.

1. EXPERIMENTAL

In order to study axial profiles of the plasma parameters of the dc glow discharge with a hollow cathode we employed the discharge chamber the scheme of which is depicted in Fig. 1. A fused silica tube had an inner diameter of 56 mm. The diameter of the flat stainless steel anode was 55 mm. A hollow cathode consisted of two plates 3 mm thick each, which were located at a distance of 8 mm from each other and were fixed to a flat disc 55 mm in diameter. The plate ends were at a distance of 37 mm from the flat part of the cathode. The entire cathode was made of aluminum. The distance between the flat parts of the electrodes was 100 mm. Studies were performed in nitrogen within the pressure range of p = 0.05…0.5 Torr.

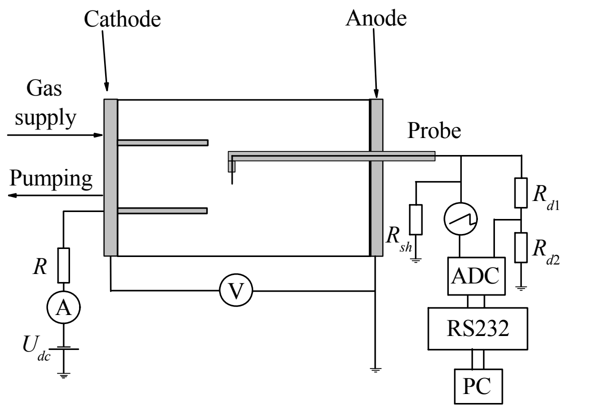

Fig. 1. Experimental device setup

Axial profiles of plasma parameters were registered with a single cylindrical Langmuir probe out of nichrome 3.2 mm in length and 0.18 mm in diameter. The saw-like voltage was fed from the generator, the potential difference between the "saw" ends amounted to about 300 V. This voltage was reduced via a resistive divider (containing R_{d1} and R_{d2} resistors) and fed to 24-digit analog-to-digital converter (ADC). The registered probe current was reduced with a shunt (R_{sh} resistor) and also fed to ADC. The ADC signal travelled through the galvanic decoupling and via the RS232 interface 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 measured according to the technique described in papers [4, 5].

2. EXPERIMENTAL RESULTS

At low pressure the hollow-cathode discharge is burning in a high-voltage mode when a high-energy electron beam is leaving the cathode cavity. The photo of such a discharge is depicted in Fig. 2. Secondary electrons hit out of the cathode surface by positive ions are accelerated and focused by the electric field inside the cavity and they form an electron beam propagating up to the anode surface as evidenced by the photo.

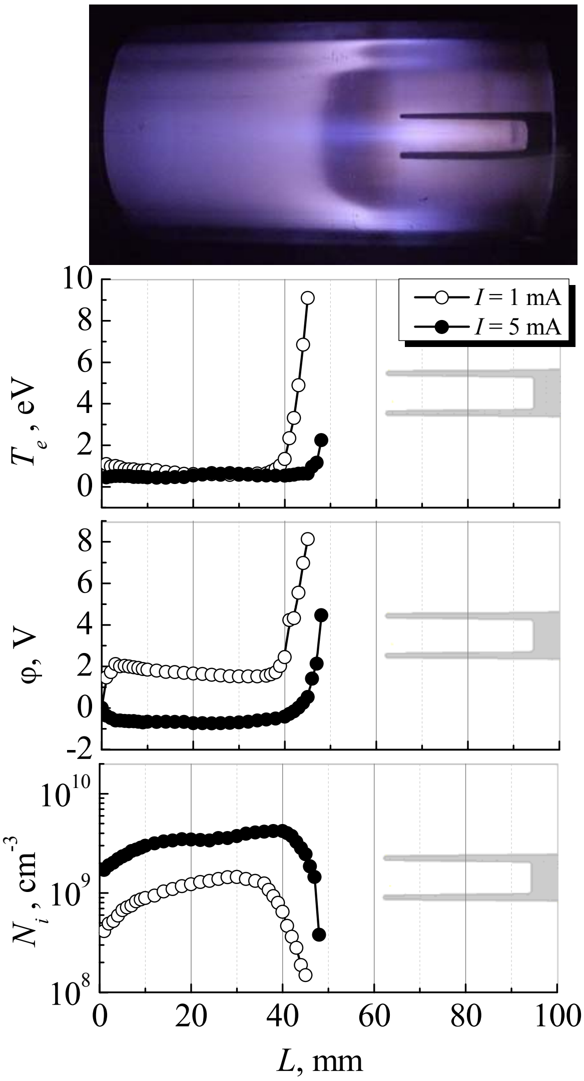

Fig. 2. Discharge photo and axial profiles of electron temperature, plasma potential and plasma concentration for discharge current values of 1 mA and 5 mA

Probe measurements in this case were performed from the anode surface to the cathode sheath boundary because directed flows of positive ions and electrons were moving to the cathode surface inside the cathode sheath thus impeding considerably the subsequent interpretation of the results obtained.

Fig. 2 also presents the axial profiles of plasma parameters for two values of the discharge current (1 mA and 5 mA) and the nitrogen pressure of 0.05 Torr. Almost throughout the plasma region the electron temperature amounted to about 1 eV for both current values, but on approaching the cathode sheath boundary one observes an abrupt increase of the electron temperature up to 9 eV for 1 mA and 3 eV for 5 mA of the discharge current. The voltage drop across the cathode sheath was about 700…900 V for the current values given, therefore one can assume that the beam may contain electrons with energies of tens or even hundreds electronvolts. With the 1 mA discharge current the plasma potential amounted to 2 V and it was positive with respect to the grounded anode. The voltage drop across the anode sheath controls the chaotic electron current to the anode surface equaling it to the current in the discharge circuit. The high energy electron beam may transfer a substantial current, and the presence of the decelerating potential in the anode sheath indicates that the coldest electrons are confined in the plasma and they do not approach the anode surface. However with the discharge current of 5 mA the decelerating potential near the anode decreases and even it is substituted with a small accelerating potential, which can now permit the anode to collect cold electrons. The attention is attracted to the presence of a rather high potential barrier near the boundary of the cathode sheath (for 1 mA current the height of this barrier comprises 8 V). The plasma potential pattern within the cathode sheath remains not to be studied because it is impossible to make probe measurements inside it. However one may assume that this potential barrier decelerates a portion of fast electrons inducing them to perform more efficient ionizing collisions with gas molecules. As this potential barrier is positioned between the plasma concentration maximum (located in the negative glow) and the cathode sheath boundary, it is hardly intended for confining cold electrons in the vicinity of this maximum.

For discharge current values of 1 and 5 mA the maximum plasma concentration values are equal to $1.4\cdot10^9$ and $4.2\cdot10^9$ cm^{-3}. However, on increasing the current the maximum location shifts closer to the cathode and it is at a distance of 30 and 40 mm from the anode, respectively. With the discharge current growth the cathode sheath thickness decreases thus shifting the plasma parameters to the cathode side.

In the photos presented in Fig. 3 for the nitrogen pressure of 0.15 Torr, one clearly observes two different modes of the hollow-discharge burning. At the low discharge current of 2 mA one observes the glow mode in which the glow in this cathode cavity is almost absent, the cathode sheath envelops the cathode walls from all sides, however, the negative glow from the anode side possesses a wedge-like profile and it tries to penetrate into the cathode cavity. The negative glow occupies only a portion of the gap between the hollow-cathode edge and the anode, and it gives its place to the dark Faraday space, whereas near the anode surface the anode glow is observed with an anode spot under formation. At higher discharge current of 25 mA the discharge is burning in the cavity mode when the cavity is filled with the brightly glowing plasma, the negative glow from the anode side becomes narrower, the dark Faraday space becomes more elongated, and an anode spot is observed on the anode surface. Fig. 3 also presents the axial profiles of plasma parameters. The anode glow at weak as well as high currents is characterized by the high electron temperature values (up to 4.5 eV), caused by the presence of the positive voltage drop (about 12…15 V), which accelerates electrons collected by the anode and leads to an enhanced ionization in this discharge region. In the negative glow the electron temperature is small with large as well as with weak current, and it is equal to about 1 eV.

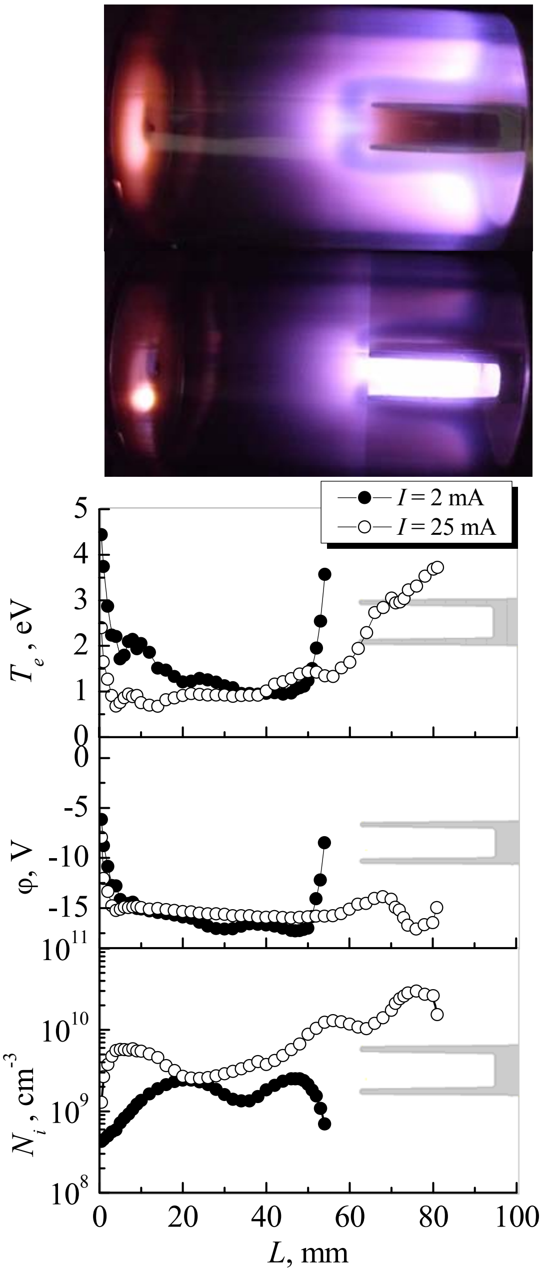

Fig. 3. Discharge photos and axial profiles of electron temperature, plasma potential and plasma concentration at the nitrogen pressure of p = 0.15 Torr and the discharge current values of 2 mA and 25 mA

In the glow mode the electron temperature in the dark Faraday space grows uniformly towards the anode whereas in the cavity mode it decreases weakly. In the hollow mode the electron temperature grows uniformly from 2 to almost 4 eV when one moves from the edge deep into the cavity. Near the cathode cavity edge a potential well about 3 V deep is observed. The presence of this well helps to contain cold electrons inside the cavity. Such a potential well was discovered inside the cavity in paper [6] with probe technique. This figure also shows that two maxima are available in the axial profile of the glow mode one of which is located in the negative glow near the cathode sheath edge and another one is located in the dark Faraday space. The axial profile of the plasma concentration for the cavity mode possesses three maxima: the first one is located inside the cavity (with the concentration of $3 \cdot 10^{10}$ cm^{-3}), the second one is in the negative glow near the cavity outlet (with the concentration of $1.3 \cdot 10^{10}$ cm^{-3}.), and the third one is observed near the anode surface and it is probably related to the presence of the anode spot in this region.

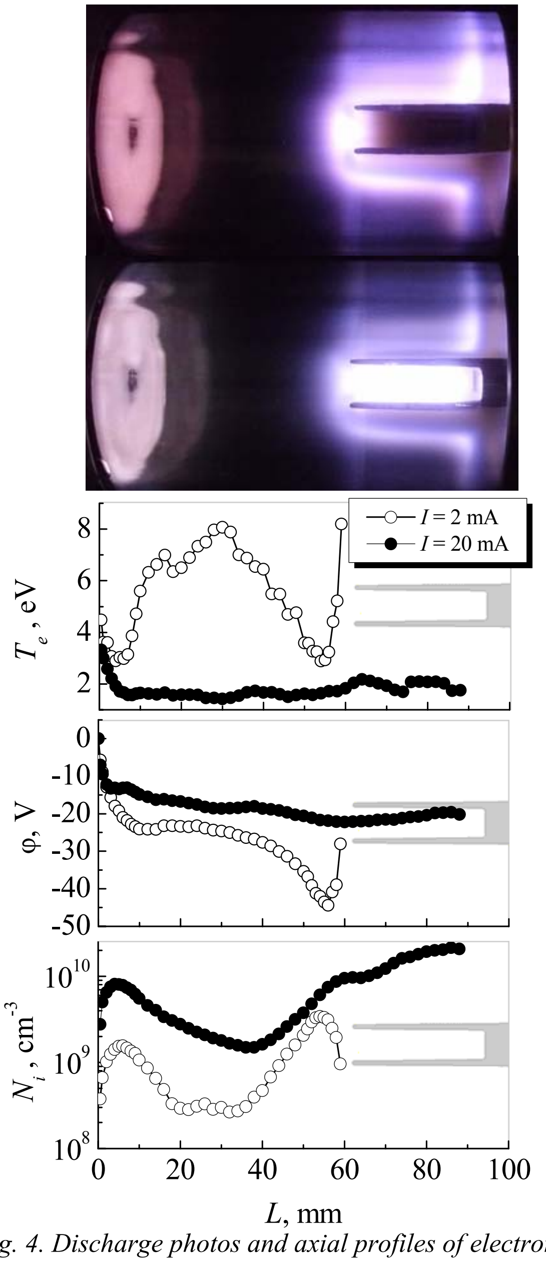

Fig. 4. Discharge photos and axial profiles of electron temperature, plasma potential and plasma concentration at the nitrogen pressure of p = 0.3 Torr and the discharge current values of 2 mA and 20 mA

Consider now the results for the nitrogen pressure of $p = 0.3$ Torr and the values of the discharge current of 2 and 20 mA presented in Fig. 4. For the moderate current (2 mA) one observes three regions of enhanced heating in the electron temperature profile. The first of them is pressed to the anode and it corresponds to the anode glow, and the voltage drop across the complete anode sheath approaches 20 V. Near the anode one also observes a plasma concentration peak (about $1.5 \cdot 10^9$ cm^{-3}). The broad maximum of the electron temperature is observed in the dark Faraday space with which a rather substantial plasma potential gradient is associated but the plasma concentration sustained is very small (about $3 \cdot 10^8$ cm^{-3}). The third section with high electron temperature is observed in the negative glow on approaching the cathode sheath boundary. Similar to the preceding case of the gas pressure of 0.15 Torr, the negative glow possesses the wedge-like shape directed to the cathode cavity. Cold electrons in this region are trapped in the potential well preventing their escape to the anode and the plasma concentration is supported at a rather high level ($3 \cdot 10^9$ cm^{-3}). After the discharge experiences a transition to the cavity mode (at the discharge current of 20 mA), the anode glow persists, again near it one observes high values of electron temperature and plasma concentration. The maximum of the electron temperature in the dark Faraday space disappears, now the electron temperature along this entire region comprising about 1.5 eV. The potential gradient also decreases considerably and the plasma concentration grows. Within the cathode cavity the electron temperature exceeds 2 eV, a potential well about 3 V deep is formed again and it contains cold electrons inside the well whereas the plasma concentration there approaches the value of $2 \cdot 10^{10}$ cm^{-3}.

On growing the gas pressure the potential well depth in the cathode cavity (in the hollow mode) decreases and the well disappears at 0.5 Torr.

CONCLUSIONS

This paper reports the axial profiles of such plasma parameters as electron temperature, plasma concentration and plasma potential outside as well as inside the hollow cathode we registered in different discharge modes.

We demonstrate that at low gas pressure (0.05 Torr) the discharge is burning in the high-voltage (electron-beam) mode. Electron temperature is small being approximately equal to 1 eV through the total plasma region and increasing abruptly only near the cathode sheath boundary. We found a rather high potential barrier near it (for the current of 1 mA the height of this barrier amounts to about 8 V), which perhaps decelerates a portion of fast electrons inducing them to perform ionizing collisions with gas molecules more efficiently.

At the nitrogen pressure of 0.15 Torr (as well as at higher pressure values) two different modes of discharge burning are well expressed: glow one and hollow one. With the discharge current of 2 mA a glow mode is observed when the negative glow from the anode side possesses a wedge-like profile and it tries to penetrate the cathode cavity. Here one can also observe a potential barrier near the cathode sheath boundary. At higher discharge current of 25 mA the discharge is burning in the hollow mode in which the cavity is filled with high concentration plasma of bright luminosity, and the electron temperature grows uniformly from 2 to almost 4 eV on moving from the edge deep into the cavity. A potential well approximately 3 V deep is observed near the edge of the cathode cavity. One observes maxima on the plasma concentration axial profile inside the cavity (with the concentration of $3 \cdot 10^{10}$ cm^{-3}), in the negative glow near the cavity outlet (with the concentration of $1.3 \cdot 10^{10}$ cm^{-3}), whereas the third maximum is observed near the anode surface.

For the nitrogen pressure of $p = 0.3$ Torr and a moderate current (2 mA) one observes a broad maximum of the electron temperature in the dark Faraday space with the associated considerable plasma potential, but the supported plasma concentration is very small (about $3 \cdot 10^8$ cm^{-3}). In the hollow mode (with the current of 20 mA) the maximum of electron temperature in the dark Faraday space vanishes. Inside the cathode cavity the electron temperature exceeds 2 eV, the depth of the potential well is about 3 V, and the plasma concentration approaches $2 \cdot 10^{10}$ cm^{-3}.

On gas pressure growing the depth of the potential well inside the cathode cavity (in the hollow mode) decreases and it vanishes at 0.5 Torr.

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ОСЕВАЯ СТРУКТУРА ТЛЕЮЩЕГО РАЗРЯДА ПОСТОЯННОГО ТОКА С ПОЛЫМ КАТОДОМ В РАЗЛИЧНЫХ РЕЖИМАХ ГОРЕНИЯ

В.А. Лисовский, И.А. Богодельный, В.Д. Егоренков

Осевые профили температуры электронов, плотности плазмы и потенциала тлеющего разряда с полым катодом в азоте были исследованы зондовым методом. Показано, что при низком давлении (0.05 Торр) разряд горит в высоковольтном (электронно-лучевом) режиме, когда электронный пучок формируется в катодной полости. Вблизи границы катодного слоя обнаружен потенциальный барьер. При давлениях газа, начиная с 0.15 Торр, при низких разрядных токах наблюдается тлеющий режим. При более высоком разрядном токе разряд горит в полом режиме, в котором полость катода заполнена плазмой высокой концентрации. Потенциальная яма глубиной до 3 В наблюдается в полости катода. С повышением давления газа ее глубина уменьшается, и при 0.5 Торр яма исчезает.

ОСЬОВА СТРУКТУРА ТЛІЮЧОГО РОЗРЯДУ ПОСТІЙНОГО СТРУМУ З ПОРОЖНИСТИМ КАТОДОМ У РІЗНИХ РЕЖИМАХ ГОРІННЯ

В.О. Лісовський, І.А. Богодельний, В.Д. Єгоренков

Осьові профілі температури електронів, густини плазми і потенціалу тліючого розряду з порожнистим катодом в азоті були досліджені зондовим методом. Показано, що при низькому тиску (0.05 Торр) розряд горить у високовольтному (електронно-променевому) режимі, коли електронний пучок формується в катодній порожнині. Поблизу межі катодного шару виявлено потенційний бар'єр. При тиску газу, починаючи з 0.15 Торр, при низьких розрядних струмах спостерігається тліючий режим. При більш високому розрядному струмі розряд горить в порожнистому режимі, в якому порожнина катода заповнена плазмою високої концентрації. Потенційна яма глибиною до 3 В спостерігається в порожнині катода. З підвищенням тиску газу її глибина зменшується, і при 0.5 Торр яма зникає.

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