Effect of cathode heating and positive column contraction on the spatial distributions of parameters in a cathode region

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The cathode heating as a result of discharge current flow in dc normal atmospheric-pressure glow discharge with constricted positive column leads to increase in the interelectrode voltage if the cathode is not cooled and its temperature increases. With additional cathode heating with an external heat source the interelectrode voltage decreases. Radially inhomogeneous profiles of the reduced electric field on the uncooled cathode surface have been measured.

1. Introduction

In the high-current atmospheric pressure glow discharges, when discharge chamber walls are far from discharge axis, contraction degree of the positive column should be determined by the relation of its diameter relative to the negative glow dimension. In connection to this, as it is shown in [1], positive column at gap of 10 mm and at current of 1 A is diffuse in nitrogen APGD, slightly constricted in helium one and is strongly constricted in argon one. The gas in the discharge cathode sheath and at the cathode surface under the sheath is heated with the discharge current. Volumetric heat release in different regions of constricted discharges will be quite varied. Different theoretical and experimental results [2-8] show that the cathode temperature has a significant influence on the glow discharge parameters. In the experiments [7], heating of a tungsten cathode to candescence during less than 1 s is accompanied by the interelectrode voltage increases by 60-70 V. As it is shown in [8], the cathode heating leads to the changes in the cathode fall parameters. In particular, the cathode fall voltage is increasing. Moreover, a radial dependence of electric field strength appears in the cathode fall. It looks strange, since in accordance with the similarity laws the cathode potential drop should be the same. In this paper, the investigations of cathode heating impact and positive column contraction on the spatial distributions of parameters in a cathode region of helium APGD are presented.

2. Experimental results

The experimental setup used in these investigations is the same as in [8]. Glow discharge is ignited between two electrodes in air-locked chamber with quartz glass windows. A weak flow of helium (about 1 litre/min) is provided through the discharge chamber. The step-up transformers with typical bridge rectifiers and capacitive filtering are used in power supplies. Output voltage is varied from 0 up to 3 kV.

In the experiments a flat copper cathode is used. Its diameter is about 36 mm, which is larger than the observed negative glow diameter, i.e. the effects connected with abnormal discharge are absent. For the case of sufficient cathode cooling, the discharge view is shown in the inset *a* (Fig. 1) at a current of 1 A and 10 mm interelectrode gap. As it can be seen the positive column is constricted, since its diameter is 2-3 mm while a thin layer of the negative glow is about 6-7 mm in diameter. According to [7], the electric field strength in the cathode fall is constant in the radial direction and linearly drops in the axial direction from 60 kV/cm at the cathode surface to zero at the distance of 70 microns from the cathode (Fig. 1, squares), which defines the cathode fall thickness. In the presented case the cathode fall is about 210 V, which is near to the classical value 177 V for the pair copper-helium.

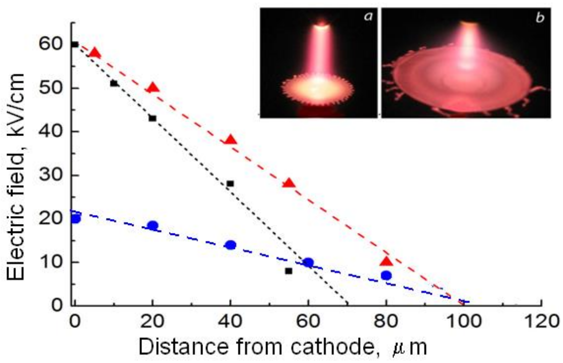

Fig. 1. Longitudinal electric field profiles for cooled (squares) and uncooled (triangles, axial; circles, 8 mm from axis) cathodes. The inset presents the discharge images with cooled *(a)* and uncooled *(b)* cathodes.

An image of the discharge under the same conditions (current of 1 A and gap 10 mm), but without the cathode cooling is shown in the inset *b* (Fig. 1). It can be seen, the changes in the positive column are not drastic in comparison with the case shown in inset *a*, and they are mainly observed close to the cathode region. The negative glow area has increased by almost one order of magnitude.

Discharge becomes more constricted. In this case, the electric field strength decreases towards a discharge periphery by a factor of 3 (Fig. 1, triangles and circles). The thickness of the cathode fall has increased by a factor of about 1.5. Figure 1 gives information about the values of voltage drop: at the periphery of cathode fall the voltage drop is about 100 V, at the discharge axis it is about 300 V.

Creation of the APGD with diffuse positive column at large gap and high current is a hard challenge even in helium. In Fig. 2 the images of helium APGD for two gaps at current of 1 A are presented. As one can see, a diffuse positive column can be obtained only at gaps less than 5 mm. At larger gaps it is constricted. Average current density on the cathode changes from ~0.3 A/cm^2 to ~0.4 A/cm^2 during transition from diffuse to constricted discharge mode. At the same time, the current density in positive column increases drastically – from 0.3 A/cm^2 (diffuse positive column) to ~20 A/cm^2 (constricted).

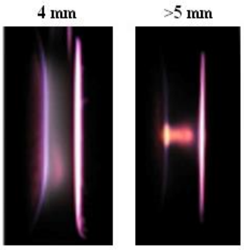

Fig. 2. Images of the diffuse and constricted helium APGD with uncooled cathode at current of 1 A.

Normalized H_β line profiles registered at the distance of about 0.03 mm from cathode surface and at the discharge axis in the cases of diffuse and constricted discharges are shown in Fig. 3. As it can be seen, a transfer of the APGD from diffuse mode to constricted one is accompanied by the larger H_β line broadening. It means, that electric field at this distance increases. Performed estimation gives the electric field growth from 30 kV/cm to 40 kV/cm. It can be assumed that it causes an increase in cathode fall voltage at a discharge axis.

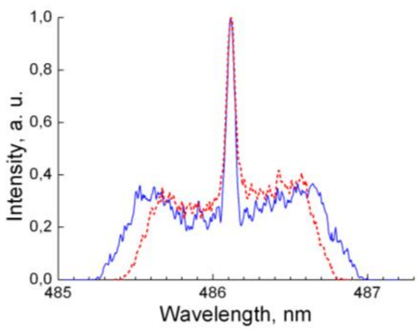

Fig. 3. Normalized H_β line profiles at the distance of about 0.03 mm from cathode surface in the cases of diffuse (dash) and constricted (solid) discharges.

Axial gas temperature profiles in the APGD for both states of positive column are shown in Fig. 4. The gas temperature T_g was determined by using the resolved rotational band $(B\,^2\Sigma^+_u - X\,^2\Sigma^+_g)$ of nitrogen ions N^+_2. As it can be seen (Fig. 4), in this case the diffuse positive column gas temperature is the same along the axis in practically whole discharge gap.

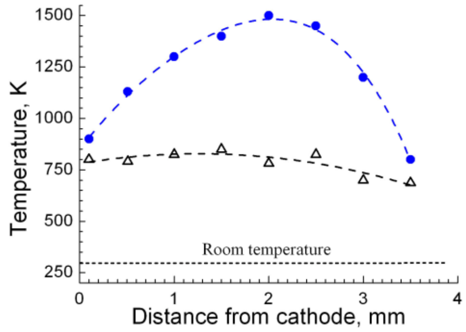

Fig. 4. Axial temperature profiles in the APGD with diffuse (triangles) and constricted (circles) positive columns at discharge current of 1 A.

In constricted positive column (Fig. 4, circles), temperature is higher and its maximum is in the middle of the column. It is due to high current density here (~20 A/cm^2). Taking into account the electric field strength in positive column at 1 A (~100 V/cm according to [1]) we obtain volumetric electric power density of about 2 kW/cm^3. This value is more than one order of magnitude less in comparison with power density in cathode fall (>60 kW/cm^3). However, this huge heat generation takes place in thin cathode fall layer of about 0.1 mm and the main heat removal from this region occurs through the cathode. At the same time, a heat removal from positive column is possible through the radiation transfer and heat transfer to surrounding cold gas. Still, these two ways probably are not so effective and we observe temperature gradients (~2500 K/cm) on axial temperature profile for constricted positive column in both directions, namely, to the cathode and to the anode. The temperature gradients provide evidence to the heat fluxes from positive column in axial narrow channel, transverse dimension of which is defined by the positive column diameter. What is the surface temperature distribution along the cathode for the diffuse and constricted APGDs? The following experiment gives an answer to this question.

On the cathode underside a hardly visible homogeneous red incandescence is observed. Its diameter is close to the diameter of the negative glow. If the interelectrode gap is increased to larger than 5 mm, a red spot with the diameter of about

5 mm appears on the cathode backside under the positive column (Fig. 5, *b*). It indicates that the cathode heating is inhomogeneous in the case of discharge with the constricted positive column.

A schematic diagram of experimental setup is shown in Fig. 5, *a*. The discharge chamber has two

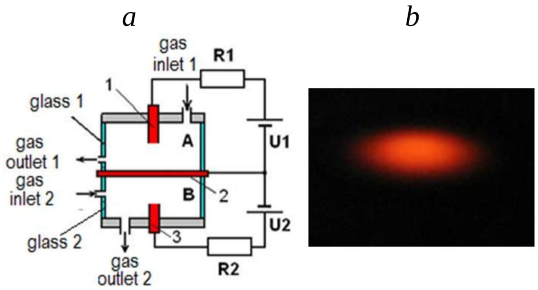

Fig. 5. Experimental setup with additional cathode heating *(a)* and an image of the hot spot on the cathode plate underside *(b)*. 1 and 3 – anodes, 2 – cathode plate, R1 and R2 – ballast resistors, U1 and U2 – power supplies.

independent sections divided by 0.5 mm thick stainless steel cathode plate 2. A copper disk is used as anode 1 and its surface is parallel to the cathode. The discharge is initiated by touching the electrodes. At a current of 1 A and interelectrode gap of 2-3 mm the discharge is diffuse (as shown in Fig. 2, 4 mm).

Let's consider an influence of the cathode heating from external heat source on the APGD parameters. A testing glow discharge in helium (Fig. 6, *a*) is initiated between cathode plate 2 and anode 3

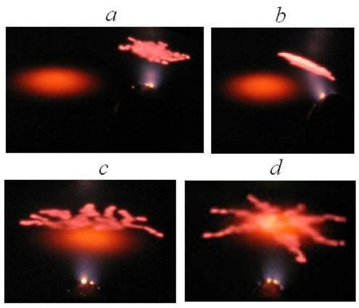

Fig. 6. Images of the helium APGD in section B at its shifting

(Fig. 5, *a*). Let's move the anode of tested discharge in section B parallel to the cathode surface keeping constant the gap (5 mm) and the current (50 mA). In the experiment the voltage on electrodes is about 260-270 V if measured far away from the spot (Fig. 6, *a*). However, when anode 3 is moved towards the spot center (Fig. 6, *b*) the voltage decreases to 240-250 V close to the periphery of hot spot. At further anode displacement the negative glow stays at the periphery of the hot spot (Fig. 6, *c*). Even when the anode is facing the spot center the negative glow doesn't occupy central part of the spot; it becomes inhomogeneous and consists of several arms (Fig. 6, *d*). If now the heating discharge in section A is turned off, then the discharge voltage increases to 290 V during the first several seconds of the cathode cooling.

It is known that the normal current density of helium glow discharge is one of the lowest among the discharges in other gases. Consequently, the heat generation in the cathode region is also relatively small. Thus, at a current of 50 mA the gas temperature in the negative glow of helium APGD is about 500 K [1]. Therefore, additional cathode heating can strongly influence the parameters of the cathode region. In nitrogen discharge, for example, the current density on the cathode is about 10 A/cm^2 and the gas temperature in the negative glow reaches the value of 1750 K at a current of 50 mA [1]. In the experiment a flow of nitrogen is organized through section B (Fig. 5, *a*) and APGD is allowed in 5 mm gap at a current of 50 mA and electrode voltage of 560 V. In the presence of high current (0.5 A) in? constricted discharge in section A, the negative glow of the nitrogen discharge in section B shifts to the periphery of the hot spot and the electrode voltage significantly decreases – from 560 to 400 V.

4. Discussion

Thus, in normal dc APGD with constricted positive column (the width of the positive column is much smaller than the width of the negative glow) the additional cathode heating by heat flux from the positive column leads to the increase in the interelectrode voltage in comparison with the voltage of the discharge with cooled cathode. At that, this increase in voltage occurs due to change of cathode fall. In the case of cathode heating by external heater the interelectrode voltage decreases.

In any strongly constricted glow discharge, gas heating in cathode sheath under positive column results in heat generation here and heat flux from positive column. Gas heating in cathode sheath at its periphery happens only due to heat release here. Therefore, there is a larger heat flux to the cathode at the discharge axis in comparison with the sheath periphery. However, since a heat conductivity of copper is high, the cathode temperature along whole surface will not differ significantly. That means, that part of heat from a cathode center will propagate in the radial direction and result in additional gas heating in periphery cathode sheath. It should be noticed that the parameters of the cathode region in the diffuse APGD fit more or less the scaling laws. In strongly constricted discharge, scaling laws are fulfilled at the periphery of cathode fall and mismatch at its center due to an increase in the cathode fall voltage.

Let us consider the current distributions in cathode region of strongly constricted glow discharge (white line in Fig. 7). Close to the discharge axis the picture is clear. In cathode fall, the current flows perpendicular to the cathode surface according to the electric field direction. This current direction spreads in Faraday dark space up to positive column beginning (marked by arched white curve). Voltage falls between cathode surface and the beginning of the positive column defined by cathode fall voltage at the axis, voltage drop in the negative glow and Faraday dark space. The length of the last is about 1.5 mm.

Other picture is at the edge of cathode sheath. In the cathode fall, current flows perpendicular to the cathode surface as well. Voltage fall between cathode surface and beginning of positive column should be the same as at the axis it consists of the same parts, i.e. cathode fall voltage at the edge of sheath, voltage drop in negative glow and Faraday dark space. However, these components differ in

Fig. 7. Schematic of current flow in cathode region of constricted glow discharge.

comparison with the axial ones. The cathode fall is less than axial one. Voltage drop in negative glow probably changes slightly in radial direction. The increase in length of Faraday dark space and voltage drop along this way probably compensates the reduction of the cathode fall at the periphery of cathode sheath.

It seems to be an acceptable explanation for radial dependence of electric field strength close to cathode surface in the case of uncooled cathode (Fig. 1, triangles and filled circles). However, the cathode fall voltage is defined in preference by a secondary electron emission coefficient. The secondary electron emission coefficient used in glow discharge models is an effective value taking into account various possible secondary emission processes including ion impact, metastable impact and photoemission [9]. From the analysis of experimental results, Phelps and Petrovic [9] have deduced an effective γ as a function of the reduced field strength at the cathode, E/N, due to the relative importance of the different electron emission processes for different discharge conditions.

According to experimental data, presented in [10], for example, the metastable atoms concentration is maximal at the discharge axis and works to zero at the cathode fall periphery. This indicates that the relative contributions of metastables to the electron emission processes at the edge of cathode sheath and in its center in helium APGD can be quite different.

As it is known from literature the oxide films can lead to increase or decrease in the secondary electron emission coefficient and consequently to the changes in the cathode fall voltage. However, even if the oxide films are developed, the same behaviour of the electrode voltage is observed anyway: the voltage increases at cathode heating by discharge current and decreases at cathode heating by external heat source.

4. Acknowledgments

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5. References

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