The parameters of anode spots in wide DC current range in the atmospheric pressure helium discharges

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The experimental results of observations of anode spots behavior in the wide current range are presented. Some parameters of these spots have been determined. Current densities in low (5 mA) and high (2.5 A) current spots do not strongly differ and are of about 200 A/cm^2 and 400 A/cm^2 respectively. Gas temperature in low current spot is about 500 K while in high current spot it is about 1500 K. No strong electric fields are identified in the spots.

1. Introduction

At present, there is an interest in the phenomena of self-organized structures in different discharges [1]. Anode current spots patterns are considered to be an example of such self-organization in glow discharges. The experimental results [2] have shown that the spots forming stable patterns on anode in the DC atmospheric pressure glow discharge (APGD) in helium are fluctuating. The correlation between fluctuations of both integral light intensity of spots and discharge current (or voltage) has been established. In this report, we present experimental results of observations of anode spots behavior in the wide current range along with some results of their parameters determination.

2. Images of the anode spots pattern at various discharge condition

In a two-electrode configuration similar to [2], the APGD is ignited between electrodes in an air-locked discharge chamber. In the experiments, the cathode is always flat and made out of copper. It is cooled down with water when discharge current is larger than 0.5 A. The shapes of the copper or tungsten anodes are flat or rounded. Helium flow of about 1-2 l/min at atmospheric pressure is supplied through the chamber.

Canon PowerShot A350 camera is used for photographing the discharge. Time resolution of the anode spots blinking is performed by a Princeton Instruments PI-MAX intensified CCD camera. A scanning 0.5-meter monochromator (two gratings with 1200 grooves/mm) is used for photoelectric registration of the APGD emission spectra. Its inverse linear dispersion is ~0.5 nm/mm. The photoelectric multiplier FEU-171 is used as a converter of light intensity into electric signal. The discharge image is focused onto the entrance slit of the monochromator with the help of lens. To obtain spatial distributions of light emission intensity the discharge chamber is placed on a specially designed platform. Positioning of the platform can be adjusted transversely to optical axis by micrometer screws.

In Fig. 1, a side view of the DC APGD (a) and images of the anode (b) and cathode (c) pattern at the

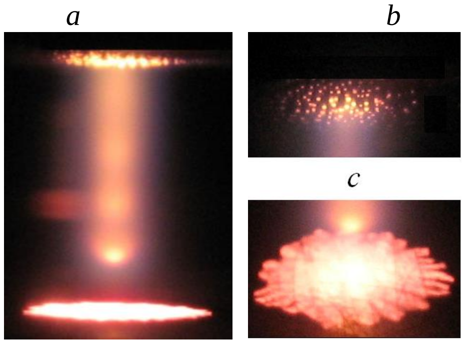

Fig. 1. Side view of the APGD (*a*) and images of the anode (*b*) and cathode (*c*) pattern at the angle (~30 degrees) to the electrode surfaces.

angle (~30 degrees) to the electrode surfaces are shown. In the presented case the gap is 8 mm and DC current is 0.8 A. In this report, we investigate anode region only. Structures on cathode are a subject of a separate study.

The number of anode spots, their intensity and anode area that they occupy primarily depends on the discharge current and the interelectrode gaps. The influence of anode shape and its material is not that strong. Images of anode patterns for different anode shapes for the same discharge current of 0.8 A and the

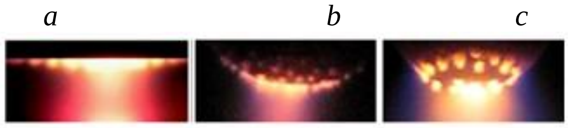

Fig. 2. Images of anode spots structures on the flat *(a)* and rounded anodes (*b* - radius 6 mm, *c* - 3 mm)

gap of 10 mm are shown in Fig. 2.

The images of the discharges at discharge current of 40 mA at different gaps are shown in Fig. 3. Gap is varied from about 0.07 mm up to 1.8 mm. At a gap of about 0.07 mm (Fig. 3, *a*), the transverse dimensions of both anode layer luminosity and negative glow are practically the same. Anode surface is covered by weak homogeneous luminosity. At a

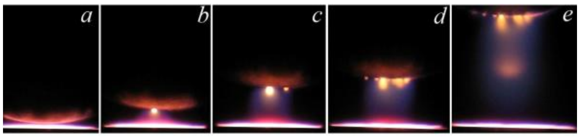

Fig. 3. DC helium APGDs at discharge current of 0.04 A against different gaps: *a* – 0.07 mm, *b* – 0.25, *c* – 0.5, *d* – 0.7 and *e* – 1.8 mm.

gap of about 0.25 mm a single spot appears close to the anode surface (Fig. 3, *b*). The number of spots increases sequentially, while the gap increases until the positive column appears (Fig. 3, *e*). At larger gaps, the positive column length increases, but the number of anode spots does not change.

At higher currents the number of spots becomes larger and they cover significant area of the anode. Images of the DC helium APGDs at discharge current of 2 A against different gaps are shown in Fig. 4. At small gaps (images *a*-*c*) when the positive column is absent, a lot of spots cover the anode surface. At gaps

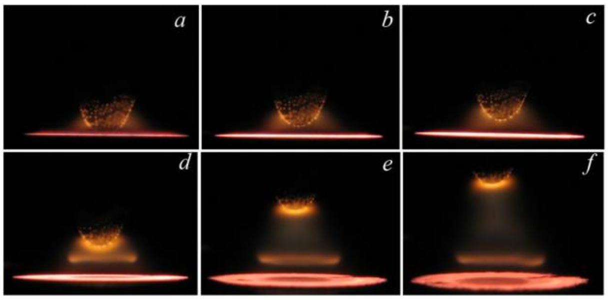

Fig. 4. Images of the DC helium APGDs at discharge current of 2 A against different gaps: *a* – 0.07 mm, *b* – 0.5 mm, *c* – 1 mm, *d* – 2 mm, *e* – 7 mm, *f* – 10 mm.

of around 2 mm and larger the positive column appears. A bright stripe parallel to the negative glow at a distance of 1-2 mm from it (images d-f in Fig. 4, b) indicates the beginning of the positive column. With an advent of the constricted positive column the diameter of the spots located closer to the discharge axis increases. Spots become brighter and their number decreases.

It should be noted that the presence of anode spots in helium APGD does not depend on the state of the positive column. However the structure spots pattern in the case of a constricted and diffuse positive column are different. For the cases, when the photos in Fig. 5 were taken, the transverse dimension of the positive column is comparable with the diameter of the negative glow. Generation of the APGD with a diffuse positive column at high discharge current and large gap is a difficult task. For example, in our case a diffuse helium APGD at a discharge current of 1 A existed at gaps up to slightly more than 4 mm (Fig.

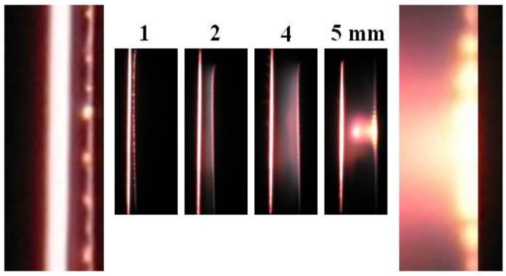

Fig. 5. The APGD images in helium at various gaps (the anode is located on the right). The left and the right images present magnified central parts of anode region for 1 mm and 5 mm, correspondingly. Discharge current is 1 A.

5). In this experiment, two flat copper electrodes of disc shape, with 36 mm diameter and 8mm thickness, were used without forced cooling.

A further increase in the gap leads to an abrupt transition of the positive column to a constricted mode (Fig. 5, image at the gap of 5 mm). Transition from the diffuse mode to a constricted one takes place at different gaps depending on discharge current and efficiency of the electrodes cooling. It can occur at a gap of 0.2–0.3 mm at a current of 40 mA (Fig. 3) or 0.8–1 mm at a current of 0.5 A.

As it can be seen in the photos, the glowing spots are located over the entire surface of the anode (Fig. 5, 1 mm gap), which may become more blurred when the gap increases. With the contraction of the positive column, the light spots concentrate in the center of the anode region, grow in size and become much brighter (Fig. 5, 5 mm gap).

At higher currents (a few amperes), a collapse of anode spots pattern happens similarly to how it is shown in Fig. 4, and one more intensive spot with larger diameter appears. Fig. 6, *a* demonstrates this transition. As it can be seen, at the discharge current of 2.6 A (image *c*) a spasmodic transition occurs from the anode spots pattern to single spot of higher intensity and larger diameter compared to the separate spots in the pattern at lower currents. This spot is maintained at the further current increase.

If we decrease the current, this single spot disappears at currents less than 1.8-2 A (image *f* in Fig. 6, *a*). One can notice in Fig. 6, *b* such distinctive feature in the V-I characteristics as voltage jump of 6-8 V at discharge current of about 2.7 A. In Fig. 6, *b*, the letters *a*-*f* with the arrows show the current values corresponding to the images of discharge obtained at these currents and labeled with the same letters in Fig. 6, *a*. Thus, there is a hysteresis in V-I characteristic and the voltage jumps are connected with the collapse/onset of the anode spots pattern. It

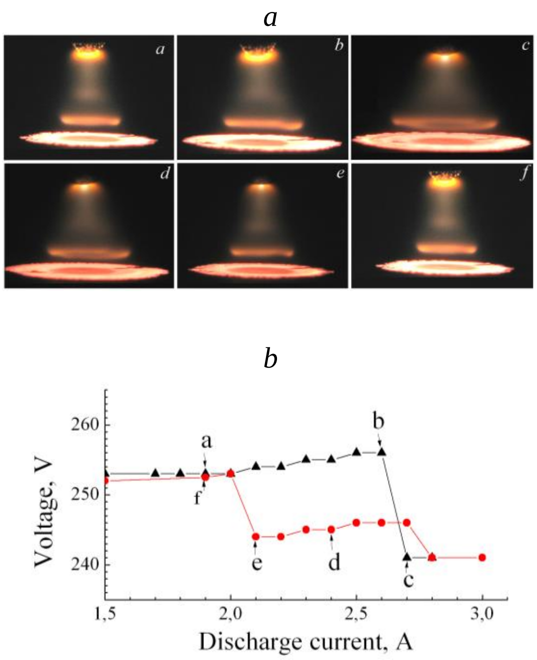

Fig. 6. *a* – Discharge images at different discharge currents: *a* – 1.9 A, *b* – 2.6, *c* – 3.0, *d* – 2.4, *e* – 2.1 and *f* – 1.9 A; *b* – Part of the current-voltage characteristic of helium APGD at discharge gap of 10 mm. Triangles reflect the dependence when current increases and circles – when current decreases.

should be noted, that the potential changes of 6-8 V in the discharge space, as it is demonstrated in [3] with the help of a probe, take place only close to the anode surface.

Let us turn the attention to the behaviour of anode spots pattern at the glow-to-arc transition. Naturally, high current glow discharge is not stable relative to this transition. The interelectrode voltage for arc is only about 50 V. The cathode spot of arc in this condition is strongly unstable and moves quickly along the cathode surface. Anode region is connected with the confined anode surface. That allows to observe the changes in the anode region at the glow-to-arc transition. The discharge images immediately before/after this transition are shown in Fig. 7. Expose time is 0.001 s. It should be noticed, that in the case when anode spots pattern exists in glow regime (Fig. 7, *a*) this spots pattern is also saved in arc regime (Fig. 7, *b*). If there is only one spot on the

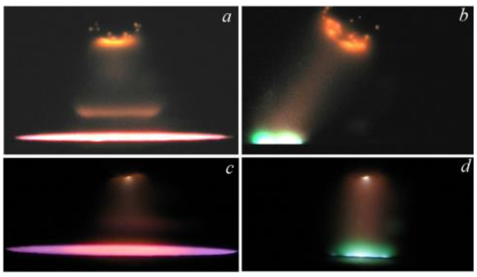

Fig. 7. Glow and arc discharge images at the glow-to-arc transition in case of spots pattern and single spot.

anode surface, then this spot exists in both discharge regimes (Fig. 7, *c, d*). This fact can serve as evidence that the properties of the anode region in glow discharge and arc are the same.

Behaviour of anode spots at a microseconds time scale is investigated using Princeton Instruments PI-MAX ICCD camera. In the experiments, the camera gate is about 1 μs with a repetition rate of 1000 Hz. Thus, a series of frames with a repetition period of 1 ms is made. The images are taken in the direction perpendicular to the axis of the discharge at discharge current of 40 mA, discharge gap of about 1.5 mm and helium flow rate of 1 l/min. Flat copper electrodes

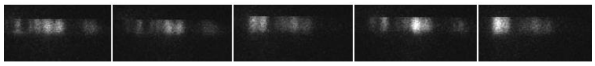

Fig. 8. Series of photos of the anode region at the side-on observation.

with the diameter of 20 mm were used. A series of 5 pictures demonstrating what? is shown in Fig. 8. As one can see, the location of the spots maintains in time, but their intensity varies from frame to frame. As ICCD camera is not synchronized with the discharge, we can assume that the fluctuations in the intensity of the spots shown on a series of images in Fig. 6 occur randomly. At the same time, discharge voltage and current oscillations may have amplitudes up to 10-15% of their average magnitudes and frequency in MHz frequency range and these characteristics are highly harmonic [2].

3. Anode spots parameters

Let us focus on some anode spot parameters. We use the non-perturbing optical and spectroscopic diagnostics. First, we estimate current density for the case of single spots (Fig. 3, *b* and *Fig. 6, c*) using transverse size of their light emission regions. Although weak luminosity is observed around these spots, we assume that all current flows through one spot only.

For the case shown in Fig.3, b, calculation can be at acceptable accuracy by comparing the anode spot size with negative glow size. According to [3], current density is ~2.3 A/cm^2 in the cathode region of helium APGD with a copper cathode. Using the transverse dimensions of the spot and the negative glow shown in Fig. 3, *b*, one can determine the ratio between their areas, which is about 100. Thus, current density in the spot reaches about 200 A/cm^2.

For the case in Fig. 6, *b*, the spot diameter is 0.9-1 mm, and it can be measured using corresponding image on the screen. At discharge current of 3 A, the calculated current density is in the range of 350-400 A/cm^2.

Fig. 9 shows the emission spectra of the single anode spot at currents of 5 mA and 2.5 A at discharge

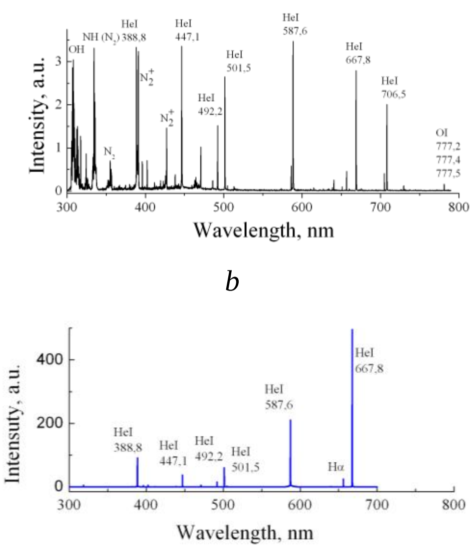

Fig. 9. Emission spectra of the single anode spots at 5 mA *(a)*, 2.5 A *(b)*

gaps of about 1 mm and 10 mm, respectively. In the blue region of the emission spectrum of the single spot at 5 mA the molecular rotational-vibrational bands are observed along with helium lines. Their sources are trace gases in the cylinder with helium.

Emission spectrum of the single spot at a current of 2.5 A (Fig. 9, *b*) is much more intense and it mostly consists of helium lines. The intensity of the vibrational-rotational bands of impurities is 1-2 orders lower than that of the helium lines. Such large difference in the intensities of helium lines and impurities bands can be explained by assumption that an excitation of impurities bands mainly occurs in

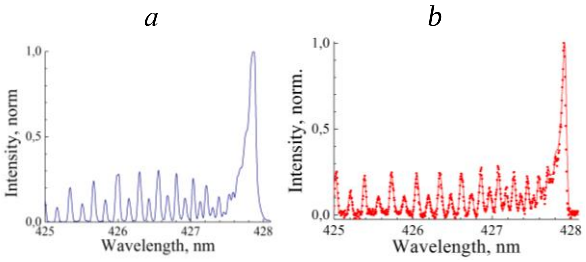

Fig. 10. The vibrational bands of first negative nitrogen system at currents of 5 mA (*a*) and 2.5 A (*b*)

peripheral spot region. In low current spot (5 mA, Fig. 3, *b*), the volumes of peripheral and bright spot regions are probably comparable.

Resolved vibrational-rotational bands of molecular nitrogen ion (0,1) N_2^+ $(B^2\Sigma_u^+ - X^2\Sigma_g^+)$ are presented in the spot spectra. That allows to determine gas temperature in spots. In Fig, 10, the corresponding emission spectra of the single anode spots at currents of 5 mA and 2.5 A are shown. Boltzmann plot applied for the spectrum in Fig 10, *a* gives gas temperature of about 500 K. For the case of the spot at high current (Fig. 10, *b*), the temperature is determined by matching experimental spectrum to a simulated one. It is about 1500 K.

Differences in the HeI 492.2 nm line profiles are observed for both spots and cathode fall (Fig. 11). This data shows that there are no strong electric fields in the anode spot. Moreover, these line profiles are

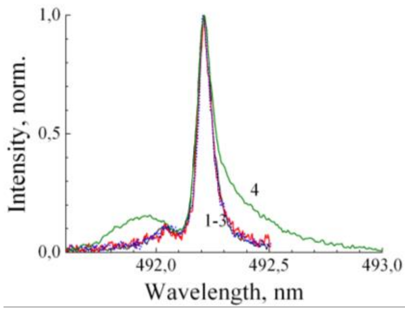

Fig. 11. Profiles of the HeI 492.2 nm line in the middle of the anode spot and at ±20 microns from its middle (1-3) and at about 30 microns from cathode surface (4).

practically the same for the spots at currents of 0.04 A and 2.5 A. It means that plasma condition in single spots are approximate at low and high currents.

4. Acknowledgments

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5. References

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