Non-Steady State Processes in a Micro-Hollow Cathode Discharge[1]

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Abstract – The paper deals with the investigations of a gas discharge with hollow cathode at a typical size of the gap spacing essentially less than 1 mm and at a pressure up to 1 atm. Although at a current level of about 10 mA and less the discharge is capable of burning in a glow-type regime, some non-steady state phenomena are characteristic of such discharges. In particular, an abrupt transition from suppressed mode of burning to abnormal mode and glow-to-spark transition are observed in the experiments. These effects are discussed and interpreted in the paper.

1. Introduction

Considerable interest is currently being demonstrated in investigation of so-called high-pressure glow-type microdischarges [1–4]. When speak of the microdischarge we imply that a typical geometrical size of the gap is essentially less than 1 mm. However, the pressure is rather high so that the electrons are capable of providing the impact ionization in the gap. Then the properties of the microdischarges with a hollow cathode or with a plane cathode resemble the properties of the classical low-pressure glow discharge in parallel-plane geometry. It offers a possibility to use the well-known experimental data, related to the classical glow discharge, in the interpretation of the phenomena as applied to the microgaps.

The paper gives interpretation to some non-steady state processes in the microdischarges. In particular, specific features of transition from suppressed mode of burning to abnormal mode and of the glow-to-spark transition are discussed.

2. Typical experimental electrode configurations

Electrode system of a microgap is powered from DC power supply whose voltage V_0 is about 1 kV and less. The discharge current through the gap can be varied by the voltage V_0 and by the ballast resistor R. Typical electrode configurations for the microdischarges are shown in Fig. 1.

The electrode system in Fig. 1, *a* is, as a matter of fact, the arrangement for providing a glow discharge between the hollow cathode C and the hollow anode *A* that are separated from each other by means of the insulating mica ring. In most cases for such configuration, the depth of the cavity h is comparable with the diameter D or exceeds the diameter. For example, in the experiments [1] D=0.7 mm, h=2.1 mm, and d=0.25 mm.

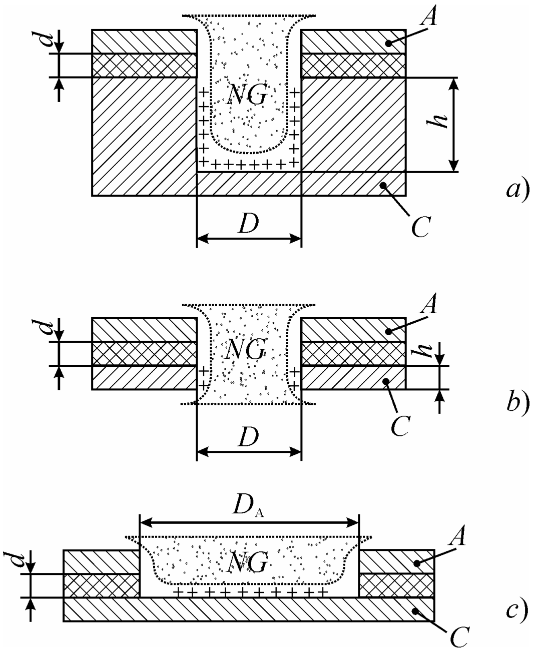

Fig. 1. Typical electrode configurations for the microdischarges

The other type of the electrode system corresponds to the design as the cathode aperture is open (Fig. 1, *b*). Beside that, the electrode configuration with a flat cathode (Fig. 1, *c*) is used in the experiments.

In all above cases, the negative glow plasma *NG* is sustained in the gap, and the discharge current closes to the anode via this plasma. Between the boundary of the *NG* plasma and the cathode surface, the cathode voltage drop region of length l_c with an excess space charge of the positive ions exists. For the configurations (*a*) and (*b*) the effect of the hollow cathode plays an important role in the discharge.

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3. Measured gas pressure and reduced to the temperature pressure in the discharge region

For further consideration, it is important to have information on the parameters of the cathode voltage drop region. In classical glow discharge these parameters can be defined in terms of the similarity laws [5]. The basic similarity parameter for the near cathode layer is the current density reduced to pressure j/p^2. The other similarity parameters: cathode voltage drop value V_c, production pl_c, and reduced electric field at the cathode surface E_c/p are determined by j/p^2.

The above parameters include in itself the gas pressure p. However, strictly speaking the process of electron impact with the gas molecules is specified by the neutral particle density n_a. The situation may occur when temperature in the discharge operation region is much higher than the temperature in the rest part of the discharge chamber. Then the neutral particle density in the discharge region will be lower than that in the rest of the space. This situation is characteristic of our case (especially for a high pressure range), so that for interpretation of the experimental data we have to use not the pressure in the discharge chamber p, but an effective pressure p^* which takes into account the conditions that the neutral particle density in the discharge area is decreased.

The problem was discussed in more detail in [4], where some estimates based on experimental data [3] had been made for the electrode configuration shown in Fig. 1, *c* (D_A=1.5 mm, d=0.25 mm). For example, in a regime of normal glow discharge at a pressure p=200 Torr and current i=2.56 mA we had estimated $p^*\approx$30 Torr. In subsequent interpretation of the experimental data, we will use the fact that neutral particle density in the discharge region decreases due to an increase in temperature.

4. Transition from suppressed glow discharge with hollow cathode to abnormal discharge

One of the non-steady state processes for the high-pressure microdischarges can be illustrated by the current voltage characteristics shown in Fig. 2 [1].

This is the case of comparatively low pressure so that we can say that $p\approx p^*$. At the curve for pressure p=7.5 Torr, we can see the part *ab* of the characteristic where the current increases with the voltage, i.e. the curve has a positive slope. The operation regime in the point b can be referred to as a critical point. The further smooth increase in the voltage results in the abrupt change of the discharge mode. The operation point at the characteristic is shifted abruptly from point *b* to point *c*, that is the discharge transforms from the regime with a low current and a high voltage to the regime of a decreased voltage but an increased current. After that, the current-voltage characteristic has again the positive slope.

At a lower gas pressure (3.5 Torr and 5 Torr) we can observe only the section *ab* of the characteristic, and the abrupt transition to the regime with an increased current does not occur.

The phenomenon can be understood if we analyze the results with taking into account the quantitative data on similarity parameters for glow discharge in argon [5]. Let initially consider the case p=3.5 Torr.

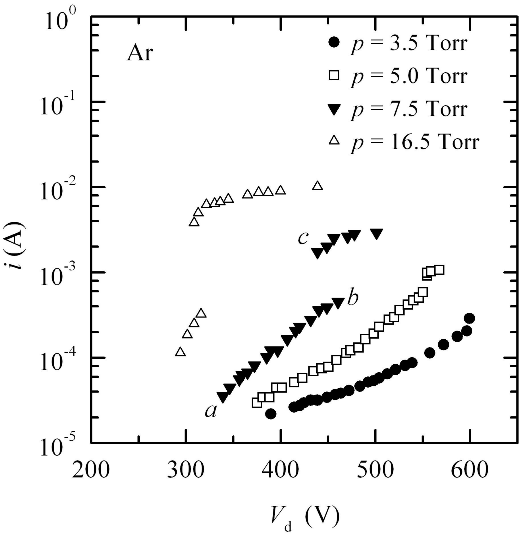

Fig. 2. Current-voltage characteristics for discharge in argon with the electrode system shown in Fig. 1, a. D=0.7 mm, d=0.25 mm, h=2.1 mm

The discharge current i, the discharge burning voltage V_d, and the calculated similarity parameter j/p^2 are presented in Table 1.

Table 1

i, mA	0.1	0.2	0.4
V_d, V	500	550	600
j/p^2, μA/cm^2×Torr^2	180	360	520

Addressing to the data on the normal glow discharge in argon for the parallel plane geometry [5] we can readily see that $V_{cn}\approx150$ V, $j_n/p^2\approx150$ μA/cm^2·Torr^2, $pl_{cn}\approx0.3$ Torr·cm, and $E_c/p\approx0.8$ kV/cm·Torr. Hence, for the case under discussion the reduced current density at the cathode surface is comparable or exceeds the current density in the classical normal glow discharge. Such a high current density definitely indicates that the section ab of the characteristic corresponds to the conditions when the electric field in the cathode cavity is distorted by the space charge of the positive ions.

The important issue for the further consideration is whether the length of the cathode voltage drop region is comparable with the diameter of the cathode cavity or essentially less than the diameter. An estimate for lc value can be made on the basis of data for the glow discharge in parallel plane geometry. For the discharge burning voltage $V_d\approx V_c$=600 V, we can estimated the parameter $pl_c\approx0.09$ Torr×cm, so that with p=3.5 Torr the length of the cathode voltage drop region has to be 0.26 mm or larger. It means that the length of the cathode voltage drop region is comparable with $D/2$. In these conditions, there is no distinctively expressed negative glow plasma in the cathode cavity. Examination of the end-on photographs of the discharge shows [1] that the area of a bright luminosity at the discharge axis has a small diameter of about 0.15 mm (remind that D=0.7 mm). Thus, the discussed regime of the discharge burning can be characterized as a suppressed hollow cathode discharge.

At increased gas pressures (p=7.5 Torr and 16.5 Torr, Fig. 2) the abrupt transition from the point b to the point c at the current-voltage characteristics occurs. Optical observation of the discharge image demonstrates that this transition is accompanied by a sharp increase in the diameter of the negative glow (up to 0.54 mm). In other words the length of the cathode voltage drop region sharply decreases to a value l_c=0.08 mm, i.e. l_c becomes essentially less than the diameter of the cathode cavity. We can say that starting from the point c the glow-type discharge with hollow cathode burns in non-suppressed regime.

Transition to the glow discharge with hollow cathode occurs at the point b (V_c=460 V, and $j/p^2 \approx 270\ \mu\text{A/cm}^2\cdot\text{Torr}^2$). From data on glow discharge [5] with a voltage V_c=460 V we obtain $pl_c \approx 0.1$ Torr·cm, so that the length l_c=0.13 mm. Thus, the transition is accompanied by formation of the column of the negative glow plasma whose diameter is comparable with the diameter of the cathode cavity.

5. Breakdown over the dielectric surface and glow-to-spark transition phenomenon

The same regularities, related to the suppressed and abnormal regime of the discharge burning, are characteristic of the electrode system shown in Fig. 1, b. Typical current-voltage characteristic is presented in Fig. 3 [2], where the part ab corresponds to suppressed discharge. Beside that, Fig. 3 is rather illustrative to discuss the other non-steady state phenomena, namely, breakdown over the dielectric surface and glow-to-spark transition process.

When the glow type discharge is ignited in the electrode systems shown in Fig. 1, it is implied that the discharge develops over a long pass but not over the dielectric surface. In order that the breakdown occurs across the balk gas, the product pd has to fall in the left branch of Paschen curve. Only in this case the breakdown voltage over the surface can be less that that over a long pass across the gas.

The products $(pd)_m$ corresponding to minimum of the Paschen curve are presented in Table 2.

Table 2

Gas	He	Ne	Ar	Xe	N2
$(pd)_m$, Torr×cm	4.5	4.0	2.5	0.8	0.6

It can readily be seen that for a typical size of $d \approx 0.2$ mm starting from a pressure p=300 Torr the conditions of breakdown definitely correspond to right branch of Paschen curve. In this connection a special attention should be paid to the electrode systems with a smaller thickness of the insulator. However unlimited decreasing the thickness d is also impossible as far as the breakdown strength of the dielectric materials is limited.

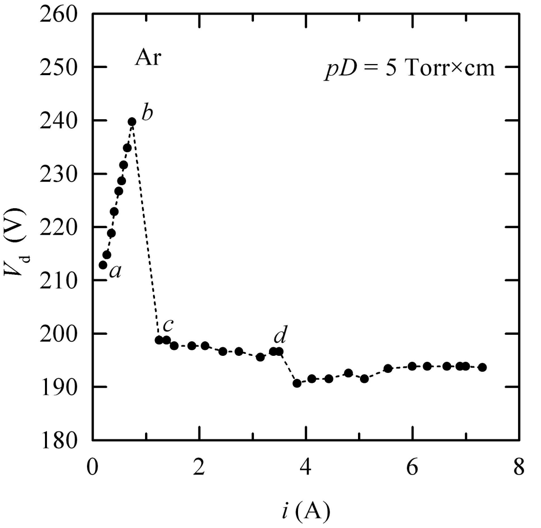

Fig. 3. Current-voltage characteristics for discharge in argon with the electrode system shown in Fig. 1, b. D=0.2 mm, d=0.25 mm, h=2.1 mm, p=250 Torr

Now let consider a typical version of the discharge development with time when the pressure is rather high (pd falls to the right branch of Paschen curve). In so doing we have to take into account that for the microdischarge devices the spurious interelectrode capacitance C can be large enough even for a single microgap. For example in [2] this capacitance is estimated as C=50 pF. With a ballast resistor R of about 100 kΩ we obtain the characteristic charging time for the capacitance RC=5 μs.

When we increase the voltage of the power supply, the spurious capacitance C is charged to the static breakdown voltage and the very first breakdown occurs over the dielectric surface. This breakdown is accompanied by a fast discharging of the capacitance C, which results in a pulsed current of a short duration (from 10 to 100 ns). A current value is much higher than V_0/R.

The important feature of the external electric circuit lays in the fact that the current from the power supply is limited by the ballast resistor of a high value. With this condition after the breakdown the discharge is not capable of burning in the arc form since a current of the order of ten milliamperes is certainly not enough to maintain the steady state arc discharge.

After the very first breakdown the process of charging the capacitor C from the external power supply is repeated. When the charging process goes on microsecond time scale the dielectric strength of the gap is not recovered completely. In other words, the residual plasma from the preceding pulse influences to the process of the discharge ignition when the capacitance is charged repeatedly. It will lead to the situation that the next breakdown occurs at a lower voltage than the very first breakdown. The capacitance is abruptly discharged again and the process is repeated.

Thus, at the first stage of the discharge development we will have a series of succeeding current pulses and the system itself operates in a regime of *RC* generator. At this stage the gas is gradually heating and the atomic particle density in the gap is gradually decreasing. From the viewpoint of the breakdown process, the product p^*d is shifted to the left and finally the conditions begin to correspond to the left branch of Paschen curve. After that the steady state glow discharge burns in the gap.

The described scenario is an ideal case in some extent. For example, if we carefully examine the discharge luminosity for the conditions of [5] we reveal that the actual glow-type discharge is observed only for a pressure p=200 Torr. For the increased pressures (400 and 600 Torr) the end-on photographs of the discharge image demonstrate that the partial pulsed discharges over the dielectric surface exist simultaneously with the background glow discharge.

In general, the above-discussed surface breakdowns can be treated as a variety of the glow-to-spark transition process. This process develops at a background of the residual discharge plasma from a preceding pulse. Since the current in the external circuit is not sufficient to maintain the steady state arc, the glow-to-spark transition manifests itself as the partial discharges of about 10 to 100 ns duration. The physical reason for igniting the micro-spark discharge in this particular case is the initiation of the cathode spot in the triple point (between the cathode and the insulating film).

Beside that the glow-to-spark transition can occur when the reduced pressure p^* becomes low and a kind of "steady state" glow discharge appears in the gap. It is reasonable to discuss the mechanism of the glow-to-spark transition for this particular case. With increasing the current density the reduced electric field at the cathode surface E_c/p increases as well. At a certain critical value of the electric field E_c instability in the cathode voltage drop region develops [5, 6]. The essence of this instability is an irreversible growth in the field emission current from the separate micropoints of the cathode surface, which leads to an explosion of the micropoint and ignition of the cathode spot. Depending on the conditions at the cathode surface, the critical value of electric field can be from 10^5 to 10^6 V/cm [6].

Such a type of the glow-to-spark transition had been observed in [2]. For interpretation of the cathode spot ignition process, it is convenient to appeal to Fig. 3. The discharge images obtained in [2] allow us estimating the length of the dark region near the cathode i.e. the length of the cathode voltage drop region l_c and the electric field E_c.

For the suppressed discharge (part *ab* of the characteristic) a typical value of l_c is 0.07 mm. Then with V_c=240 V we obtain E_c=68 kV/cm. This value is still insufficient for initiation of the explosive emission instability. When the discharge abruptly transforms into the abnormal mode of operation the length l_c sharply decreases to a typical value of 0.03 mm that is the electric field at the cathode surface increases to E_c=130 kV. Just in the regime of the abnormal discharge with hollow cathode the glow-to-spark transition phenomenon is observed in the experiments [2]. Starting from the point *d* of the current-voltage characteristics the regular current spikes at a background of an average current are recorded in the experiment.

The value E_c of about 100 kV/cm is the critical electric field for the glow-to-spark transition in most experiments with the microdischarges. This comparatively low electric field is associated with the reason that a triple point is available at the cathode surface.

The regime of the abnormal glow discharge, when the glow-to-spark transition occurs, does not seem reasonable for applications in the sources of radiation especially if we deal with the array of microcavities when the spurious capacitance of the system is large. The general recommendations to avoid the microsparks can be reduced to the following: we have to decrease the thickness *d* and the diameter of the cathode cavity in order that to keep the discharge in suppressed regime of burning.

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