High-Current Low-Pressure Pulsed Glow Discharge with a Hollow Cathode[1]

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Abstract – Different regimes of burning for a low-pressure high-current discharge with hollow cathode are considered. A model for the current sustaining mechanism in the glow stages of the discharge is proposed. The problem of limited current density at the cathode surface is discussed.

1. Introduction

A low-pressure gas discharge with hollow cathode and hollow anode is widely used in a variety of applications: in plasma surface processing, for production of electron and ion beams, for switching the pulsed current, and the like. In typical applications a total discharge current in a steady state mode is about several amperes and less. However, in a pulse regime (with short pulse duration) the discharge is able to operate at extremely high current. For example, in so-called pseudospark switches the current in the glow modes can achieve a level of several kiloamperes and even more [1].

A model for the current sustaining mechanism in the cathode cavity of the glow type discharges is described in this paper.

2. Qualitative Description of the Model and Condition for Establishing a Self-Sustained Current

The spatial structure of the discharge regions and the corresponding potential distributions are shown schematically in Fig. 1. The hollow cathode *C* has a form of cylinder whose diameter is *D* and height is *h*. To simplify the problem the plate anode *A* is placed near the exit aperture of the hollow cathode. In this case we can consider that the hollow anode plasma is absent and the electron current flows to the anode directly from the hollow cathode plasma.

The total discharge current to the inner surface of the hollow cathode i_c is a sum of an emission current i_{em} and an ion current i_i:

$$i_c = i_{em} + i_i = (1 + \gamma)i_i, \qquad (1)$$

where γ is the secondary emission coefficient.

The electrons emitted from the cathode are accelerated in the cathode voltage drop region and their energy is spent for generation of the hollow cathode plasma. A steady state plasma density in the hollow cathode is sustained due to a balance between the rate of ionization and the processes of the losses of the charged particles.

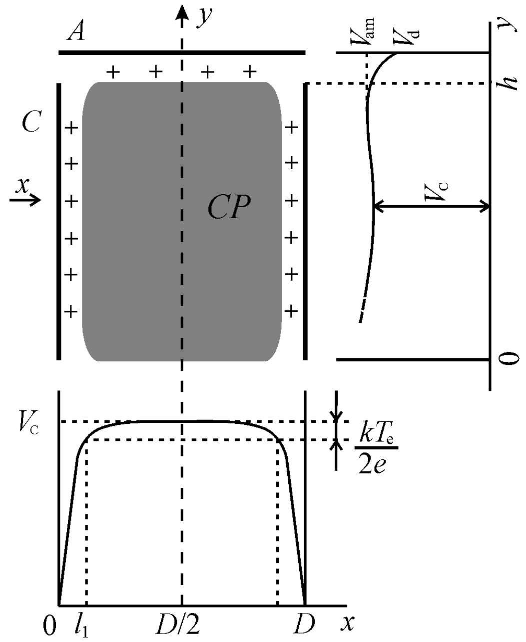

Fig. 1. Discharge regions and potential distribution for dense glow discharge with hollow cathode

Below we do not take into account the recombination process. Then the ions disappear from the hollow cathode plasma due to their outflow to the cathode. The originated ions move in collisionless regime under a potential difference $kT_e/2e$, which is applied to so-called pre-sheath area. Since the recombination losses are negligibly small and $l_1 << D/2$, the length of the pre-sheath layer approximately corresponds to $D/2$.

The discharge current to the anode is provided by the fast electrons from plasma that are able to overcome the potential barrier $e\Delta V = e(V_{am} - V_d)$:

$$i_a = i_c = S_p \frac{1}{4} e n_e v_e \exp\left(-\frac{e\Delta V}{kT_e}\right), \qquad (2)$$

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where S_p is the area of the plasma column, $v_e = (8kT_e/\pi m)^{1/2}$ is the average velocity of the electrons in plasma.

Let derive the condition for establishing the self-sustained current proceeding from the power balance in the hollow cathode plasma [2]:

$$i_{em}V_c = i_i\left(V^* + \frac{kT_e}{2e}\right) + i_c\left(\frac{3kT_e}{2e} + \Delta V\right) + i_{em}V_c\frac{S_D}{S_c}, \quad (3)$$

where V^* is the energy which the electron beam spends for one act of ionization, S_D is the area of the cathode aperture, and S_c is the area of the hollow cathode.

The right side in the last equation incorporates the following terms: the power losses from the plasma due to the ion current to the cathode; the power that is taken away by the electrons due to electron flow to the anode; and the losses due the fast electrons, which go away from the cathode cavity through the aperture S_D.

Proceeding from (1) and (3) we obtain:

$$\gamma\frac{V_c}{V_1}\left(1 - \frac{S_D}{S_c}\right) = 1, \quad (4)$$

where $V_1 = V^* + (2kT_e/e) + (3\gamma kT_e/2e) + (1 + \gamma)\Delta V$.

The physical meaning of V_1 is the cost of ionization under the effect of electron beam. The energy of electron beam is expended both for production of the ions and for maintaining the electron temperature in the cathode plasma. The value V^* is larger than the ionization potential of the gas atom, as far as beside the ionization the electron beam expends its energy also for excitation and elastic collisions.

3. Discharge Current

Any type of steady state glow discharge represents a self-arranged system. In this system the total discharge current is requested by the external electric circuit. The inner characteristics of the discharge (the cathode voltage drop, the electron temperature and density, the negative potential barrier near the anode, and the like) has to be arranged self-consistently in accordance with (4) in order that just the prescribed current flows from the cathode to the anode. In such system it is convenient to use the discharge current as an independent external parameter and to estimate the other characteristics proceeding from the current value.

The ionization rate ψ in the cathode cavity is determined by the power, introduced in the cavity due to dissipation of energy of electron beam:

$$\psi = \frac{4}{\pi}\frac{\gamma}{1+\gamma}\frac{V_c}{V_1}\frac{i_c}{e}\frac{1}{D^2 h}\left(1 - \frac{S_D}{S_c}\right). \quad (5)$$

The steady state plasma density in the cavity ($n_e \approx n_i$) can be estimated from the balance between the ionization rate and the rate of losses of the charged particles:

$$\frac{dn_i}{dt} = \psi - \frac{n_i}{T_i} = 0, \quad (6)$$

where T_i is the average time of ion outflow from the cathode cavity.

Since the ions move in the collisionless regime and the velocity of ion at the entrance in the cathode voltage drop region is $v_i = (kT_e/M)^{1/2}$, then the average time of ion outflow T_i is reasonable to introduce as

$$T_i = \frac{D/2}{v_i} = \frac{D}{2}\left(\frac{M}{kT_e}\right)^{1/2}, \quad (7)$$

where M is the mass of ion.

The total current to the inner surface of the cathode cavity can be written with a use of n_i (6) and an average velocity of the ions at the entrance in the cathode voltage drop region. Assuming that the average velocity of ions is equal to $v_i/2$ we obtain:

$$i_c = (1+\gamma)\pi D h e n_i \frac{v_i}{2} = (1+\gamma)\frac{\pi D^2 h}{4} e\psi. \quad (8)$$

The last equation is convenient for estimation of the plasma density that has to establish in the cathode cavity when a total discharge current is i_c. Beside that Eq. (8) demonstrates that the cathode cavity represents a kind of ionization chamber. The current in the chamber is determined by the total charge, which is generated under effect of electron beam in the volume $\pi D^2 h/4$ per unit of time. The ion component of the current flows to the cathode and the same electron current outflows to the anode.

In order that the cathode plasma *CP* be able to pass the current i_c in the anode direction, the chaotic current density in the plasma has to exceed a current density $j_c = 4i_c/\pi D^2$. Then the plasma density in the cathode cavity has to obey the following condition:

$$n_e >> 4j_c/ev_e. \quad (9)$$

Taking into account that $v_e = (8kT_e/\pi m)^{1/2}$ and $v_i = (kT_e/M)^{1/2}$, after simple manipulations with (8) and (9) we obtain the criterion that the electron component is able to carry the total discharge current to the anode:

$$\frac{1}{1+\gamma}\left(\frac{1}{8\pi}\frac{M}{m}\right)^{1/2}\frac{D}{h} >> 1. \quad (10)$$

It is seen that when the height and the diameter of the cathode cavity are comparable with each other the last criterion is definitely fulfilled.

The above-described consideration is related to the case when the losses of the charged particles due to recombination process are negligibly small. There is no difficulty to expand the model for the conditions when the recombination process has to be taken into account.

The distance between l_1 and $D/2$ can be conditionally subdivided for two layers: $(l_2 - l_1) \approx l_2$ and

$(D_2 - l_2)$. The ions from the central part of the cathode cavity $(D_2 - l_2)$ do not take part in the carrying of the current to the cathode since they are mainly lost in the process of two-body recombination. Only the ions that appear in the layer l_2 are able to come to the cathode. Then it is reasonable to find the size of layer l_2 from the assumption that a characteristic time of ion outflow from the layer l_2 is comparable with a characteristic recombination time:

$$\frac{l_2}{v_i} \approx \frac{1}{(\psi\beta)^{1/2}} = \frac{1}{\beta n_e}, \tag{11}$$

where β is the coefficient of two body recombination.

Then (6) continues to hold true. However the characteristic time of ion outflow in this equation has to be determined as

$$T_i = \frac{l_2}{v_i} = l_2 \left(\frac{M}{kT_e}\right)^{1/2}. \tag{12}$$

With taking into account (11) the plasma density in the cathode cavity can be expressed both in terms of the balance between the ionization and recombination and in terms of the balance between ionization and outflow of ions:

$$n_i = n_e = \psi \frac{l_2}{v_i} = \left(\frac{\psi}{\beta}\right)^{1/2}. \tag{13}$$

The equations for the discharge current takes the form

$$i_c = (1+\gamma)\frac{\pi D h}{2} e n_i v_i = (1+\gamma)\frac{\pi D l_2 h}{2} e\psi. \tag{14}$$

4. Limited Current in a Regime of Classical Glow Discharge

As far as the condition for the current sustaining in the cathode cavity (4) does not include in itself the discharge current it could be concluded that the glow discharge with hollow cathode is able to operate with any current value. However, there is a physical reason that set a limit on the discharge current density. At a high current density the electric field at the cathode surface E_c reaches some critical value so that the field emission current from the separate micropoints of the cathode surface becomes noticeable.

In such conditions a specific instability in the near cathode layer develops. An enhanced emission current from a micropoint results in an enhanced ion current to this point. Then, at a high local electron and ion current density, a microexplosion of the local area of the cathode surface occurs and a metal vapor appears on the vicinity of the micropoint. As a matter of fact, the microexplosion of the cathode is the primary stage of initiation of the cathode spot, i.e. the primary stage of the glow-to-arc transition process. Numerous experiments show that the critical electric field for microexplosion is $E_c \approx 10^6$ V/cm [1].

As applied to our consideration the electric field at the cathode surface can be estimated on the basis of assumption that the ion current across the layer l_1 obeys the Child-Langmuir low:

$$j_i = \frac{4\sqrt{2}}{9}\varepsilon_0 \left(\frac{e}{M}\right)^{1/2} \frac{V_c^{3/2}}{l_1^2}, \tag{15}$$

where ε_0 is the dielectric constant.

Then with a linear approximation of behavior of electric field $E(x)$ we obtain the expression, which together with (15), offers a possibility to estimate the electric field E_c:

$$E_c \approx 2V_c/l_1. \tag{16}$$

5. Discussion of the Model as Applied to the Hollow Cathode Discharges

The above-described model allows estimating for a variety of regimes of the glow discharge with hollow cathode. One of the typical regularities for such type of discharge is that the discharge burning voltage weakly depends on the current. In terms of the model it means that the cathode voltage drop value is not changed with variation of the current in a wide range. This conclusion follows directly from the condition for establishing a self-sustained current (4).

The steady state plasma density in the hollow cathode for a prescribed current value depends on the mass of ion. According to (8) for heavy gases the plasma density has to be increased as compared to light gases, since the velocity of ion v_i in heavy gases is larger than that for light gases.

The glow-to-arc transition is initiated by the microexplosion of the cathode surface when the electric field E_c achieves a critical value. Equations (15) and (16) demonstrate that the critical electric field in heavy gases is achieved with a lower level of current as compared to light gases.

Although the model is formally intended for description of the steady state discharge it is rather illustrative for interpretation of the phenomena in pulsed regime of operation (at least at a qualitative level). One of the types of high-current hollow-cathode discharge, which is intensively investigated during the last time, is the discharge in so-called pseudospark switches [1]. The electrode system of the switch consists of two cavities that communicated through the axial bore holes. In a regime of high current the area inside the bore hole can play a role of hollow cathode.

In its temporal development (during increasing the current in external circuit) the discharge transits via different stages. After the stage of delay time to breakdown, a quasi-state phase of a high-current dense glow discharge is established in the gap. This stage can be described by the above-presented model.

The cathode plasma is mainly sustained by ionization of the gas molecules.

At a certain value of the ion current density at the inner surface of the bore hole the conditions for microexplosion are fulfilled. The discharge abruptly transforms in so-called superdense glow stage. The characteristic discharge regions and the corresponding potential distributions for the superdense glow discharge are shown schematically in Fig. 2.

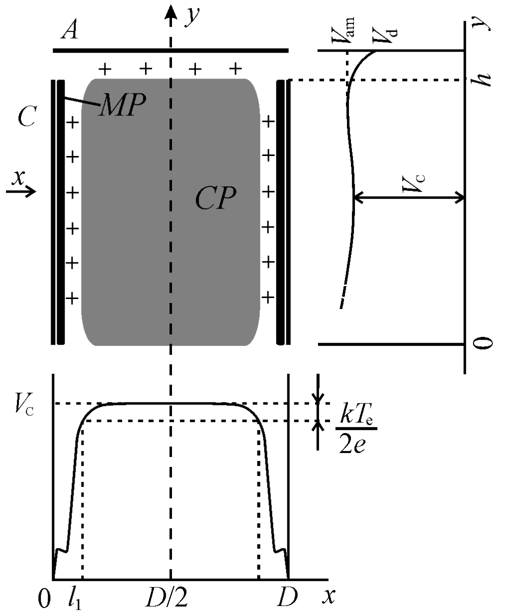

Fig. 2. Discharge regions and potential distribution for the stage of superdense glow discharge with hollow cathode

The reason for transition from the dense glow discharge to the superdense glow discharge is the numerous microexplosions that arise simultaneously at the inner surface of the borehole. The metal vapor is ionized in immediate vicinity of the surface of the borehole so that the metal vapor plasma *MP* is generated near the surface. In the stage of the superdense glow the borehole area mainly starts playing the role of the hollow cathode.

As distinct to the classical glow discharge with a solid metal cathode, in this case we have the situation when the metal vapor plasma *MP* serves as a kind of a plasma cathode. There is a double electric layer with an excess space charge of the positive ions l_C between the metal plasma *MP* and the hollow-cathode plasma *CP*. Conceptually this layer represents the cathode voltage drop region for the superdense glow discharge with hollow-cathode.

As we have already noted, the act of microexplosion is actually the primary stage for initiation of the cathode spot. However, the glow-to-arc transition process does not occur immediately in time. As far as a lot of microexplosions arise at the surface simultaneously, there is no preferable attachment of the current to a single microexplosion at this stage so that the process of initiation of a distinctively expressed cathode spot is suppressed. This stage of the discharge burning is still can be interpreted as a variety of the glow discharge. The discharge burning voltage in the superdense glow stage is lower than that for the dense glow discharge.

At last, the process of the glow-to-arc transition is completed and the discharge transforms into an arc mode with the distinctively expressed constricted cathode spots. At this stage the discharge burning voltage decreases to 100 V and less.

The process of the transition from the dense to superdense glow discharge can be readily treated in the terms of the presented model. The abrupt generation of the metal plasma *MP* means that the secondary emission coefficient γ abruptly becomes extremely high (even more that unity). In such conditions, in accordance with (8), the current can be sharply increased and the cathode voltage drop V_c, in accordance with (4) has to be decreased.

It is also important that the case when the electrons are emitted from plasma boundary differs essentially from that for the metal surface. The emission current from the metal plasma is controlled by the negative potential barrier, which exists at the outer boundary of plasma. Depending on the external conditions of the discharge burning, the emissivity of the plasma cathode can be readily adjusted due to variation in height of the negative potential barrier. In the other words the value of γ can be readily adjusted to provide the self-consistent arranging of the discharge in accordance with the total current which is requested by external electric circuit.

The experiments show that the transition from the dense to superdense glow discharge in hydrogen occurs at a higher current level as compared to the discharge in xenon. This fact is easily illustrated on the basis of the model. In the Tables below the calculated parameters of the discharges in hydrogen and xenon are presented. The current i_c to the inner surface of the borehole is taken here as the external parameter. The size of the borehole is $D = 4$ mm, $h = 4$ mm, and the gas pressure $p = 0.6$ Torr [1].

i_c, A (H_2)	100	150	200	250	300
n_e, 10^{15} cm^{-3}	1.14	1.71	2.28	2.85	3.42
E_c, 10^6 V/cm	0.62	0.76	0.87	0.98	1.07

i_c, A (Xe)	10	20	30	40	50
n_e, 10^{15} cm^{-3}	0.96	1.81	2.72	3.62	4.53
E_c, 10^6 V/cm	0.55	0.79	0.96	1.11	1.24

It is seen that the critical electric field at the cathode surface $E_c \approx 10^6$ V/cm for the discharge in hydrogen is achieved at a current of about 250 A, while the same field for xenon corresponds to a current only 30 A.

References

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