HOLLOW CATHODE DISCHARGE IN LOW PRESSURE OXYGEN: TRANSIENT MODE

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Glow characteristics of the discharge with cylindrical hollow cathode at oxygen pressure in a range of 0.015…0.09 Torr are determined. Dependencies of radial electric field in the plasma on the discharge parameters are defined, and particular fact of creation at pressure higher than ~ 0.06 Torr the potential barrier at the boundary between negative glow plasma and cathode layer, which limits ion escaping to the cathode. As well, limits of the discharge glow characteristics are determined, which result in appearance of the hollow cathode effect.

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INTRODUCTION

Hollow cathode discharge phenomenon was described in scientific literature yet in 1916 by Paschen at the studies of helium emission spectra – substitution of flat cathode by hollow cylinder shaped one resulted in essential growth of the discharge current under the same discharge voltage [1]. In subsequent decades hollow cathode discharge (HCD) was widely used in atomic absorption and emission spectroscopy [2] due to its ability to generate intense ligh emission in wavelength range fom vacuum ultraviolet till near infrared. Later, along with other discharge types, HCD found its usage in plasma-technological applications [3], particularly, for low temperature deposition of hydrogenated amorphous silicon material, a-Si:H [4], for modification of the surface of Ti implants by the production of rough surfaces that consist of a mixture of Ti-oxides [5] and so on.

It should be noted at once that in the literature (e.g. see [6]) all hollow cathode discharge appearances are conditionally subdivided into three types: glow, high voltage, and arc ones. Everyone oh those discharge possesses its own peculiarities. In the following, only glow discharge type will be considered.

The most common criterion of hollow cathode discharge is a requirement that transverse dimension of the cathode cavity should be comparable with those of the discharge cathode regions, such as cathode layer and glow plasma ([6], p. 6). When cathode transverse dimension is considerably less than those of the discharge cathode regions, fast electrons accelerated in the cathode layer can undergo essential number of oscillations in the negative glow plasma before spending practically total their energy for gas ionization and excitation, and their coming to the discharge anode due scattering at the gas atoms/molecules. With the use of cylindrical cathode shape, plasma density at the cathode axis also increases due to “ballistic” focusing of fast electrons.

The literature devoted to study of hollow cathode discharges is rather extensive (e.g. see [6 - 12] and references therein). However, practically all researches were accomplished with the use of noble gases as working media. Usage of molecular gases, particularly, electronegative ones, was a rare event [13, 14], although it is known that negative ions essentially influence the plasma features. Besides, the researches were usually performed at high enough pressure values (a couple of Torr and above) using hollow cathodes of small radius (several millimeters). These circumstances limited possibilities of correct determining plasma parameters in such discharge. Particularly, it regards determining the cathode layer thickness (that is, the discharge region with high electric field strength). Usually, it was assumed that the cathode layer boundary coincides with one between the dark space and the negative glow. It is not totally correct, since the negative glow consists of two parts: one of those fills a portion of the cathode layer, whereas another one belongs to the plasma (plasma part of the negative glow) [15, 16].

As it was already noted above, the hollow cathode effect occurs when the hollow cathode transverse dimension is less than the discharge glow length. In the opposite case, the discharge behavior is practically identical to usual short (that is, without positive column) discharge with flat cathode.

Purpose of the present work is the study of peculiarities of hollow cathode discharge with large dimensions (tens centimeters) at oxygen pressure lower than 0.1 Torr, particularly, those regarding the discharge transition from flat cathode operation mode to that with realization of the hollow cathode effect.

1. EXPERIMENT SET-UP AND MEASUREMENTS

The discharge hollow cathode was elaborated from stainless steel and had the following dimensions: 38 cm diameter and 42 cm length (the cathode simultaneously served as vacuum chamber). The discharge made of copper having 30.5 cm diameter was located near back side of the cathode/chamber. From another side, the cathode cavity was closed by a door with transparent window having 280 mm diameter. An advantage of copper anode was the fact that the resistance value of oxide layer formed at the anode surface during its operation in oxygen had practically no effect on the plasma parameters. Use of the anode with large dimension (comparable with the cathode diameter) enabled obtaining high longitudinal uniformity of the plasma. With such anode, longitudinal uniformity of the plasma density inside the cathode (excluding the regions of about 3…4 cm thickness near the anode and the door) was not worse than ±20%.

The discharge power supply was provided by DC source with controlled voltage and current values in ranges of 400…800 V and 100…600 mA, respectively. The cathode/chamber was grounded, and positive potential was applied to the anode. Power W_d introduced in the discharge could be varied in range of 50…350 W which corresponded to specific power in the discharge $W_s \approx 1…7$ mW/cm^3.

Cathode was evacuated down to pressure of about ~ 10^{-5} Torr, and after that working gas was supplied to the chamber until reaching of predetermined pressure value. Working gas pressure P of oxygen in the cathode was varied in range of $10^{-2}…2\cdot10^{-1}$ Torr.

The electric field in the plasma was measured using double Langmuir probes, which could be moved along and across the cathode. The probes were made of two parallel 0.75 mm diameter wires having 10 mm length located at 10 mm distance from each other. To avoid the effect of contamination of the probes surface on the electric field value, the probes after each measurement were cleaned by means of ion current from the plasma (for that purpose, the probes were grounded for 5…10 s).

2. EXPERIMENTAL RESULTS AND DISCUSSION

For correct determining the cathode layer thickness, measurements of radial distributions of electric field strength E_R in the plasma were performed at the discharge power values W_d of 100 and 250 W, and oxygen pressure values P = 0.015, 0.3, 0.6 and 0.9 Torr. Fig. 1 presents the results of E_R measurements, as well as calculated on a basis of these values radial potential fall U_R in the plasma at W_d = 100 W and four values of O_2 pressure. The values of potential U_R were normalized so that they should coincide at the system axis. One can see from Fig.1,a that at all P values the dependence of E_R on R possesses non-monotonous behavior – at first, it grows until a maximum with radius increase, after that it decreases, and after reaching a minimum it grows up again (the last E_R growth corresponds to the region of cathode fall of the potential). Oxygen pressure increase results not only in decrease of electric field value E_R in the plasma, but as well in a shift of E_R minimum position towards the cathode surface. At that, with the pressure variation from 0.03 to 0.06 Torr, position of the minimum changes in a jump-like manner from ~ 12 to ~ 16 cm. Besides, at oxygen pressure values of 0.06 and 0.09 Torr the field E_R in a region of the minimum exhibits double change of its sign – at first, it becomes negative, and in subsequent it changes to positive again. It is an evidence of formation of potential barrier in this region, which prevents coming of the ions, originated in the negative glow plasma, to the cathode.

The discharge power increase up to 250 W could lead just to increase of E_R and U absolute values, without principal change of the overall behavior.

A point of crossing the tangents to U vs R profile was taken as the cathode layer boundary. It was assumed that electric field in the cathode layer possesed linear dependence on R:

$$E_R(R) = \begin{cases} -E_O(1-R/d), R<d \\ 0, R>d \end{cases}$$

that is E ≈ U_d/d, where U_d is the discharge voltage, d is the cathode layer thickness (influence of potential fall at the discharge plasma and anode potential fall could be neglected in our case due to their small values).

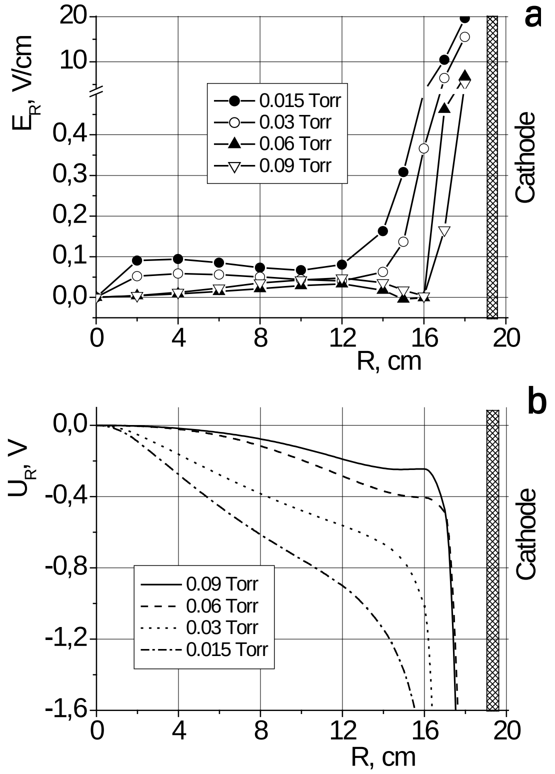

Fig. 1. Radial dependencies of radial component E_R of electric field in the plasma (a) and potential U (b) at different oxygen pressure values. W_d = 100 W

Dependence of the discharge voltage U_d on reduced discharge current density J_d/P^2 (reduced CVC of the discharge) is presented in Fig. 2.

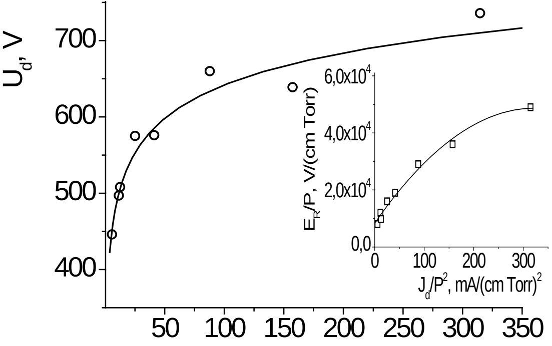

Fig. 2. Reduced CVC of the discharge at oxygen pressure variation in a range of 0.015…0.09 Torr, and W_d values of 100 and 250 W. An insert shows reduced electric field E_R/P dependence on J_d/P^2 obtained under the same conditions

One can see from the figure that at J_d/P^2 ~ 30…40 mA/(cm·Torr)^2 this dependence exhibits a bend – rapid U_d growth is substituted by its slower increase. (It should be noted that J_d/P^2 grows up with the pressure decrease, so that the left part of the curve (before the bend) corresponds to oxygen pressure values ~ 0.09…0.06 Torr). Thus, the pressure decrease below 0.06 Torr results in a change of the discharge glow mode.

Dependence of reduced cathode layer thickness Pd on J_d/P^2 (Fig. 3) possesses the same peculiarity – abrupt decrease of Pd at J_d/P^2 ~ 30…40 mA/(cm·Torr)^2.

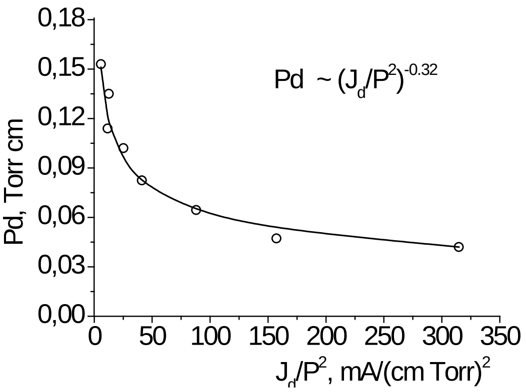

Fig. 3. Dependence of reduced cathode layer thickness Pd on J_d/P^2 in oxygen plasma at pressure variation from 0.015 to 0.09 Torr, and W_d value of 100 and 250 W

For understanding what is going on in the discharge at oxygen pressure decrease below ~ 0.06 Torr, let us consider, how a run path of fast electrons Λ_f, which defines a length of the negative glow plasma [15] filling the cathode cavity, changes with the pressure variation. Authors of [16] for an estimation of Λ_f value have proposed empiric formula

$$\Lambda_f(U_d) \approx U_d / pB, \qquad (1)$$

where B is a constant in empiric Townsend formula for ionization coefficient

$$\alpha / p = A\exp(-Bp/E). \qquad (2)$$

The authors motivate a correctness of such estimation by fact that in electron energy range of interest for us (~ 10…1000 eV) the dependencies of a majority of excitation and ionization cross sections possess very shallow maxima. Λ_f value obtained from (1) is in a good enough agreement with experimentally measured negative glow dimensions for nitrogen (Fig. 2 in [16]). However, table data for B in the case of large electric field values ($>10^3$ V/(cm·Torr)) are absent in the literature, while as one can see from Fig. 2, in our case reduced electric field E_R/P in the cathode layer exceeds V/(cm·Torr). Due to that, constant B value was estimated by us on a basis of experimentally measured dependence of ionization coefficient α/P for oxygen on reduced field E/P [17]. In variation range E/P ~ $10^3…10^4$ V/(cm·Torr) B value was about 260…280 V/(cm·Torr). Estimations of electron run path Λ_f in our oxygen plasma are presented in Fig. 4. Unfortunately, reliable data on differential cross section of elastic scattering of electrons with energy up to ~ 10^3 eV are practically absent, and as a result, in many papers it is assumed that scattering of electrons with energy up to ~ 50 eV occurs only in forward direction. Due to that, in our estimations we also followed from this assumption. One can see from the figure that at oxygen pressure of 0.09 Torr the run path Λ_f is about 15…20 cm, which is close to the cathode radius R. Pressure decrease down to 0.03 Torr leads to Λ_f increase already to ~ 50…60 cm, which corresponds to about 1.5 R.

Let us consider a relation between the behavior of radial distribution of the plasma density N_e at different oxygen pressure values and estimated by us run path Λ_f values. For that that purpose we'll use experimental data obtained in [18] with the same cathode dimensions and discharge parameters – power W_d = 250 W, and oxygen pressure values P = 0.09 and 0.03 Torr.

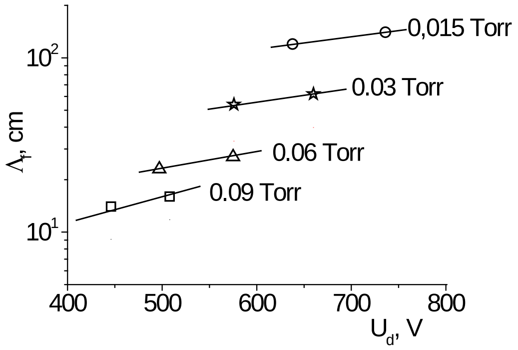

Fig. 4. Dependence of the run path of fast electrons Λ_f on voltage U_d for different oxygen pressure values

Fig. 5 exhibits experimental dependencies of radial distributions of the plasma density N_e obtained in [18] and schematic trajectories of fast electron motion inside the cathode cavity (length of the arrows corresponds to estimated run path Λ_f values).

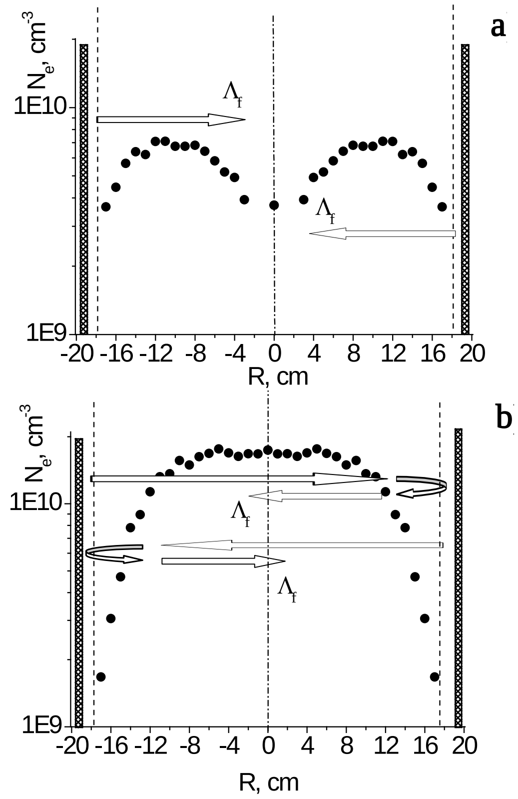

Fig. 5. Radial distributions of oxygen plasma density N_e (-•-) at P = 0.09 Torr (a) and 0.03 Torr (b); W_d = 250 W [18]. Arrows indicate trajectories of fast electron motion inside the cathode cavity

One can see from Fig. 5 that at 0.09 Torr pressure the plasma density distribution has double-humped shape with a minimum at the cathode axis. It is due to fact that fast electrons accelerated in the cathode layer spend their whole energy without reaching the chamber axis. Since in that case an "overlapping" of negative glow plasmas does not occur, our discharge should be considered as a version of the discharge with flat cathode. Completely different behavior is observed at gas pressure decrease down to 0.03 Torr. The run path Λ_f is at that long enough, which enables fast electrons to cross the cathode cavity along its diameter, reflect from the cathode layer and subsequently return to the system axis. That is, an "overlapping" of negative glow plasma occurs, and fast electrons perform ionization not just in "their own plasma" (that is, in plasma where they started their path), but as well in the whole volume of the cathode cavity. It results in both abrupt increase of the plasma density, and establishing its essentially more uniform spatial distribution. In turn, it should lead to change of the discharge characteristics, which can be seen in Figs. 2, 3. This change occurs at P ~ 0.06 Torr (see above), which corresponds to the run path Λ_f ~ 25…30 cm, that is, shorter than the cathode diameter. Thus, one can see that in our case the hollow cathode effect is exhibited at fast electron run path Λ_f being not shorter than ~ 3R of the hollow cathode.

In the present work plasma characteristics of the discharge in low pressure oxygen with cylindrical hollow cathode having 38 cm diameter are determined. It is shown that oxygen pressure increase from 0.015 to 0.09 Torr results in non-monotonous variation of radial profile of radial electric field component in the plasma and creation at pressure higher than $P \approx 0.06$ Torr the potential barrier at a boundary between the negative glow plasma and the cathode layer, which limits ion escaping to the cathode. As well, limits of the discharge glow characteristics are determined, which result in an appearance of the hollow cathode effect.

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РАЗРЯД С ПОЛЫМ КАТОДОМ В КИСЛОРОДЕ НИЗКОГО ДАВЛЕНИЯ: ПЕРЕХОДНОЙ РЕЖИМ

В.Ю. Баженов, С.В. Мацевич, В.М. Пиун, В.В. Циолко

Установлены характеристики горения разряда с цилиндрическим полым катодом при давлениях кислорода 0,015…0,09 Торр. Найдены зависимости радиального электрического поля в плазме от параметров разряда, в частности, установлен факт образования при давлениях больше ~ 0,06 Торр потенциального барьера на границе между плазмой отрицательного свечения и катодным слоем, ограничивающего уход ионов на катод. Также установлены граничные характеристики горения разряда, при которых начинает проявляться эффект полого катода.

РОЗРЯД З ПОРОЖНИСТИМ КАТОДОМ У КИСНІ НИЗЬКОГО ТИСКУ: ПЕРЕХІДНИЙ РЕЖИМ

В. Ю. Баженов, С.В. Мацевич, В.М. Піун, В.В. Ціолко

Встановлено характеристики горіння розряду з циліндричним порожнистим катодом при тисках кисню 0,015…0,09 Торр. Знайдено залежності радіального електричного поля в плазмі від параметрів розряду, зокрема, встановлено факт утворення при тисках більше ~ 0,06 Торр потенціального бар'єру на границі між плазмою негативного світіння та катодним шаром, який обмежує вихід іонів на катод. Також встановлено граничні характеристики горіння розряду, при яких починає проявлятися ефект порожнистого катода.