PLASMA-BEAM DISCHARGE, GAS DISCHARGE AND PLASMACHEMISTRY

POSITIVE ION MOTION IN CATHODE SHEATH OF GLOW DISCHARGE IN N_2O

V.A. Lisovskiy[1,2], E.P. Artushenko[1,2], V.D. Yegorenkov[1]
[1] V.N. Karazin Kharkov National University, Kharkov, Ukraine;
[2] Scientific Center of Physical Technologies, Kharkov, Ukraine
E-mail: lisovskiy@yahoo.com

It is established which of the Child-Langmuir collision law versions is most appropriate for describing the processes in the cathode sheath in the N_2O. At low pressure (up to 0.3 Torr) the Child-Langmuir law version relating to the constant ion mobility holds. At N_2O pressure values starting from 0.75 Torr and above, one have to employ the law version for which it is assumed that the ion mean free path within the cathode sheath is constant. In the intermediate pressure range (between 0.3 and 0.75 Torr) neither of the Child-Langmuir law versions gives a correct description of the cathode sheath of the glow discharge in the N_2O.

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INTRODUCTION

Dc discharge in N_2O is widely applied in gas discharge infrared lasers (where N_2O is used instead of CO_2) [1, 2]. N_2O also serves in radiation dosimetry and in plasma processing. Discharges in N_2O are broadly employed for depositing films of silicon oxides and oxinitrides, hafnium oxides as well as diamond-like films. Recently the interest to N_2O grew because of its role in the greenhouse effect.

Despite a large number of papers devoted to studying elastic and inelastic collisions between electrons and N_2O molecules, the available references lack data on transport properties of positive ions taking place in the cathode sheath of this discharge. Therefore this paper aims at registering current-voltage characteristics (CVCs) and the cathode sheath thickness as well as clarifying the applicability of several versions of the collision Child-Langmuir law for description of the cathode sheath in the N_2O glow discharge.

In laboratory and technological vessels the low-temperature plasma is conventionally in contact with their walls as well as with electrodes, Langmuir probes etc. A transient region is formed in the contact area between the plasma and the surfaces of solid bodies, this region being called the near-electrode (near-probe, near-wall) sheath. In order to describe such a sheath one usually employs the relation connecting the voltage drop across the sheath U, the sheath thickness d_{sh}, as well as the ion current density through the sheath J. This relation is called the Child-Langmuir law. Child [3] and Langmuir [4, 5] made an analytical study of the problem about a flat gap between the cold anode and the heated cathode out of which electrons were emitted. Taking into account the negative space charge effect on electron motion from the cathode to the anode and neglecting the collisions between the electrons and the gas molecules, Child and Langmuir obtained the following relation [3 - 6]:

$$J = K_i \varepsilon_0 \left(\frac{2e}{M} \right)^{1/2} \frac{U^{3/2}}{d_{sh}^{\ 2}}, \qquad (1)$$

where K_i = 200/243=0.82 [6], ε_0 is the dielectric permittivity of vacuum, e is the elementary charge, M is the charged particle (ion) mass. This collisionless Child-Langmuir law is called the “3/2” law, because in (1) the ion current density J is proportional to the voltage drop across the sheath U to the 3/2 power.

In their papers Child and Langmuir considered the electron motion between the cathode and the anode ignoring the effect of the space charge of positive ions on the sheath characteristics. But in paper [7] Langmuir presented the theory of the cathode sheath in the glow discharge taking into account the presence of electrons as well as positive ions and clarified the necessity of accounting for the space charge of just ions. Within the cathode sheath, especially near the cathode surface, a strong electric field is available quickly sweeping the easily mobile electrons out of the sheath, therefore the concentration of positive ions in the sheath exceeds that of electrons. Consequently, the positive space charge is present in the cathode sheath determining the potential distribution inside the sheath and its thickness; it also controls the flux of positive ions having entered the sheath from the negative glow and accelerated by the strong electric field to the cathode.

Conventionally, ions crossing the cathode sheath collide with gas molecules therefore this sheath is not free of collisions. In order to simplify the sheath description one assumes that either the mean free path λ_i or the ion mobility μ_i do not depend on ion velocity. Then the collision-dominated laws (we also call them Child-Langmuir laws) assume the following forms, respectively, [6]:

$$J = 1.68 \varepsilon_0 \left(\frac{2e\lambda_i}{M} \right)^{1/2} \frac{U^{3/2}}{d_{sh}^{\ 5/2}}, \qquad (2)$$

$$J = \frac{9}{8} \varepsilon_0 \mu_i \frac{U^2}{d_{sh}^{\ 3}}. \qquad (3)$$

In the general case formulas (1) - (3) may be cast as follows:

$$J = k \frac{U^m}{d_{sh}^{\ n}}, \qquad (4)$$

where for (1) $m = 1.5$ and $n = 2$, for (2) $m = 1.5$ and $n = 2.5$, for (3) $m = 2$ and $n = 3$. As the current density obeys the relation $J = I/S$, where I is the discharge current, S is the cathode area, expression (4) may be written in the form

$$I = k_1 \frac{U^m}{d_{sh}^{\ n}} \ . \qquad (5)$$

Fig. 1. Discharge photo for the inter-electrode distance of 25 mm, the N_2O pressure value of 0.05 Torr and the current value of 4.6 mA. The line indicates the location of the cathode sheath boundary

In Fig. 1 we depict the photo of the discharge in the N_2O gas where one can see how the cathode sheath thickness was determined. Actually the problem is reduced to registering the discharge current, the voltage across the electrodes and cathode sheath thickness for which there is no necessity in complicated measuring devices and techniques. In all cases we studied the abnormal glow discharge completely covered the cathode surface, because for a correct determination of the ion current density one requires an exact knowledge of the area occupied by the discharge on the cathode. In the case of a normal mode it is difficult to do it. For processing we chose such photos in which only the cathode sheath and the negative glow were present. In this case it may be assumed that the voltage applied across the electrodes drops only on the cathode sheath.

The studies of dc discharge in N_2O were performed for the inter-electrode gap values $L = 5\ldots150$ mm within the pressure range of $p = 0.05\ldots1$ Torr. The inner diameter of the cylindrical discharge glass tube was 56 mm.

EXPERIMENTAL RESULTS

Fig. 2 presents the discharge CVCs and the thickness of the cathode sheath against voltage for several N_2O pressure values within the range of 0.06…0.75 Torr. The inter-electrode distance was 20 mm. The figure demonstrates that on increasing the voltage across the electrodes the discharge current increases fast and the cathode sheath thickness decreases.

We determined the values of the $U^m/d_{sh}^{\ n}$ ratio employing the data in Fig. 2 for each of the pair m and n.

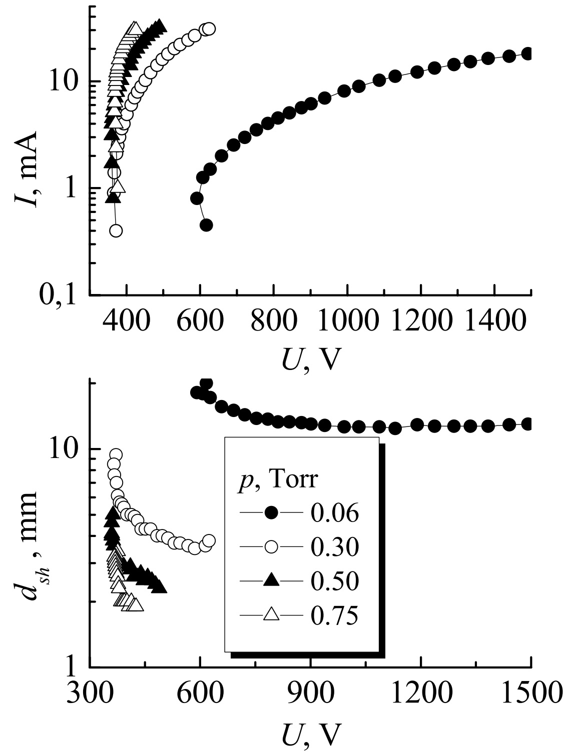

Fig. 2. Discharge current and cathode sheath thickness against voltage for different N_2O pressure values and the inter-electrode distance of 20 mm

Further these $U^m/d_{sh}^{\ n}$ values are to be normalized because they may differ considerably for different m and n and their comparison is impeded. The normalization consists in dividing each $U^m/d_{sh}^{\ n}$ ratio value by its average value. The discharge current I against the normalized $U^m/d_{sh}^{\ n}$ parameters is presented in Fig. 3. When the dependencies $I = f(U^m/d_{sh}^{\ n})$ processed in this manner for any of the pairs m and n fit a straight line starting from the origin of coordinates, then the respective Child-Langmuir law version is considered to hold. It follows from Fig. 3 that for the N_2O pressure values between 0.06 and 0.3 Torr the dependence closest to the straight line is observed for $m = 2$ and $n = 3$. At the pressure of 0.5 Torr none of the $I = f(U^m/d_{sh}^{\ n})$ dependencies for different m and n fit a straight line. And at the N_2O pressure of 0.75 Torr the dependency for $m = 1.5$ and $n = 2.5$ is a linear one.

Measurements at higher pressure are difficult to make for the 20 mm inter-electrode distance because throughout the current range we studied the discharge either is burning only in the normal mode or an anode glow is observed in the vicinity of the anode (with 10…15 V voltage drop across the anode sheath). Therefore one experiment was attempted for the inter-electrode distance value of 5 mm and the N_2O pressure of 1 Torr. At higher gas pressure values the cathode sheath thickness does not exceed 1 mm; therefore it is difficult to register it with good accuracy. Fig. 4 depicts our cathode sheath thickness data and discharge current values against the voltage and the $U^m/d_{sh}^{\ n}$ ratio. This figure demonstrates that the linear pattern is the best fit for the results with $m = 1.5$ and $n = 2.5$.

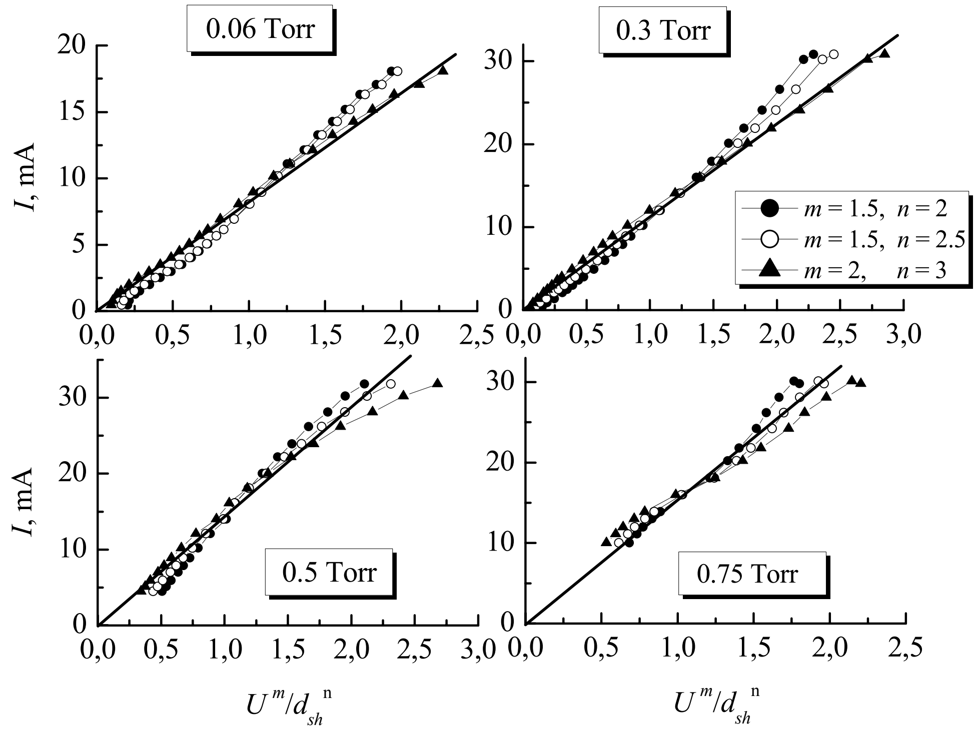

Fig. 3. Discharge current against U^m/d_{sh}^n ratio (m = 1.5, n = 2; m = 1.5, n = 2,5; m = 2, n = 3) for different N_2O pressure values. Inter-electrode difference is 20 mm

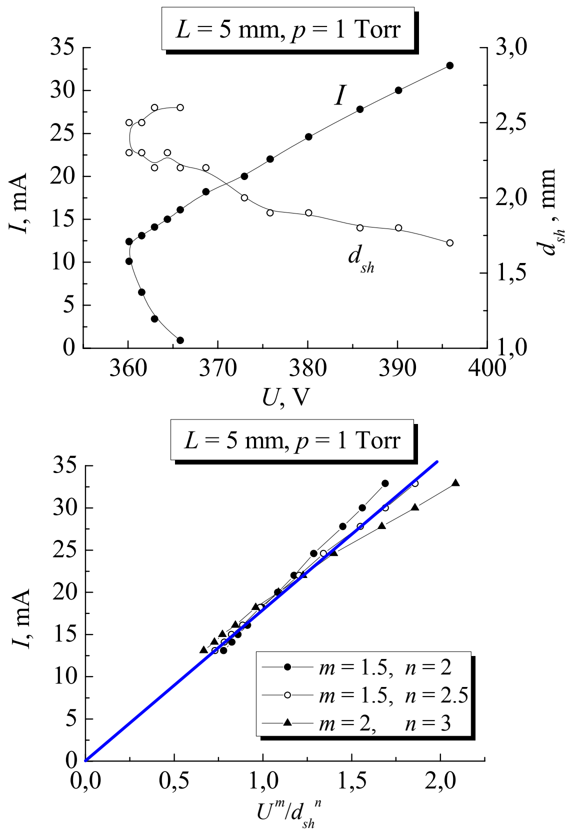

Fig. 4. Discharge current and cathode sheath thickness against voltage for the N_2O pressure of 1 Torr and the inter-electrode distance of 5 mm, as well as discharge current against the U^m/d_{sh}^n ratio values (m = 1.5, n = 2; m = 1.5, n = 2,5; m = 2, n = 3)

Analyzing the data in Figs. 3 and 4 may furnish the following conclusion. At low pressure (up to 0.3 Torr) the collision-dominant Child-Langmuir law version (3) for constant ion mobility is applicable for describing processes in the cathode sheath. At N_2O pressure values starting from 0.75 Torr and higher one has to use the law (2) supposing the constant ion mean free path in the cathode sheath. In the intermediate pressure range (between 0.3 and 0.75 Torr) none of the Child-Langmuir law versions furnishes a correct description of the cathode sheath of the glow discharge in the N_2O gas.

Our data for large pressure values agree with the conclusion of paper [8], where it was demonstrated that the normal current density effect in the rf discharge in the N_2O gas is best described by the model assuming the constant mean free path of N_2O^+ ions in the near-electrode sheath. Note that conventionally the normal mode is observed in the rf discharge in N_2O at the pressure values order of or above 1 Torr.

However at low N_2O pressure below 0.3 Torr the approximation of the constant ion mean free path is replaced with the approximation of the constant ion mobility in the cathode sheath. One may assume that at low pressure a considerable dissociation of N_2O molecules via electron impact [9] occurs with subsequent ionization of NO molecules formed. Positive NO^+ ions cannot experience charge exchange when colliding with N_2O molecules because the ionization potential of NO molecules is 9.26 eV being less than the ionization potential of N_2O molecules amounting to 12.89 eV [10]. Consequently their motion through the cathode sheath has to be described with the Child-Langmuir law version (3) valid for the constant ion mobility. Note that the cathode sheath of the dc discharge in low pressure nitrogen (0.1 Torr) is well described by equation (3) with the constant ion mobility [11].

CONCLUSIONS

Thus this paper reports the studies of the cathode sheath thickness and the voltage drop across it for different discharge current density values as well as it clarifies which of the collision-dominated Child-Langmuir law versions is the best for describing the processes within the cathode sheath. We demonstrate that at low pressure (up to 0.3 Torr) one can apply the collision-dominated Child-Langmuir law version for constant ion mobility. Starting from the N_2O pressure value of 0.75 Torr and above one has to apply the law version for which the constant ion mean free path within the cathode sheath is assumed. In the intermediate pressure range (between 0.3 and 0.75 Torr) neither of the two versions of the collision Child-Langmuir law furnishes a correct description of the cathode sheath of the glow discharge in the N_2O gas.

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ДВИЖЕНИЕ ПОЛОЖИТЕЛЬНЫХ ИОНОВ В КАТОДНОМ СЛОЕ ТЛЕЮЩЕГО РАЗРЯДА В N_2O

В.А. Лисовский, Е.П. Артюшенко, В.Д. Егоренков

Выяснено, какой из столкновительных законов Чайльда-Ленгмюра наиболее пригоден для описания процессов в катодном слое в N_2O. Показано, что при низких давлениях (вплоть до 0.3 Торр) для описания процессов в катодном слое применим столкновительный закон Чайльда-Ленгмюра для постоянной подвижности ионов. При давлениях N_2O, начиная с 0.75 Торр и выше, нужно использовать закон, в котором предполагается постоянной длина свободного пробега ионов в катодном слое. В промежуточной области давлений (между 0.3 и 0.75 Торр) ни один из законов Чайльда-Ленгмюра не описывает корректно катодный слой тлеющего разряда в N_2O.

РУХ ПОЗИТИВНИХ ІОНІВ У КАТОДНОМУ ШАРІ ТЛІЮЧОГО РОЗРЯДУ В N_2O

В.О. Лісовський, К.П. Артюшенко, В.Д. Єгоренков

З'ясовано, який із законів Чайльда-Ленгмюра із зіткненнями найбільш придатний для опису процесів у катодному шарі в N_2O. Показано, що при низькому тиску (аж до 0.3 Торр) для опису процесів у катодному шарі можна застосувати закон Чайльда-Ленгмюра з постійною рухливістю іонів. При тиску N_2O, починаючи з 0.75 Торр і вище, потрібно використовувати закон, в якому зберігається постійною довжина вільного пробігу іонів у катодному шарі. У проміжній області тиску (між 0.3 і 0.75 Торр) жоден із законів Чайльда-Ленгмюра не описує коректно катодний шар тліючого розряду в N_2O.