ISSN 0018-1439, High Energy Chemistry, 2024, Vol. 58, Suppl. 3, pp. S308–S312. © Pleiades Publishing, Ltd., 2024.

Assessing Apparent Secondary Electron Yields from Current–Voltage Characteristics of Low-Pressure DC Glow Discharges in Nitrogen

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Received September 11, 2024; revised September 11, 2024; accepted September 11, 2024

Abstract—The problem of assessing apparent secondary emission coefficient γ_{eff} based on electrical properties of DC glow discharge is considered for the case of low-pressure discharges in nitrogen. Estimation method was based on a previously developed analytical model of a DC glow discharge which has been shown to provide informative data on γ_{eff} for discharges with copper electrodes in argon. Preliminary estimates based from current–voltage characteristics of discharges in nitrogen with copper electrodes were obtained and analyzed. While the averaged value of γ_{eff} agreed well with the one corresponding to conditions of a clean copper cathode, the dependence of γ_{eff} on reduced electric field for each considered CVC exhibited a pronounced decrease. Reasons for such dependence are attributed to uncertainties in the analytical formulation of nonlocal ionization source for nitrogen used during calculations.

DOI: 10.1134/S0018143924701066

INTRODUCTION

The direct problem of gas discharge simulation is to predict or provide estimates of electric (current and voltage characteristics, CVC) and plasma (charged particle densities and fluxes, electric potential, their spatial distributions) properties of a discharge for given experimental conditions. Solution of this problem requires some a priori knowledge on the emission of secondary electrons. Typically, the ion-induced emission of secondary electrons via the Auger process is assumed to be the dominant emission mechanism [1, 2], and the data on the corresponding emission coefficients γ_i is usually taken from beam experiments in controlled surface environment under vacuum conditions. In these experiments in the lower ion kinetic energy range the secondary electron yield per incident ion is independent from the ion energy [3], and constant values of γ_i are frequently used for simulations.

On practice, however, the situation is complicated by the fact that oftentimes it is very difficult to ensure perfectly clean state of the cathode surface during discharge operation, and various contaminations (due to, e. g., oxidation and contact with different substances in the ambient air) are possible. secondary emission coefficients depend in a complex way on discharge conditions, since a number of processes in addition to ion-induced emission (kinetic mechanisms of electron knockout by fast ions and neutral particles, photoemission) can contribute to the total flow of secondary electrons from the cathode surface, which are largely sensitive to the state of the cathode surface [3]. The situation is also complicated by the fact that over the course of discharge, various impurities (e.g., hydrogen) often escape from the cathode material, which directly affect the properties of the discharge and lead to doping of the cathode surface, which leads to changes in the properties of the discharge from experiment to experiment and even within a single measurement [4].

Systematic analysis of experimental data on electric characteristics of abnormal DC glow discharges in argon and numerical models available at the time led to a conclusion that secondary emission of electrons from the cathode surface and corresponding coefficients should be treated as *primary unknows* in numerical modelling due to lack of information on the cathode surface conditions in a given experiment [5]. To a large extent such situation remains to this day.

Some information on secondary electron emission for given experimental conditions can be obtained by solution of the inverse problem of gas discharge simulation—to use experimentally measured electric properties of a discharge in order to calculate the value of apparent secondary emission coefficient γ_{eff}, which, by definition, includes contribution to secondary electron emission of all possible processes [6]. Only a few works have considered the inverse problem, and usually only in the context of development of a numerical model aimed at solution of the direct problem [6–10].

As the result of solution of the inverse problem are numerical values of γ_{eff}, the requirements to the numerical model used become considerably stricter

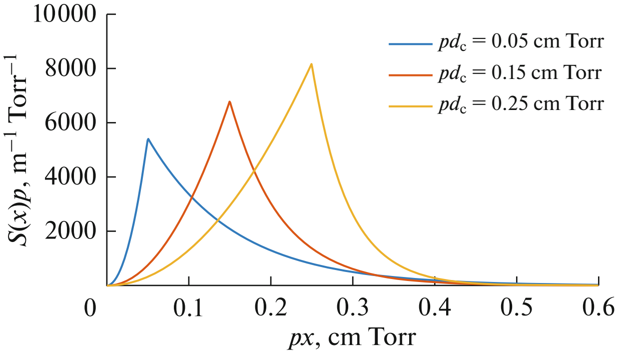

Fig. 1. Spatial distribution of non-local ionization source for different values of cathode sheath thickness for $V_c = 250$ V.

than for the direct problem, as all the inaccuracies in quantitative description of both charged particle generation and transport can contribute to the errors in obtained values of γ_{eff} [6]. In this regard, the values obtained during solution of the inverse problem can be used to assess a model's validity for description of a gas discharge for any given experimental configuration. It should be noted that the information content of the values γ_{eff} obtained in this way is largely determined by the care taken in ensuring controlled discharge conditions in the experiment and obtaining reproducible current-voltage characteristics. To date, in most published works on the subject of glow discharges, with rare exceptions (see, for example, work [4] and references therein), the method of preliminary preparation of cathodes and discharge tubes is described without detail or is not described at all.

In [6], a method of estimation γ_{eff} based on a simple analytical model of an abnormal DC glow discharge was suggested and tested on experimental CVCs for the case of a discharge in argon with copper electrodes. Analysis of obtained values demonstrated feasibility of the approach. In this work we use the model to assess γ_{eff} for DC glow discharges in nitrogen and demonstrate how quantitative analysis of the obtained values can be used to judge the validity of a given numerical or analytical model in general.

MODEL DESCRIPTION

The method for obtaining estimates for apparent secondary electron yield in a discharge is based on the following notions. Firstly, γ_{eff} can be expressed from the relation for the collision-dominated ion motion in the cathode sheath [5]:

$$\gamma_{eff} = \frac{j d_c^2}{2 V_c \varepsilon_0 v_{i,d}} - 1. \quad (1)$$

Here d_c is cathode sheath thickness (or position of the sheath-plasma boundary), j is discharge current density, V_c is cathode sheath voltage drop, $v_{i,d}$ is ion drift velocity, ε_0 is dielectric constant. Further, emission of secondary electrons from the cathode surface defines self-sustainment of a discharge, and the general self-sustainment condition can be written as [6, 11]:

$$\frac{j_e(d_c)}{j_e(0)} + \frac{j_i(d_c)}{j_e(0)} = 1 + \frac{1}{\gamma_{eff}}. \quad (2)$$

Here $j_{e,i}$ are the electron and ion current density, cathode surface is positioned at $x = 0$. The first term in the right-hand side of Eq. (2) corresponds to electron multiplication in the cathode sheath, while the second term corresponds to influx of ions from negative glow. Since the latter occurs due to ambipolar diffusion, and only the ions born before the position of electric field reversal in the negative glow can reach the sheath [11, 12], for a one-dimensional case eq. (6) can be rewritten as:

$$\int_0^{x_m} S_n(x)\,dx = 1 + \frac{1}{\gamma_{eff}}, \quad (3)$$

where $S_n(x)$ is the spatial distribution of the net charge particle sources and sinks divided by the electron flux at the cathode $\Gamma_e(0)$, x_m—position of the electric field reversal in the negative glow [11, 12]. For a correct interpretation of electrical characteristics of a DC glow discharge one must employ a model that takes into account the non-local highly non-equilibrium character of ionization by fast electrons in the cathode sheath and negative glow regions [13]. One way to do so is to use explicit formulation of the non-local ionization source as a function of spatial coordinate, obtained either from basic principles [11] or from Monte-Carlo simulations [13]. In this work analytical formulation of the non-local ionization source suggested by Boeuf in [13] was used:

$$S_+(x) = \begin{cases} S_{max} p \Gamma_e(0) \dfrac{x^2}{d_c^2}, & x < d_c \\ S_{max} p \Gamma_e(0) \exp[-K_p p (x - d_c)], & x \ge d_c \end{cases}. \quad (4)$$

Here p is gas pressure, $\Gamma_e(0)$ is electron flux density at the cathode, S_{max} and K_p are numerical coefficients tabulated in [13]. Spatial distribution of $\dfrac{S_+(x)}{\Gamma_e(0)}$ for nitrogen are presented in Fig. 1.

Using Eq. (2) and the ambipolar diffusion equation with approximate description of radial losses of charged particles (τ-approximation [2]) one can obtain the following self-sustainment condition:

$$S_{max} p \left[\frac{d_c}{3} + \frac{1}{K_p p + \Lambda^{-1}}\right] = 1 + \frac{1}{\gamma_{eff}}, \quad (5)$$

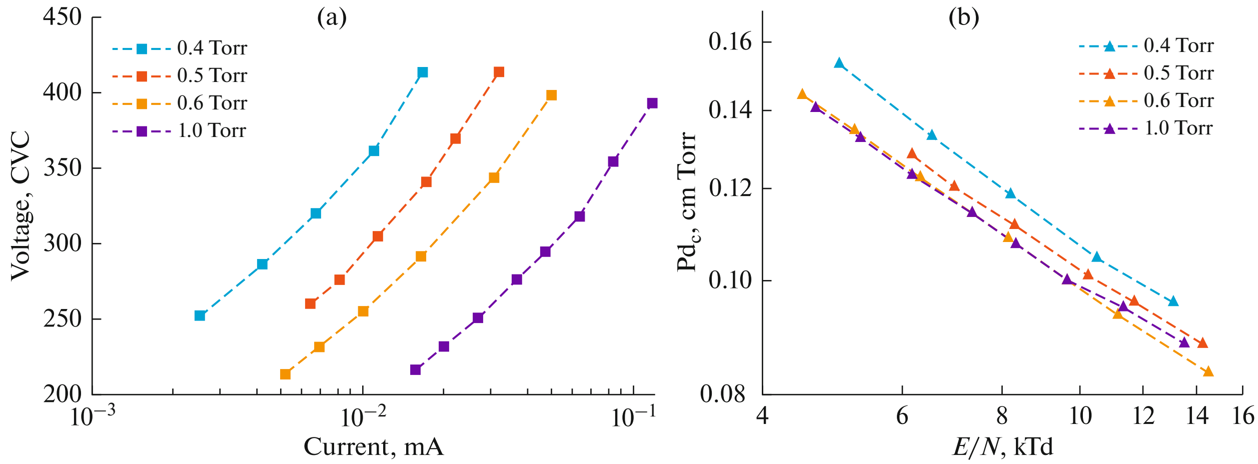

Fig. 2. (a) experimental current-voltage characteristics taken from Ref. 15 and used for calculating γ_{eff}, (b) calculated pd$_c$ values.

where Λ is the characteristic ambipolar diffusion scale ($\Lambda = R/2.4$ for a cylindrical discharge tube with radius R). Solving Eqs. (1) and (5) using the current voltage characteristics of a dc discharge for j and V_c one obtained γ_{eff} and d_c.

The initial calculations of $S_+(x)$ in [13] assumed that only N_2^+ ions are produced. While some amount of atomic nitrogen is present in the discharge, in this study we also assumed that it is small compared to N_2 to have a direct contribution to discharge self-sustainment. However, it is known that small admixtures can have a considerable effect on discharge properties via charge transfer reaction and influencing ion transport in the discharge. Data on ion drift velocity for N_2^+ in N_2 was taken from [14] and approximated using mean reduced electric field E/N (N is neutral density) in the cathode sheath $\overline{(E_N)} = V_c/(d_c N)$ as:

$$v_{i,d} = \frac{8\overline{E_N}}{\left(1 + \left(0.008\overline{E_N}\right)^{\frac{3}{2}}\right)^{\frac{1}{3}}}. \quad (6)$$

It must be noted that the model requires knowledge of the cathode sheath voltage drop V_c. Therefore the current voltage characteristics most suitable for assessment are those of short DC glow discharges (without positive column), where V_c is approximately equal to total discharge voltage. While it is possible to obtain estimates of γ_{eff} in a longitudinal DC glow discharge (with positive column) using self-consistent numerical modelling [15], such consideration introduces additional factors that can contribute to the uncertainty $\Delta\gamma_{eff}$.

RESULTS AND DISCUSSION

Previously in [6] presented approach was used for estimations of γ_{eff} based on experimental CVCs of abnormal DC glow discharges in argon with copper electrodes obtained by separate research groups. The obtained γ_{eff} values could be divided into two groups with different average values, which was attributed to possible differences in cathode preparation techniques used. Values close to those corresponding to a clean cathode surface were obtained for data from [16]. The work also presented data for nitrogen discharges, which we use here for preliminary assessment of model applicability for a glow discharge in nitrogen.

Values of numerical coefficients in $S_+(x)$ for nitrogen can be found in [12]. The range of applicability of these coefficients is 150–400 V in terms of V_c and 0.05–0.30 in terms of pd_c. Figure 2a shows the data on CVCs of a DC discharge in nitrogen taken from [16], only the data corresponding to the abnormal glow discharge at pressures 0.4–1.0 Torr and below 400 V was considered in order to remain within the range of applicability of the present model and of the analytical approximation of the non-local ionization source. Figure 2b shows the calculated pd_c values, decreasing with reduced electrical field E/N and remaining well within the 0.05–0.30 cm Torr range.

Figure 3 shows the calculated dependences $\gamma_{eff}(E/N)$ for all considered current-voltage characteristics. It can be seen that the dependence is decreasing, which does not agree with the known increasing dependence due to the kinetic electron ejection taking effect at higher ion energies and which was observed in [5–9] for discharges in argon. If one assumes that the cathode was sufficiently clean and emission of secondary electrons was due to N_2^+ bombardment, then the obtained dependence could be attributed to overestimation of ionization rate at higher E/N. Similar

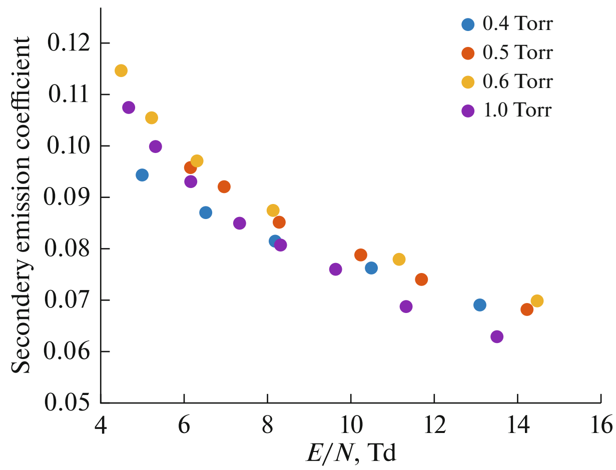

Fig. 3. Obtained values of γ_{eff}.

dependence was obtained preliminarily for discharges in helium, in-depth analysis of the issue together with updated recommendations on ionization source formulation will be reported separately.

Nevertheless, the mean value and deviation of γ_{eff} for the data considered are 0.085 ± 0.014, which is close to the estimations obtained using N_2 ionization potential I and copper work function W_f [2]:

$$\gamma_i = 0.016(I - 2W_f) \approx 0.1.$$

Such estimates are often used as reference values γ_{eff} in the analysis of secondary electron emission processes in gas discharges of various types [19–21]. The value of 0.1 is often used in modeling glow discharges in nitrogen [22, 23].

Based on the obtained value we can conclude that the assumption of N_2^+ being the dominant ion for considered discharge conditions was adequate, as otherwise errors in ion drift velocity would have produced unrealistic values of γ_{eff} [5].

CONCLUSIONS

Preliminary results of assessing apparent secondary electron yield γ_{eff} in abnormal DC glow discharges in nitrogen by analysis of experimental current-voltage characteristics using an analytical discharge model were presented. Obtained values of γ_{eff} demonstrated decreasing trend with reduced electric field, contrary to what could be expected based on previous data for argon discharges, which is likely due to overestimation of the non-local ionization source at high electric fields. The obtained average value of γ_{eff}, on the other hand, was found to be close to the one estimated for a nitrogen ions bombarding clean copper cathode. Given the previous conclusion that the methods of cathode preparation used in the initial work likely ensured clean cathode surface during CVC measurement, we can assume that the obtained average value of γ_{eff} is informative and can be used for future reference. Overall, the present method, while containing aspects that require further improvement, is adequate for obtaining estimates of γ_{eff} in experiments with short DC glow discharges.

ACKNOWLEDGMENTS

The work was supported by Russian Science Foundation (Grant No. 22-72-00045).

FUNDING

This work was supported by ongoing institutional funding. No additional grants to carry out or direct this particular research were obtained.

CONFLICT OF INTEREST

As author of this work, I declare that I have no conflicts of interest.

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