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L. V. MYKHAYLOVSKA [1], *A. S. MYKHAYLOVSKA* [2]

[1] I.I,Mechnikov Odesa National University, 65082, Odesa, Ukraine
[2] Ruhr-Universitдt Bochum, 44780, Bochum, Germany
E-mail: lidam@onu.edu.ua

INFLUENCE OF THE STEP IONIZATION PROCESSES ON THE ELECTRONIC TEMPERATURE IN THIN GAS-DISCHARGE TUBES

Taking into account the processes of the direct and step ionization and on the basis of the closed system of the balance equations we have performed theoretical analysis of electronic temperature dependence on the external parameters such as the value of the discharge current, pressure of the working gas and the diameter of the discharge capillary. The conditions were found which indicate the decisive role of the step ionization in charged particles creation.

INTRODUCTION

The study of the low-temperature plasma of the positive column in thin tubes is interesting not only as of the active medium of the wave-guiding lasers but also for the possible creation of the small-size energy sources for the gas laser emitting devices of low pressure. The out-come characteristics of the devices which use the gaseous discharge depend on the inner parameter of the positive column (PC) which is characteristic for the discharge. A significant number of theoretical and experimental papers [1-5] is devoted to the studies of the inner parameters in the active media of gaseous lasers. In these papers the main attention is paid to the influence of the discharge current I_r the gas pressure p and the inner radius of the discharge capillary R_0 on the longitudinal electric field strength E_z, the electronic concentration N_e, as well as on the electronic temperature T_e [3-6] assuming their Maxwell-type distribution over the velocity values. The inner parameters of the discharge processes are defined by the given external parameters.

The condition required for the stationary gaseous discharge existence is the temporal stability of the electronic concentration. The balance of the charged particles in the plasma of low-pressure PC is formed by ionization processes in the gaseous volume and the following deficiency of the charged particles due to the drift of electrons and ions towards the wall of the tube. It should be noted that the probability of the charged particles creation as well as the processes concerning the decrease of the charged particles, depend on the electronic temperature.

SCOPE OF THE WORK

In the present paper, basing on the closed system of equations obtained in [7], for the evaluation of the inner parameters of PC of the discharge tube, the stable value of electronic temperature with the simultaneous account of the direct and step ionization. Usually, either the ionization of non-excited atoms (direct ionization), or the ionization of the excited atoms (step ionization) is taken into account [4, 6]. The simultaneous account of the direct and step ionization allows to evaluate and compare the input of these two processes into atoms' ionization. The analysis is conducted with the use of two main approximations — the diffuse regime of the discharge and the Maxwell distribution of electrons over the velocity values.

Let us write down the simplified (interpolated) equations for direct and step ionizations with the simultaneous account of the balance between the number of charged particles N_e and metastable atoms N_m in the discharge controlled by the diffusion

$$\nu_{0i} N_e + \nu_{mi} N_e = \nu_{ad} N_e . \qquad (1)$$

$$\nu_{0m} \cdot N_e = \left(\nu_{md} + \nu_{mj}\right) \cdot N_m . \qquad (2)$$

Here $\nu_{0i} = k_{0i} N_0$ – the frequency of direct ionization, $\nu_{mi} = k_{mi} N_m$ — the frequency of step ionization from the metastable level, ν_{ad} — the frequency of the diffuse departures of the electrons towards the tube walls, $\nu_{0m} = k_{0m} N_0$ — the frequency of the metastable level's excitation as a result of the atoms, being in the basic state, coincidence with the free electrons, ν_{md} — the frequency of diffuse departure of metastable atoms to the walls of the tube, $\nu_{mj} = k_{mj} N_e$ — the frequency of the metastable atoms extinguishing due to their coincidence with free electrons, k_{0i}, k_{mi} — the constants of the direct and step ionization velocity, correspondingly, k_{0m} and $k_{mj} = k_{mi} + k_{m0}$ — the constants of the excitation and extinguishing velocities of the metastable state by electron impact, correspondingly. The main role in the process of states' destruction is played by the metatstable state ionization with the constant k_{mi}, as well as the transition of the excited atom to the ground state with the constant k_{m0}.

MODEL AND DISCUSSION

It is known that the frequency of the diffuse departures in the cylindrical PC is being expressed by $\nu_d = D/\Lambda^2$, where D — the corresponding diffusion coefficient, $\Lambda = R_0/2.405$ — diffusion length, R_0 — the discharge tube capillary radius. For the charged particles, the ambipolar diffusion coefficient is: $D_{ad} = \mu_i kT_e/e$, where μ_i — the ions' mobility. According to [2], the ions' mobility with the account of the resonant recharging, is proportional to the ion's velocity and inversely proportional to the gas pressure. That's why, the ambipolar diffusion coefficient is: $D_{ad} = D_{a0} \cdot T_e \sqrt{T}/p$, and the corresponding frequency equals to $\nu_{ad} = D_{a0}\left(T_e\sqrt{T}/p\right)\left(2.405/R_0\right)^2$.

For metastable atoms, the diffusion coefficient is proportional to the atoms' velocity and inversely proportional to the density of gas. Thus, one obtains $D_{md} = D_{m0} \cdot T\sqrt{T}/p$ and then the corresponding of diffusive departures is $\nu_{md} = D_{m0}\left(T\sqrt{T}/p\right)\left(2.405/R_0\right)^2$. The values of the constants D_{a0}, D_{m0} are defined by the type of gas and the system of units chosen [7].

In the written above simplified balance equations the particles' space distribution over the area of the capillary cross-section is not considered. It is assumed that N_0, N_m correspond to the values of the particles' concentration in the ground and metastable states at the center of the tube and N_e — the concentration of the electrons at the center of the tube. It should be noted that according to the Mendeleev-Clapeiron law, the density of atoms N_0 is mutually connected with gas temperature through the relation $N_0 = p/kT = N_{00} \cdot p/T$ (p—gas pressure in the discharge tube, T— gas temperature, and the constant N_{00} value is determined by the system of units choice).

According to [2], while the energy spectrum of electrons is of the Maxwellian type, the frequency of the direct ionization of the atom from the ground state and that for the atom transfer from the ground to the excited one the following expression could be used:

$$\nu_{0i} = \bar{v}_e C_i \left(eU_{0i} + 2kT_e\right)\exp\left(-eU_{0i}/kT_e\right) \cdot N_0 . \quad (3)$$

Here $\bar{v}_e = \sqrt{8kT_e/\pi m}$ — average thermal velocity of the electron, C_i — the constant characteristic for the given process, U_{0i} — ionization potential for the atom transfer to the excited state.

The frequency of the step ionization is determined by Thomson formula and could be written as:

$$\nu_{mi} = \frac{C_{mi} \cdot \bar{v}_e}{kT_e \cdot eU_{mi}} \times \left(\exp\left(-\frac{eU_{mi}}{kT_e}\right) - \frac{eU_{mi}}{kT_e} \cdot \int\limits_{\frac{eU_{mi}}{kT_e}}^{\infty} \frac{\exp(-t)dt}{t} \right) \cdot N_m , \quad (4)$$

где C_{mi} — the constant for given process, U_{mi} — the excited atom ionization potential.

It is seen that one could get the following expressions for the density of metastable atoms and electronic density from the balance equations (1-2) as a functions of electronic temperature, pressure and the temperature of the working gas and of the radius of the discharge tube:

$$N_e\left(T_e, p, T, R_0\right) = \frac{\left(\nu_{ad} - \nu_{0i}\right)\nu_{md}}{\nu_{0m}k_{mi} - \left(\nu_{ad} - \nu_{0i}\right)k_{mj}} , \quad (5a)$$

$$N_m\left(T_e, p, T, R_0\right) = \frac{\nu_{ad} - \nu_{0i}}{k_{mi}} = \frac{\nu_{0m}N_e}{\nu_{md} + k_{mj}N_e} . \quad (5b)$$

It is seen, also, that for $N_m \geq 0$ and $N_e \geq 0$ only if $\nu_{ad} - \nu_{0i} \geq 0$ and $\nu_{0m}k_{mi} - \left(\nu_{ad} - \nu_{0i}\right)k_{mj} > 0$. From these equations, with the use of the definitions made earlier, for D_{ad} and N_0, the following boundary value could be proposed for the combination pR_0:

$$\frac{D_{a0} \cdot T_e \cdot T\sqrt{T}}{N_{00} \cdot \left(k_{0i} + k_{0m}k_{mi}/k_{mj}\right)} < \left(\frac{pR_0}{2.405}\right)^2 \leq \frac{D_{a0} \cdot T_e \cdot T\sqrt{T}}{N_{00} \cdot k_{0i}} . \quad (6)$$

The two boundary equations for the electronic temperature follow the simplified balance equations (1) and (2). So, when the excited atoms are absent in the plasma of gaseous discharge, and only the non-excited atoms are being ionized the Schottky condition could be obtained from (1) or (5b) for the evaluation of the electronic temperature:

$$\nu_{ad}\left(T_e\right) = \nu_{0i}\left(T_e\right) \quad (7a)$$

what means the equality of the frequencies of the ionization and of the diffuse departures of electrons to the walls of the tube. Inserting the expressions for the frequencies into this equality, one could obtain the following equation for the T_e under the given pressure p and the gas temperature T in the tube of the radius R_0

$$\frac{T_e}{k_{0i}\left(T_e\right)} = \frac{N_{00}}{D_{a0}}\left(\frac{pR_0}{2.405}\right)^2 \frac{1}{T\sqrt{T}} . \quad (7b)$$

During the increase of the electrons' density caused by the increase of the discharge current the number of the metastable atoms increases as well and the mechanism of the step ionization starts to act. In the limit of $N_e \to \infty$ one could obtain from (5a) or (5b) the other following equation for the evaluation of T_e

$$\nu_{0m}\left(T_e\right) = \frac{k_{mj}\left(T_e\right)}{k_{mi}\left(T_e\right)}\left[\nu_{ad}\left(T_e\right) - \nu_{0i}\left(T_e\right)\right] , \quad (8a)$$

which is the analog of Schottky condition with the account of the processes of creation and destruction of the metastable atoms. Using the expressions for the frequencies, we obtain the following equation for T_e

$$\frac{T_e k_{mj}\left(T_e\right)}{k_{0i}\left(T_e\right)k_{mj}\left(T_e\right) + k_{0m}\left(T_e\right)k_{mi}\left(T_e\right)} = \frac{N_{00}}{D_{a0}}\left(\frac{pR_0}{2.405}\right)^2 \frac{1}{T\sqrt{T}} . \quad (8b)$$

CALCULATION RESULTS

At Fig.1 are presented the solutions of the equations (7b) (curves 1) and of the equation (8b) (curves 2), as well as the difference between these solutions (curves 3) in dependence of the product pR_0. It is seen that the solutions of these equations behave almost uniformly in the chosen range of pR_0. The difference between these solutions decreases with the increase of pR_0. The increase of the working gas temperature T causes the somewhat increase of the corresponding electronic temperature along with the non-significant increase difference between solutions. The character of the dependencies is not changing.

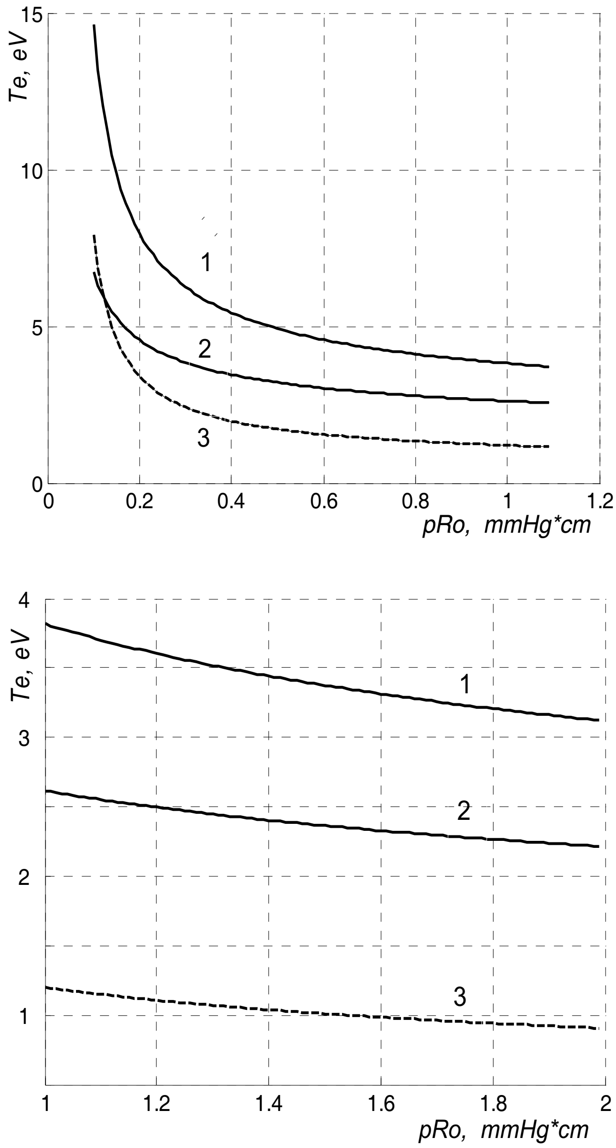


Fig.1. The dependencies of the equations (7) and (8) solutions on the product pR_0 for two regions of pR_0 changes. Curves 1 — solutions of equation (7), curves 2 — solutions of equation (8), curves 3 — the difference of these solutions

In two limiting cases which correspond to $N_e \to 0$ and $N_e \to \infty$, the equations (7) and (8) for the electronic temperatures do not include the electronic concentration. From other part, in general case, the electronic density depends on the total discharge current, which could be written in the form $I_r = 2\pi e \mu_e E_z \int_0^{R_0} r N_e(r) dr$, where $\mu_e = \mu_e(p,T)$ - the electronic mobility, E_z - the longitudinal field strength, which stabilizes in the discharge. In the PC of the discharge, the electronic distribution over the section area is Besselian $N_e(r) = N_{e0} \cdot J_0(2.405 r/R_0)$. Then, under the given discharge current, it is possible to obtain the following expression for N_{e0}

$$N_{e0}(T_e, p, R_0, T, I_r) = \frac{I_r}{5\pi e \mu_e E_z}\left(\frac{2.405}{R_0}\right)^2. \quad (9)$$

This value of electronic density should coincide with the value obtained from the balance equations (5a). That's why it is necessary to solve the following equation taking into account the both the direct and step ionization

$$\frac{(\nu_{ad} - \nu_{0i})\nu_{md}}{\nu_{0m} k_{mi} - (\nu_{ad} - \nu_{0i}) k_{mj}} = \frac{I_r}{5\pi e \mu_e E_z}\left(\frac{2.405}{R_0}\right)^2. \quad (10)$$

The strength of the longitudinal electric field held in the discharge $E_z = E_z(T_e, p, R_0, T)$ is determined by the balance equation for the electronic energy with the account of the elastic energy losses during the impact energy exchanges between electrons and atoms of the working gas as well as of the non-elastic losses on the excitation and ionization of the atoms. Besides, the energy balance in thin gas-discharge tubes includes the energy transferred by the charged particles to the tube walls [4]. In present paper the longitudinal field strength E_z is calculated through the following equation obtained in [7]:

$$e^2 E_z^2 = m\nu_m \cdot (\nu_c \cdot \Delta\varepsilon_g + \nu_w \cdot \Delta\varepsilon_w + \sum_i \nu_i \cdot \Delta\varepsilon_i). \quad (11)$$

Here ν_m — the effective electron collision frequency, ν_c — elastic collisions frequency for electron-neutral atom pairs, which in general case depends on the electronic temperature and atoms' density, $\Delta\varepsilon_g = (2m/M)\cdot(3kT_e/2)$ — energy losses during elastic collisions of electrons with neutral atoms, ν_w – electron collisions frequency with discharge tube walls which equals to the frequency of electronic diffuse departures to the walls $\nu_w = \nu_{ad}$, $\Delta\varepsilon_w$ – energy losses of the charged particles on the tube walls, ν_i — frequency of non-elastic collisions of the electrons with atoms which excites or ionizes the atom, $\Delta\varepsilon_i$ — electron energy losses given to the excitation or ionization of the atoms.

We would like to limit ourselves to the case of account only the electron energy losses on the tube walls when the power contains only the recombination energy for positive ions and electrons eU_i and of kinetic energy they possessed before the recombination $\Delta\varepsilon_w = eU_{0i} + W_{kp} + 2kT_e$, where U_{0i} is the ionization potential of the atom in the recombination state, $2kT_e$ and W_{kp} -are the average kinetic energies of the electron and ion during their approach the wall.

Taking into account the processes of direct and step ionization, one could rewrite the last term in brackets in formula (11) for the power density in the form: $\sum \nu_i \cdot \Delta\varepsilon_i = e(k_{0i} N_0 U_i + k_{0m} N_0 U_m + k_{mi} N_m U_{mi})$. Using the expression (6) for the metastable atoms' density N_m, it is evident that: $\sum_i \nu_i \cdot \Delta\varepsilon_i = e[(k_{0i} + k_{0m}) N_0 U_m + \nu_{ad} U_{mi}]$.

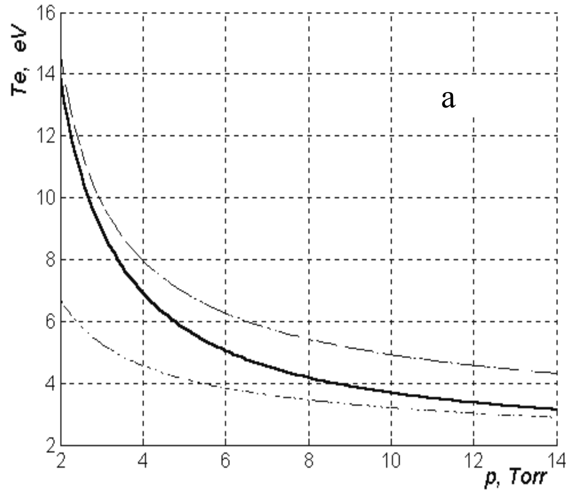
The losses on the direct iomization and atoms' excitation into metastable state without the step ionization process are described by the expression: $\sum_i \nu_i \cdot \Delta\varepsilon_i = e(k_{0i} U_i + k_{0m} U_m) N_0$. It is possible to make it clear that: $(k_{0i} + k_{0m}) N_0 U_m + \nu_{ad} U_{mi} \ge (k_{0i} U_i + k_{0m} U_m) N_0$, if $\nu_{ad} \ge \nu_{0i}$.

The results of the numeric solution of the equation (10) for the discharge in He are presented at Fig.2 — 4. The partial dependencies on the gas pressure and capillary radius are presented as they in contrary to the solutions of equations (7) and

(8), from the equation (10) the solution's dependence on the product pR_0, and $T_e \neq f(pR_0)$ doesn't follow. We have used the following constants: $C_i = 0.12 \cdot 10^{-17}$ cm²/eV, $C_m = 0.45 \cdot 10^{-17}$ cm²/eV, $C_{mi} = 6.5 \cdot 10^{-14}$ cm²/eV, $eU_{0i} = 24.6$ eV, $eU_{0m} = 20$ eV, $eU_{mi} = 4.6$ eV. Besides, it is assumed that the gas temperature equals to that of the outer walls' one. For this latter parameter we have used the experimentally measured value of $T^0C = 20^0C + 7 \cdot I_r$, where 20^0C is the temperature of the ambient, I_r — the discharge current in mA.

The numeric calculations have shown that the electronic temperature in the real situation with the account of both the direct and step ionization takes the value which doesn't coincide with any limit value determined by equations (7) and (8). At the figures presented, it is seen that the electronic temperature's value obtained as the solution of the equation (10), is smaller than the temperature obtained from the equation (7), but the greater than that obtained from equation (8). Only at small pressures and not significant discharge currents and in thin tubes, the real electronic temperature is almost the same as the electronic temperature obtained from Schottky's condition (7) (see, please, the curves at Fig.2a). With the increase of the pressure, the step ionization plays the greater role and the solution of the equation (10), even for thin tubes, differs slightly from the solution of the modified Schottky equation (8) (see, please, the curves at Figs.2, 3).

In the present paper, in the framework of the assumptions taken, the electronic temperature depends only on the temperature of the ambient and is proportional to the discharge current value. The proportionality quotient is a constant determined from the experiment. Really, according to the results of [7], the temperature of the working gas is the function of the discharge inner parameters such as: the electronic temperature, longitudinal electric field strength and electrons' concentration. As it is seen from Fig.4 (curves 1), with the increase of discharge current the metastable atoms' concentration increases as well and the electronic temperature decreases as a result. But, afterwards, under the following growth of the discharge current and of the gas temperature, the gas density decreases due to the termal gas expansion to the ballast volume. This effect is accompanied by the increase of the electronic temperature. The placement of the discharge tube into the thermostat causes the decrease of the electronic temperature which could be explained by the growing role of the step ionization due to the gas pressure increase (see, please, Fig.4, curves 2). Thus, under the taken assumptions, the working gas temperature T remains stable and the solutions of the equations (7b) and (8b) do not dependent on the discharge current as it is seen at Fig.4 (horizontal lines).



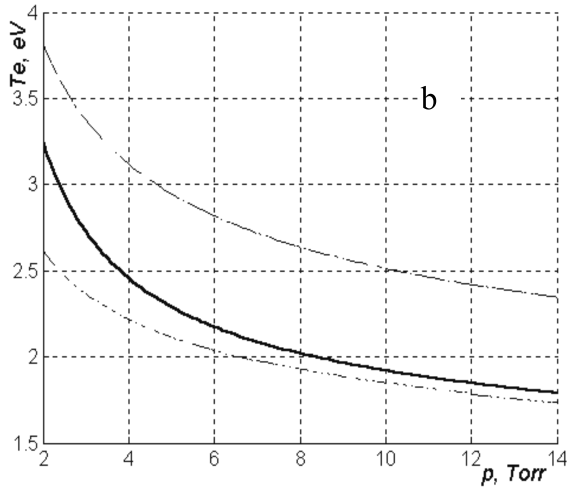


Fig. 2. The results of the numeric solution of the equation (10). The solid lines represent the dependencies of the electronic temperature during the gas pressure changes. Punctured and pin-stripe ones correspond to the solutions of the equations (7) and (8). The discharge current $I_r = 10\,mA$, gas temperature $T = 20\,^0C + 7 \cdot I_r$, a) discharge capillary radius $R_0 = 0.05\,cm$, b) discharge capillary radius $R_0 = 0.5\,cm$

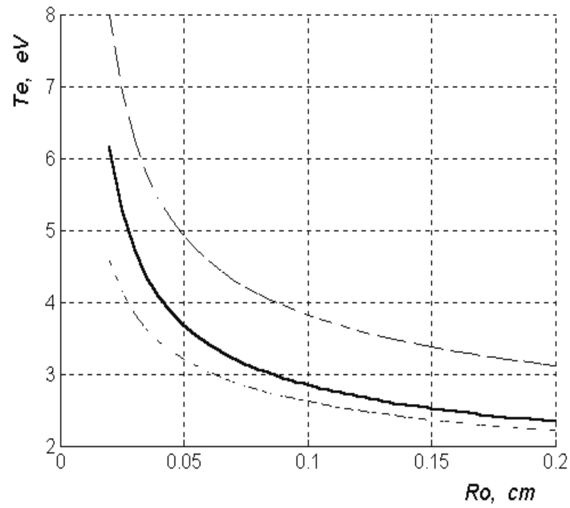


Fig. 3. The results of the numeric solution of the equation (10). The solid line represents the dependence of the electronic on the capillary radius. The punctured and pin-stripe ones correspond to the solution of the equations (7) и (8). Discharge current $I_r = 10\,mA$, gas pressure $p = 10\,Torr$, gas temperature $T = 20\,^0C + 7 \cdot I_r$

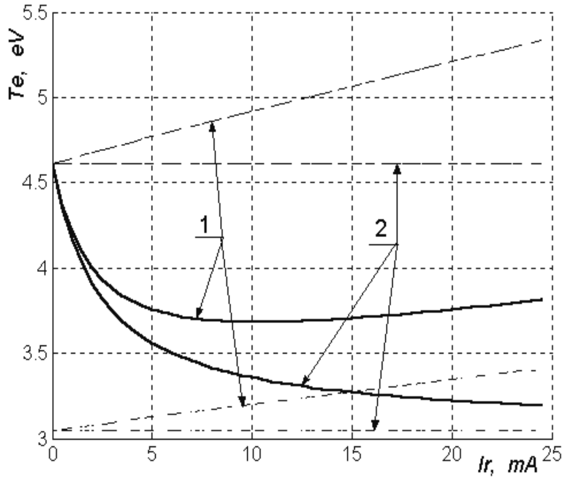


Fig. 4. The results of the numeric solution of the equation (10). The solid lines – dependencies of the electronic temperature on the discharge current. Gas pressure $p = 10\,Torr$, capillary radius $R_0 = 0.05\,cm$, 1 – gas temperature $T = 20\,^0C + 7 \cdot I_r$, 2 – gas temperature $T = 20\,^0C$.

CONCLUSIONS

As a result, we would like to make the following conclusions:

1. The performed theoretical analysis has shown that it is impossible to calculate the electronic temperature in the positive column of the gaseous discharge using only the Schottky equation (7) which takes into account the processes of direct ionization (limiting case of small discharge currents $I_r \to 0$) or the equation (8) which operates only the processes of step ionization (limiting case of extremely high discharge currents $I_r \to \infty$). In the intermediate

2. In the intermediate case of the medium values of discharge currents, the electronic temperature is determined by the equation (10) obtained in the present paper, which accounts both direct and step ionization.

3. As a result of this equation solution, the dependencies of electronic temperature on gas pressure, discharge current value as well as the capillary radius value.

4. It is shown that in the real range of discharge parameters changes such as gas pressure, discharge current and capillary radius, for the physical processes in positive column plasma adequate description it is necessary to take into account all possible ways of atoms excitation and ionization.

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L.V. Mikhaylovskaya, A.S. Mykhaylovska

INFLUENCE OF THE STEP IONIZATION PROCESSES ON THE ELECTRONIC TEMPERATURE IN THIN GAS-DISCHARGE TUBES

Abstract

The theoretical analysis of dependence of the steady-stated electron temperature on the external parameters of discharge, such, as a value of discharge current, pressure of working gas and size of radius of discharge capillary, has been done taking into account the simultaneous processes of direct and stepped ionization. This analysis has been done on the basis of solution of the closed system of the balance equations. Conditions at which a determining role in formation of the charged particles plays stepped ionization are found.

Key word: step ionization, processes, gas discharge tubes.

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Л. В. Михайловская, А. С. Михайловская

ВЛИЯНИЕ ПРОЦЕССОВ СТУПЕНЧАТОЙ ИОНИЗАЦИИ НА ЭЛЕКТРОННУЮ ТЕМПЕРАТУРУ В УЗКИХ ГАЗОРАЗРЯДНЫХ ТРУБКАХ

Резюме

С учетом процессов прямой и ступенчатой ионизации на основе решения замкнутой системы балансных уравнений проведен теоретический анализ зависимости установившейся температуры электронов от внешних параметров разряда, таких, как величина тока разряда, давление рабочего газа и размера радиуса разрядного капилляра. Найдены условия, при которых определяющую роль в образовании заряженных частиц играет ступенчатая ионизация.

Ключевые слова: ступенчатая ионизация, процесс, газоразрядная трубка.

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Л. В. Михайловська, А. С. Михайловська

ВПЛИВ ПРОЦЕСІВ СТУПІНЧАСТОЇ ІОНІЗАЦІЇ НА ЕЛЕКТРОННУ ТЕМПЕРАТУРУ В ВУЗЬКИХ ГАЗОРОЗРЯДНИХ ТРУБКАХ

Резюме

З урахуванням процесів прямої та ступінчастої іонізації на підставі рішення замкнутої системи балансних рівнянь проведено теоретичний аналіз залежності усталеної температури електронів від зовнішніх параметрів розряду, таких, як величина розрядного струму, тиск робочого газу та розмір радіуса розрядного капіляру. Знайдені умови, при яких визначальну роль в утворенні заряджених частинок грає ступінчаста іонізація.

Ключові слова: ступінчаста іонізація, процес, газоразрядна трубка.