ESTIMATION OF THE EFFICIENCY OF MATERIAL INJECTION INTO THE REFLEX DISCHARGE BY SPUTTERING THE CATHODE MATERIAL

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The processes of injection of a sputtered-and-ionized working material into the pulsed reflex discharge plasma have been considered at the initial stage of dense gas-metal plasma formation. A calculation model has been proposed to estimate the parameters of the sputtering mechanism for the required working material to be injected into the discharge. The data obtained are in good accordance with experimental results.

1. Introduction

The reflex discharge [1], also known as the Penning discharge, has a long-term story of its development and research. Now, it is widely used in various domains of science and engineering [2–7]. For instance, the study of the sputtering process of various materials into the reflex discharge plasma [5–7] is needed for the determination of a possibility of their usage as constructional ones in thermonuclear reactors. It is worth distinguishing the problem of introducing a working substance, i.e. which is to be separated, into the work space of a magnetoplasma separator on the basis of reflex discharge [8] or a discharge of any other type. It is known from the literature [9–12] that there are a number of approaches, which can be used for such purposes. Namely, these are the thermal evaporation [9], thermal evaporation with subsequent preionization [10], thermal evaporation of a substance and its introduction in the form of supersonic stream [11], and the sputtering of a separated substance [12]. In the latter case, plasma is created with the help of a source functioning on the basis of the electron-cyclotron resonance, and the substance to be separated is introduced into plasma in the form of an additional wafer with an applied negative potential. Here, dominating is a scheme (a device) for introducing the working substance, where the reflex discharge is applied. In this case, the following sequence of operations is realized. Plasma is created preliminarily; the corpuscular sputtering of a cathode material takes place; and the sputtered material penetrates into plasma, where it undergoes the subsequent ionization. This procedure does not require additional facilities, as was in work [12]. The previous experience [8, 11, 13–15] testifies that the reflex discharge is an effective instrument for producing a multicomponent gas-metal plasma. In this case, the metal plasma component is formed as a result of the ionization of cathode material particles that penetrate into the discharge, when the material is sputtered.

However, the process of cathode material sputtering and its subsequent ionization in the reflex discharge have not been analyzed in detail. Especially important is the consideration for impulse devices, for which the characteristic times of plasma formation are shorter than the equilibration time of stationary ionization. A straightforward determination of how much of the heavy fraction of multicomponent plasma was introduced into the discharge is rather a difficult task, which requires considerable material expenses. Therefore, the development of a technique for the quantitative estimation of the amount of the heavy sputtered plasma component that penetrates into the discharge is regarded as a useful and necessary task. Hence, this work aims at analyzing the processes of material introduction and ionization at the initial stage of producing a dense gas-metal plasma in a pulsed reflex discharge owing to the sputtering mechanism. In so doing, we consider it necessary to choose a

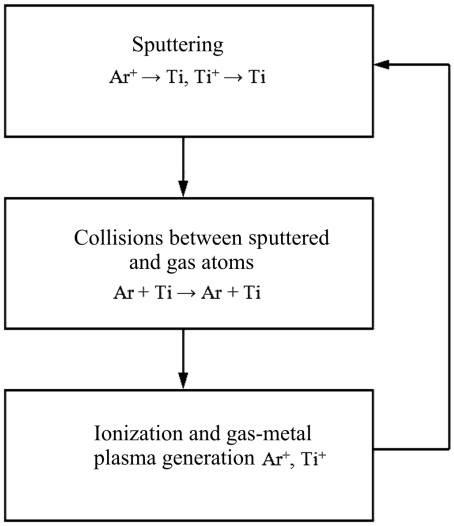

Fig. 1. Diagram of the calculation model

calculation model, in the framework of which not only the processes giving rise to the creation of a gas-metal plasma (sputtering and ionization) would be taken into account, but also the processes that are responsible for the uniform filling of the internal volume with a confining magnetic field – for instance, it may have a plug geometry – with both plasma and the neutral substance within a finite time interval. In the framework of the proposed model – its diagram that illustrates the main stages of calculation, i.e. sputtering, collisions between sputtered and gas atoms, ionization, and formation of a gas-metal plasma, is presented in Fig. 1 – the following parameters are to be calculated. For the sputtering stage, these are the dependences of the sputtering coefficient on the mass and energy of incident ions, as well as on the angle of incidence, and the total number of sputtered particles. For the stage of collision between the sputtered atom and the gas ones, these are the energy spectrum and the average energy of sputtered atoms, the mean free path of a sputtered atom in the gas, the diffusion coefficient, and the diffusion time. At the stage of ionization and gas-metal plasma generation, those parameters include the time and the degree of ionization of sputtering atoms and the content of sputtered material atoms in plasma.

2. Evaluation of Sputtering Mechanism Parameters

We will consider the processes of material sputtering and ionization at the initial stage of dense gas-metal plasma formation in the pulsed reflex discharge assuming that typical experimental conditions take place [13, 14]: namely, the discharge voltage is 3.5–4 kV, Ar is taken as an ignition gas, cathodes are made of Ti, and the time interval, during which a density of about 2×10^{19} m^{-3} is attained, is about 100 μs. The stage of discharge ignition will not be considered now, because such an analysis was carried out earlier (see, e.g., work [16]).

First, let us consider the processes associated with the interaction between the plasma and the surface of a solid. A number of processes take place at that [17], such as the sputtering, electron emission induced by the particle-surface interaction, penetration, reflection, and desorption of stimulated particles, a modification of the near-surface layer, a variation of the charge state of ions, blistering, and so on. One of the basic processes leading to the cathode material destruction and, respectively, its penetration into plasma, is sputtering. The corresponding major characteristic is the sputtering coefficient Y, which depends on the charge, mass, and energy of bombarding ions, the angle of incidence, the material that the target is made of, and the target temperature. The sputtering process has the threshold behavior with respect to the energy. The dependence of the sputtering coefficient Y on the target material reveals itself, first, as a function of the mass and the atomic number of target atoms; second, as a dependence on the surface binding energy of target atoms, U_s, which is usually considered to be equal to the sublimation energy per one atom. For a monoatomic substance, the dependence of the sputtering coefficient on the ion energy, $Y(E)$, at the normal incidence can be expressed using the empirical formula [18]

$$Y(E) = 0.042 \frac{Q(Z_2)\alpha^*\,(M_2/M_1)}{U_s} \times$$

$$\times \frac{S_n(E)}{1 + \Gamma k_e \varepsilon^{0.3}} \left[1 - \sqrt{\frac{E_{th}}{E}}\right]^s , \qquad (1)$$

where the dimensionality of the numerical multiplier is Å^{-2}; E is the energy of an incident ion [eV]; M_1 and M_2 are the masses of an incident ion and a target atom, respectively [a.m.u]; $E_{\rm th}$ is the threshold sputtering energy [eV]; $Q(Z_2)$ is a dimensionless parameter; $\alpha^*(M_1/M_2)$ is a function (independent of the energy) of the mass ratio; $S_n(E)$ is the nuclear stopping cross-section [eV$\times$Å^{-2}/atom]; k_e is the Lindhard electronic stopping coefficient; ε is a dimensionless energy variable; s is the power exponent, which weakly depends on the target material; and Γ is a factor. The dependences of the sputtering coefficients for pairs $Ar^+ \to Ti$

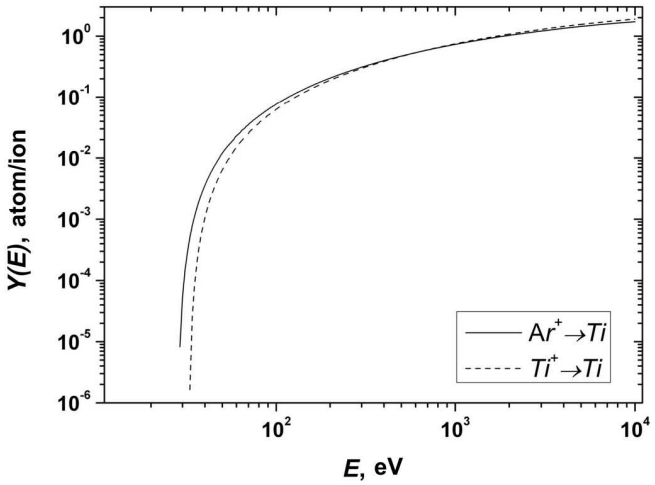

Fig. 2. Dependences of the sputtering coefficient on the energy of incident ions of various sorts at normal incidence

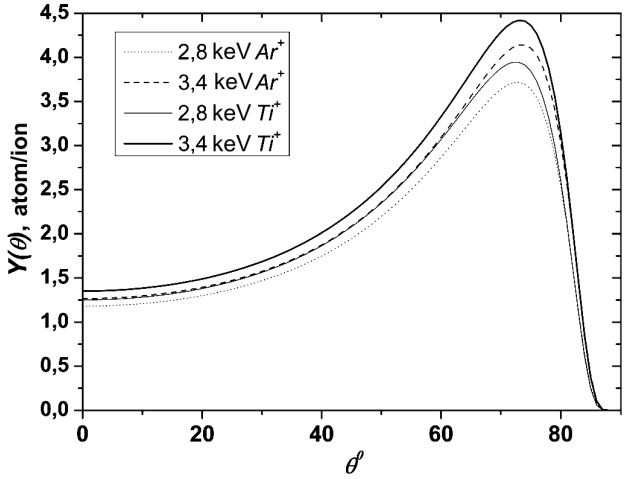

Fig. 3. Dependences of the sputtering coefficient on the angle of ion incidence onto the target for various ion energies

and $Ti^+ \to Ti$ calculated by formula (1) are depicted in Fig. 2.

One can see that the sputtering coefficients for both chosen pairs differ a little from each other and, at energies of incident ions of 1–4 keV, fall in the interval 0.73–1.44. The magnitude of threshold sputtering energy E_{th} in model [18] amounts to 28 and 32 eV for the pairs $Ar^+ \to Ti$ and $Ti^+ \to Ti$, respectively. In the reflex discharge, according to the results of work [5], the maximum of the ion distribution function over the energy is at a level of 0.8–0.85 times the applied voltage. In our case, the typical discharge voltage varied from 3.5 to 4 kV, so that the energy of ions in the distribution function maximum equals 2.8–3.4 keV. Therefore, in subsequent calculations, we will use this energy range.

The surface of a solid is known to often have rather a developed relief structure. It is also known that the interaction with ionic and plasma fluxes induces those or other relief modifications. Depending on the flux parameters and the conditions at the surface, these modifications manifest themselves as both the development and the smoothing of a relief. The effect of smoothing is usually observed either at ion energies below the sputtering threshold or at large incidence angles, when the sputtering coefficient is lower than that at normal incidence [17]. In the case of a reflex discharge, since plasma rotates, the angle of ion incidence onto the cathode surface can differ considerably from zero, which leads, in turn, to a modification of the sputtering coefficient. The dependence of the sputtering coefficient Y on the ion incidence angle θ is expressed by the formula [19]

$$Y(\theta) = Y(0)x^f \exp\left[-\Sigma(x-1)\right], \tag{2}$$

where $x = 1/\cos\theta$, and f and Σ are parameters that are either determined from the experiment or calculated. The results of corresponding calculations by formula (2) are shown in Fig. 3. The figure demonstrates that the angle, at which the maximum of the sputtering coefficient is observed, is equal to about 73°, and the sputtering coefficient at the maximum is approximately 3 times higher.

The total number of particles sputtered from the cathode surface within the time interval t equals

$$N_{\Sigma m} = \Gamma_i Y S_\Sigma t, \tag{3}$$

where $S_\Sigma = 0.01571$ m^2 is the total area of cathodes, Γ_i is the particle flux onto the cathode surface [m^{-2}s^{-1}], and t is the time [s]. The quantity Γ_i is determined as follows:

$$\Gamma_i = N_i v_s, \tag{4}$$

where N_i is the ion concentration [m^{-3}], and v_s the ion-sound velocity (the velocity of ion sound) determined as

$$v_s = 9.79 \times 10^3 \left(ZT_e/M_i\right)^{1/2}, \tag{5}$$

where T_e is the electron temperature [eV], M_i the ion mass [a.m.u.], and Z the ion charge. We adopt that the ion mass equals the mass of an argon atom, $M_i = 39.94$, and the electron temperature $T_e = (1 \div 10)$ eV to obtain $v_s = (1.5 \div 4.9) \times 10^3$ m/s.

As was indicated earlier in work [14], the time dependence of the average concentration in a gas-metal plasma can be divided into three stages: the formation,

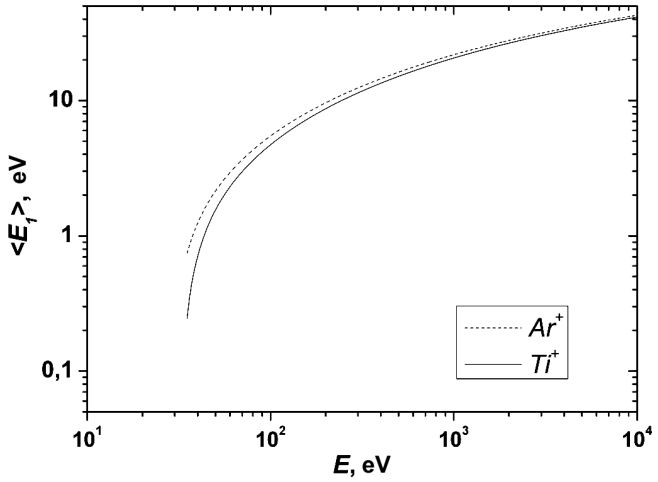

Fig. 4. Average energy of titanium atoms escaping from the target as a function of the incident ion energy

existence, and decay of a dense plasma. To estimate the total number of sputtered particles at the plasma formation stage, $N_{\Sigma m}$, we accept the variation of the particle concentration in time to be equal to that experimentally obtained in work [14], the time $t \approx 100$ μs, and the ion energy equal 0.8–0.85 times the applied voltage. In this case, the magnitude of $N_{\Sigma m}$ ranges from 7.5×10^{16} to 2.8×10^{17} particles, depending on the sputtering coefficient value. At the stage of dense plasma existence, the average sputtering coefficient is adopted to equal 0.02–0.26, and the time $t \approx 800$ μs, so that we obtain $N_{\Sigma m} \sim 10^{17} \div 10^{18}$ particles at this stage of the discharge, which is in agreement with experimental and theoretical results of work [15], $N_{\Sigma m} = 9.26 \times 10^{16} \div 8.5 \times 10^{17}$ particles.

3. Efficiency of Ionization Processes of Sputtered Atoms and Formation of Gas-Metal Plasma

The efficiencies of the processes of sputtered atom capture into the discharge and gas-metal plasma formation depend on two processes, namely, the diffusion and the ionization of atoms in the primary plasma. Let us consider these processes in more details.

According to the kinetic theory of gases, the diffusion coefficient equals [20]

$$D = \frac{1}{3}\lambda v, \tag{6}$$

where λ is the mean free path [m], and v is the velocity [m/s]. The characteristic diffusion time is equal to the time of particle arrival at the wall,

$$\tau_D = \frac{\Lambda^2}{D}, \tag{7}$$

where Λ is the characteristic diffusion length, which, in the case of cylindrical geometry, satisfies the relation

$$\frac{1}{\Lambda^2} = \left(\frac{2.4}{R}\right)^2 + \left(\frac{\pi}{l}\right)^2, \tag{8}$$

where R is the radius of the system [m], and l is its length [m]. In order to determine the mean free path from the energy of a sputtered atom moving in the gas, the atoms of which have the Maxwellian distribution over their velocities, one may use the expression obtained in work [21],

$$\lambda = \lambda_0 \left[\left(1 + \frac{1}{2\omega}\right) \mathrm{erf}\left(\sqrt{\omega}\right) + \frac{e^{-\omega}}{\sqrt{\pi\omega}}\right]^{-1}, \tag{9}$$

$$\omega = \frac{3}{2}\frac{E_1}{E_g}\frac{M_g}{M_m}, \tag{10}$$

where E_1 is the energy of a sputtered atom [eV]; E_g is the average energy of a gas atom [eV]; M_g and M_m are the masses of gas and sputtered atoms, respectively [a.m.u.]; $\lambda_0 = 1/N\sigma$; σ is the effective collision cross-section [m^2]; and N is the gas particle concentration [m^{-3}]. When a sputtered atom moves in the gas, its energy relaxes owing to collisions, and the average energy of atoms, E_F, at some distance from the sputtered surface can be estimated as [22]

$$E_F = (E_0 - kT_g)\exp\left[n \ln\left(\frac{E_f}{E_i}\right)\right] + kT_g, \tag{11}$$

where E_0 is the initial energy of a sputtered atom [J]; k is the Boltzmann constant [J/K]; T_g is the gas temperature [K]; $E_f/E_i = \Delta E/E = 2M_gM_m/(M_g + M_m)^2$ is the ratio between the energies after and before the collision; n is the number of collisions, which is determined by the formula $n = l_1 P\sigma/kT_g$, where l_1 is the path length [m]; and P is the gas pressure [Pa]. For the estimation of E_F, we adopt that $E_0 = \langle E_1\rangle$ and $T_g = 300$ K.

The average energy of atoms that escape from the target is determined as [23]

$$\langle E_1\rangle = 2U_s g(w), \tag{12}$$

where the function $g(w)$ looks like

$$g(w) = \left(\ln(w) + \frac{2}{w} - \frac{1}{2w^2} - \frac{3}{2}\right)\left(1 - \frac{1}{w}\right)^{-2}, \tag{13}$$

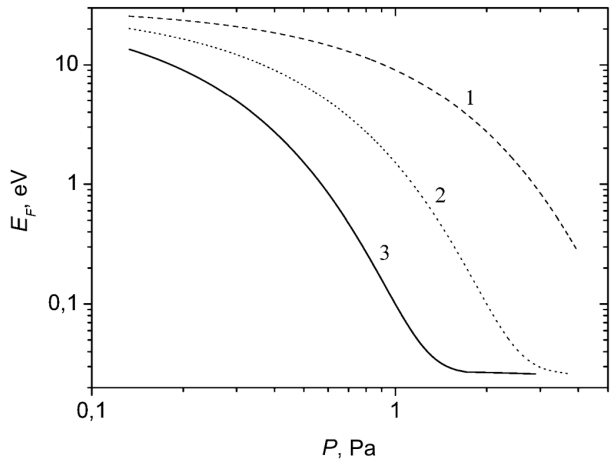

Fig. 5. Dependences of the average energy of sputtered titanium atoms on the argon pressure in a discharge chamber for various distances from the sputtered surface: 0.02 (*1*), 0.05 (*2*), and 0.1 m (*3*)

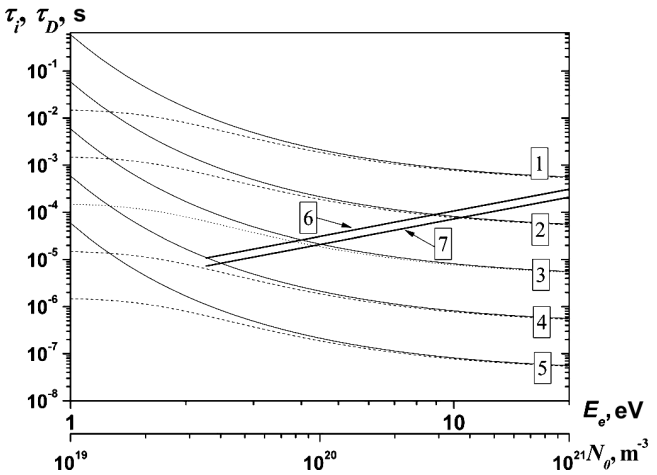

Fig. 6. Dependences of the titanium atom ionization time on the electron energy for various electron concentrations: 10^{16} (*1*), 10^{17} (*2*), 10^{18} (*3*), 10^{19} (1), and 10^{20} m^{-3} (*5*); and the dependences of the titanium atom diffusion time on the initial concentration of neutral particles of a working substance in the gas phase for various incidence angles $\theta = 73$ (*6*) and 0° (*7*). The dash-dotted and solid curves were calculated taking and not taking the charge exchange into account, respectively

and $w = E/E_{\rm th}$. The results of calculations carried out for the average energy of titanium atoms are depicted in Fig. 4. The calculated dependences of the quantity E_F on the gas pressure are shown in Fig. 5. It is worth noting that a reduction in the energy of sputtered atoms in the course of their motion in the gas (see Fig. 5) results in a decrease of the atomic path length; however, a considerable influence takes place, when the energy of sputtered atoms approaches the thermal one. Despite that the transport scattering cross-section is larger than the gas-kinetic one by not less than an order of magnitude, the collisions of sputtered atoms with gas ions prevail only at high gas ionization degrees.

The energy spectrum of sputtered atoms is described by Thompson's formula [24]. With regard for the anisotropic effects and the angle of ion incidence, it reads [25]

$$\Phi\left(E_1,\theta\right) \propto \frac{E_1\cos\theta}{\left(E_1+U_s\right)^4}\left(E_1\cos^2\theta+U_s\right). \qquad (14)$$

Using Eqs. (6)–(10) and averaging over the distribution function of sputtered atoms over the energy, which depends on the ion incidence angle, we obtain the average value for the time of sputtered atom diffusion to the chamber wall. The result of calculations is depicted in Fig. 6 (curves *6* and *7*).

Electron impact ionization is one of the main processes that give rise to the atomic ionization. In this case, the ionization time equals

$$\tau_i = \frac{1}{N_e\left\langle\sigma_e v_e\right\rangle}, \qquad (15)$$

where $\langle\sigma_e v_e\rangle$ is the rate of atom ionization by the electron impact [m^3/s] [26], and N_e is the electron concentration [m^{-3}]. An additional mechanism of ionization for titanium atoms can be the following processes [27]: (i) an ion charge exchange at an atom (the non-resonance charge exchange), $X^+ + Y \to X + Y^+ + \Delta E$ or $X^+ + Y \to X + Y^{+*} + \Delta E$, where ΔE is the mismatch of the process energy, which is equal to the difference between the ionization or excitation potentials of both colliding particles; (ii) ionization at the collision with a metastable atom (the Penning process), $X^* + Y \to X + Y^+ + e$. According to work [28], the rate of charge exchange for an argon ion with a titanium one is $k_{\rm CT} = 6.61\times10^{-15}$ m^3/s, and the rate of Penning process is $k_{\rm PI} = 2.75\times10^{-16}$ m^3/s. Therefore, the total ionization time, taking the additional processes into account, equals

$$\tau_i = \frac{1}{N_e\left\langle\sigma_e v_e\right\rangle + N_i k_{\rm CT} + N_m k_{\rm PI}}. \qquad (16)$$

As was shown in work [29], the Penning ionization dominates over the electron impact ionization in the concentration range below 2×10^{16} m^{-3} and at low temperatures. Therefore, at higher concentrations, it can be neglected. In Fig. 6, the dependences of the titanium atom ionization time are shown for various initial electron concentrations; the curves were calculated taking the non-resonance charge exchange into account and

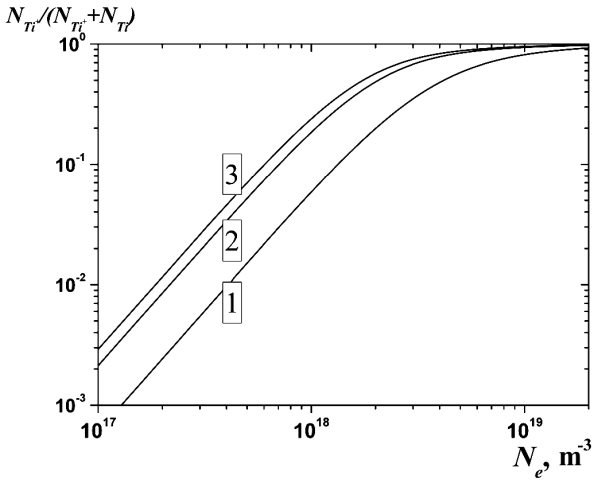

Fig. 7. Dependences of the titanium atom ionization degree on the electron concentration at various $T_e = 3$ (*1*), 6 (*2*), and 8 eV (*3*)

without this account (i.e. accepting $N_e = N_i$). One can see that the contribution made by the charge exchange becomes substantial only if $T_e \leq 3$ eV. A comparison between the characteristic times τ_i and τ_D (see Fig. 6) gives only a qualitative picture of the influence exerted by the processes of ionization and diffusion of sputtered atoms. However, it does not allow one to evaluate the ionization degree of sputtered atoms quantitatively. In the stationary case where the ionization by electrons is the major ionization process, the balance equations for particles in plasma can be written down in the form

$$\langle \sigma_e v_e \rangle N_e N_{\mathrm{Ti}} = \frac{N_{\mathrm{Ti}^+}}{\tau_{\mathrm{Ti}^+}},$$

$$\langle \sigma_e v_e \rangle N_e N_{\mathrm{Ar}} = \frac{N_{\mathrm{Ar}^+}}{\tau_{\mathrm{Ar}^+}},$$

$$N_e = N_{\mathrm{Ar}^+} + N_{\mathrm{Ti}^+}, \tag{17}$$

where N_{Ti} and N_{Ar} are the concentrations of neutral titanium and argon atoms, respectively; N_{Ti^+} and N_{Ar^+} are the concentrations of titanium and argon ions, respectively; and τ_{Ti^+} and τ_{Ar^+} are the corresponding lifetimes of ions in plasma. Taking Eq. (17) into account, the ionization degree can be expressed as follows:

$$\frac{N_{\mathrm{Ti}^+}}{N_{\mathrm{Ti}} + N_{\mathrm{Ti}^+}} = \frac{\langle \sigma_e v_e \rangle N_e \tau_{\mathrm{Ti}^+}}{1 + \langle \sigma_e v_e \rangle N_e \tau_{\mathrm{Ti}^+}}. \tag{18}$$

For the case of a pulsed discharge where the characteristic times of the plasma formation are shorter than the time of the ionization equilibrium establishment, the ionization degree strongly depends on the existence time of plasma with a given concentration. In our case, the characteristic times for concentrations of 1.4×10^{18} and 2×10^{19} m^{-3} to be attained are equal to 15 and 100 μs, respectively [14]. In the general case, in order to find the ionization degree, it is necessary to solve a system of differential equations. At the initial stage of plasma generation, the ion lifetime is usually larger than the time of the concentration growth, i.e. $\tau > t$. In view of this inequality, the system of equations looks like

$$\begin{cases} \frac{dN_e}{dt} = \langle \sigma_e v_e \rangle N_e N_{\mathrm{Ar}} + \langle \sigma_e v_e \rangle N_e N_{\mathrm{Ti}}, \\ \frac{dN_{\mathrm{Ar}}}{dt} = -\langle \sigma_e v_e \rangle N_e N_{\mathrm{Ar}} + N_{\mathrm{Ar}^+} N_{\mathrm{Ti}} k_{\mathrm{CT}}, \\ \frac{dN_{\mathrm{Ar}^+}}{dt} = -\langle \sigma_e v_e \rangle N_e N_{\mathrm{Ar}} - N_{\mathrm{Ar}^+} N_{\mathrm{Ti}} k_{\mathrm{CT}}, \\ \frac{dN_{\mathrm{Ti}}}{dt} = \frac{\Gamma S_\Sigma Y}{V} - \frac{N_{\mathrm{Ti}}}{\tau_D} - \langle \sigma_e v_e \rangle N_e N_{\mathrm{Ti}} - N_{\mathrm{Ar}^+} N_{\mathrm{Ti}} k_{\mathrm{CT}}, \\ \frac{dN_{\mathrm{Ti}^+}}{dt} = \langle \sigma_e v_e \rangle N_e N_{\mathrm{Ti}} + N_{\mathrm{Ar}^+} N_{\mathrm{Ti}} k_{\mathrm{CT}}. \end{cases} \tag{19}$$

To solve the differential equations numerically, let us set the initial conditions in accordance with experimental data [14]. Namely, the discharge voltage is 3.5 kV, i.e. $E \approx 2.8$ keV; the sputtering coefficients are taken in accordance with Figs. 2 and 3; the diffusion time of titanium atoms is taken according to Fig. 6; the variation of the electron concentration corresponds to the experiment; $N_{\mathrm{Ar}} = 7 \times 10^{19}$ m^{-3}; and, since $N_{\mathrm{Ar}} > N_{\mathrm{Ti}}$, the second equation in system (19) is ignored. The results of calculations for the dependences of the ionization degree of titanium atoms on the electron concentration and the temperature are presented in Fig. 7 (the electron distribution function over the energy was assumed to be Maxwellian). One can see that, at a concentration of 2×10^{19} m^{-3} ($t \approx 100$ μs), the ionization degree is close to 100%. The content of titanium ions averaged over the volume varies from 10 to 40%, depending on the sputtering coefficient.

As is seen from Figs. 6 and 7, the efficiency of the gas-metal plasma formation (or, equivalently, the introduction of a working metal substance into plasma followed by the metal atom ionization and the gas-metal plasma formation) governed by the mechanism of cathode material sputtering substantially depends on the initial plasma concentration. The highest efficiency of the gas-metal plasma generation is observed for the electron concentration $N_e \geq 10^{19}$ m^{-3} (see Figs. 6 and 7). In spite of the fact that our calculations were carried out for one cathode material – namely, titanium – a similar picture should be observed for other metals as well,

because their ionization potentials and ionization cross-sections are close to one another. This hypothesis is confirmed by the results obtained on an "ERIC" installation [12], where the ignition gases Ar and Kr were used. When Ni, Cu, Pd, and Gd atoms were introduced at $N_e = 4 \times 10^{16} \div 2 \times 10^{17}$ m^{-3} and $T_e = 3 \div 6$ eV, the ionization probability for sputtered atoms amounted to 4–14%, and the relative concentration of metal ions in plasma was 3–17%.

The proposed model can be applied at the initial stage of plasma formation, when the ion lifetime is longer than the time of concentration growth, i.e. $\tau > t$. In the other case, e.g., under stationary conditions, it is necessary that the ion lifetime should be taken into account (see Eqs. (17) and (18)); it consists of the recombination and diffusion times. The model does not consider the dependence of the sputtering coefficient on the target temperature, which considerably increases at $T > 0.7T_m$, where T_m is the melting temperature [17]. It also does not involve the cluster formation from two and more atoms, when the target is sputtered. In addition, there is an uncertainty in the angle of ion incidence onto the target. On the one hand, this fact is associated with initial conditions at the target surface (the surface relief). On the other hand, the angle of incidence is determined by the ion motion in crossed electric and magnetic fields before the ion collides with the target, so that the incidence angle can differ considerably from zero. However, the results obtained are in satisfactory agreement with experimental data [13–15]. Nevertheless, the estimations made with the use of the given model cannot be considered complete and ultimate. They demand that the model should be more specified according to the variation of experimental conditions.

4. Conclusions

1. According to the stated objective, a model for the quantitative estimation of the entry of heavy sputtered components into the discharge is selected. In the framework of the model used in this work, the evaluation of the parameters of a sputtering mechanism, owing to which the working substance penetrates into the discharge, is carried out. The influence of the incident ion energy is considered for the $Ar^+ \rightarrow Ti$ and $Ti^+ \rightarrow Ti$ ion-atom pairs in the cases of normal incidence and when the angle of ion incidence onto the target varies. The values of sputtering coefficient calculated numerically are in satisfactory agreement with experimental data obtained under similar conditions and published earlier in work [15]. The most rapid variation of the sputtering coefficient occurs at the energy of incident ions lower than or equal to 200 eV and at incidence angles of 40–85°.

2. To determine the efficiency of the gas-metal plasma formation (or, equivalently, the ionization of a gas-metal mixture), the following dependences are calculated: the dependences of the average energy of titanium atoms that escape from the target on the energy of incident argon and titanium ions and the pressure of argon in a discharge chamber; the dependence of the ionization time of titanium atoms on the electron energy; the dependence of the atom diffusion time on the initial concentration of neutral particles; and the dependence of the ionization degree of titanium particles on the electron concentration. The most effective generation of a gas-metal plasma is observed provided the electron concentration $N_e \geq 10^{19}$ m^{-3}. The results obtained agree well with experimental ones [13–15]. At the same time, the applied model should be additionally specified in the case where experimental conditions vary.

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ОЦІНЮВАННЯ ЕФЕКТИВНОСТІ
ВВЕДЕННЯ РЕЧОВИНИ У ВІДБИВНИЙ РОЗРЯД
ЗА РАХУНОК РОЗПИЛЮВАННЯ МАТЕРІАЛУ КАТОДА

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Р е з ю м е

У роботі розглянуто процеси, пов'язані з введенням робочої речовини у плазму імпульсного відбивного розряду за рахунок розпилюючого механізму з метою створення густої багатокомпонентної газометалевої плазми. При цьому запропоновано розрахункову модель оцінки параметрів розпилюючого механізму, за рахунок якого потрібна робоча речовина надходить у розряд. Одержані дані задовільно узгоджуються з результатами експерименту.