Numerical modeling of discharge characteristics of a planar magnetron with injection of electrons from auxiliary discharge

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Abstract. We present here a numerical model of a planar magnetron with electron injection from the plasma of an auxiliary discharge with the hollow cathode. The model is based on solving a system of stationary equations using the method of successive approximations. The model takes into account the effects of the current of the injected electrons, the operating gas pressure, the magnetic field induction, the flow of the target material into the plasma, and the change in the plasma mass-to-charge composition due to cathode sputtering by ion bombardment. Typical volt-ampere characteristics of a magnetron discharge with electron injection, as well as the mass-to-charge composition of the created gas-metal plasma, are calculated.

1. Introduction
A planar magnetron is a classical device used for depositing thin-films of metal-containing coatings, which are formed on a substrate by way of the cathode sputtering in a planar magnetron [1]. Since the operation efficiency of the planar magnetron depends entirely on the stable work of the gas discharge between the cathode and the anode in a magnetic field, the choice of the type of gas and the range of working pressure is usually limited [2]. As shown by experiments [3], the interval of the operating pressure can be essentially extended to lower values by making use of electron injection from the plasma of an auxiliary discharge with the hollow cathode through apertures in the planar magnetron cathode. These electrons, having built up energy in the cathode potential drop, additionally ionize the working gas, thereby increasing the plasma concentration and the discharge stability and ability to operate at a lower pressure, which has a positive effect on the quality (purity, stoichiometry, etc.) of deposited coatings [4]. Numerical modeling of physical processes in planar magnetrons have been carried out by a number of authors [5, 6]. Yet, specific features of the processes that determine the discharge characteristics of the planar magnetron with electron injection remain unclear despite the available experimental data. This is why it is deemed of a topical interest to develop a numerical model of a planar magnetron with electron injection.

2. Basic assumptions of the model
A planar magnetron is schematically shown in Figure 1. It is assumed that the plasma region has the shape of a disk and is bounded from below by the cathode end, and a ring-like anode from aside. Electrons, emitted from the cathode due to secondary electron emission, move in a magnetic field (for the sake of simplicity, the magnetic induction is assumed to be constant and equal $B$). The working gas is argon. The discharge current $I_d$ is independently set by an external power source. Additionally, the
model takes into account the injection of electrons from an auxiliary discharge which is controlled by the current $I_s$ and the energy determined by the cathode voltage drop $U_c$.

**Figure 1.** Schematic diagram of a planar magnetron with the injection of electrons.

Since the secondary electron emission is assumed to be the main mechanism that maintains the discharge, the cathode voltage drop $U_c$ will be directly determined by the energy of the ion-electron pair ($W_{iAr} = 30$ eV for argon and $W_{iCu} = 15.44$ eV for copper), as well as by the coefficient of the secondary electron emission $\gamma_{se}$ (assumed to be 0.1). In addition, ion sputtering of the copper target, determined by the sputtering coefficient $\gamma_{sp}$, results in the penetration of copper atoms into the inter-electrode space. By definition, the sputtering coefficient is the ratio of the flux of copper atoms $\Phi_{Cu}^{sp}$ knocked out of the target to the flux $\Phi_{iAr}$ of knocked-out argon ions

$$\gamma_{sp} = \frac{\Phi_{Cu}^{sp}}{\Phi_{iAr}} = \frac{n_{Cu}^{sp} v_{Cu}^{sp} S_t}{n_{iAr}^{sp} v_{iAr} S_t},$$

where $n_{Cu}$, $v_{Cu}$ are the concentration and velocity of knocked-out neutral copper atoms, $n_{iAr}$, $v_{iAr}$ are the concentration and velocity of argon ions moving towards the target, $S_t$ is the target area.

The sputtering coefficient is known to depend on the energy of ions incident on the target as follows [7]:

$$\gamma_{sp}(e_{iAr}) = \frac{0.06}{e_t} \sqrt{M_x} \left(\sqrt{\epsilon_{iAr}} - \sqrt{\epsilon_{th}}\right)$$

where $e_{iAr}$ is the energy of argon ions accelerated in the cathode voltage drop, $e_t = 3.11$ eV is the enthalpy of copper vaporization, $M_x = 60.62$ a.m.u. is the reduced atomic mass of argon and copper, $\epsilon_{th} \approx 124$ eV is the argon ion threshold energy for the sputtering onset.

According to references [8], the energy of knocked-out atoms ranges from 0.5 to 2 eV. Assuming the mean energy of knocked-out copper atoms $E_{Cu}$ to be 1 eV, one can estimate the velocity of copper atoms entering the plasma from the target

$$v_{Cu} = \sqrt{2E_{Cu}/M_{Cu}} \approx 1.7 \cdot 10^3 \text{ m/s}$$

The velocity of argon ions is determined by the near-cathode voltage drop $U_c$. Similarly to (3), one can write the expression for the argon ion velocity

$$v_{iAr} = \sqrt{2eU_c/M_{iAr}}$$

Thus, the dependence of the concentration of copper atoms on the concentration of argon ions, taking into account expression (1), can be written as

$$n_{Cu} = \frac{v_{iAr}}{v_{Cu}} \gamma_{sp} n_{iAr}$$

Electrons accelerated in the near-cathode layer collide with the working gas atoms or copper atoms and ionize them according to the ionization cross sections of the respective substances $\sigma_{iAr}$, $\sigma_{iCu}$, which in this model are set analytically from the referenced data [8, 9]. As a result, a gas-metal plasma is created, where the electron temperature is assumed to be 1 eV and the ion concentration $n_i$ being the sum of the argon $n_{iAr}$ and copper $n_{iCu}$ ion concentrations, is determined by the following expression
where $S_l$ is the target-cathode area, 

$$n_{i_{dr}} = \frac{I_d - I_g}{(1 + \gamma_w)S_l0.4e\sqrt{2kT_e/M_e}}(n_{e}\sigma_{de}[U_e/W_{de}])h, \quad n_{i_{Cu}} = \frac{I_d - I_g}{(1 + \gamma_w)S_l0.4e\sqrt{2kT_e/M_e}}(n_{Cu}\sigma_{iCu}[U_e/W_{iCu}])h \tag{6}$$  

Expression (6) represents the ion balance equation. The numerators in the right-hand side of the formulas for $n_{i_{dr}}, n_{i_{Cu}}$ describe the generation of argon and copper ions by electrons accelerated in the near-cathode voltage drop $U_c$, and the denominators represent the Bohm escape of ions from the plasma boundary to the target (only the target area $S_l$ is accounted for since its area is much greater than the area of the ring cathode).

Since the ions are not magnetized, and the boundary between the plasma and the cathode forms a plane-parallel gap, the density of the ion current from the plasma to cathode can be estimated from the Child-Langmuir formula

$$j_{i}(U_e) = \frac{4}{9}n_{e}v_{de} \left[ \frac{2e}{M_e} \right] \frac{U_e^{3/2}}{d_{i}(U_e)^{3/2}}, \tag{7}$$

where $U_e$ is the cathode layer voltage, $d_{i}(U_e)$ is the cathode layer length which can be approximated by the expression $d_{i}(U_e) = aU_e^{-2}$, where $a$ is a constant [10].

Equating expression (7) to the Bohm ion density from the plasma boundary, we arrive at the equation to determine the near-cathode voltage drop $U_c$

$$\frac{I_d - I_g}{1 + \gamma_w}\left[n_{e}\sigma_{de}[U_e/W_{de}] + n_{Cu}\sigma_{iCu}[U_e/W_{iCu}]\right]h/S_l = \frac{4}{9}n_{e}v_{de} \left[ \frac{2e}{M_e} \right] \frac{U_e^{3/2}}{d_{i}(U_e)^{3/2}} \tag{8}$$

The electrons are strongly magnetized, so when moving to the anode, they are forced to drift across the force lines of the magnetic field. In this case, the electron current density to the anode is defined by the formula

$$j_{e} = e\sigma_{de}v_{de}, \tag{9}$$

where $n_{e} = n_{i}$ is the plasma electron concentration that equals the concentration of ions, $v_{de}$ is the electron drift velocity across the magnetic field that can be evaluated using the formula

$$v_{de} = Eb_B \tag{10}$$

where $E$ is the electric field strength, $b_B$ is the mobility of plasma electrons across the magnetic field lines determined by the formula [11]:

$$b_B = \frac{b}{1 + b^2B^2} \tag{11}$$

where $b$ is the mobility of electrons in argon in the absence of a magnetic field determined by the formula

$$b = b_{0}\frac{T_{e}P_{e}}{T_{g}P} \tag{12}$$

where $b_{0} = 36$ m$^2$/V·s is the mobility of electrons in argon at $T_{0} = 0°C$ and pressure $P_{0} = 133.3$ Pa, $T_{g} = 300$ K is the gas temperature, and $P$ is the argon pressure.

Thus, using expressions (7) and (9), one can equate the ion current to the cathode to the electron current to the anode and derive the near-anode field $E$ from the resulting balance of currents $j_{i}(U_e)S_l = j_{e}S_a$:

$$E = \left[n_{e}\sigma_{de}[U_e/W_{de}] + n_{Cu}\sigma_{iCu}[U_e/W_{iCu}]\right] \left[ \frac{I_d - I_g}{1 + \gamma_w}\right]h/e/n_{e}b_{0}\frac{T_{e}P_{e}}{T_{g}P} \tag{13}$$

where $S_a$ is the area of the anode.

The discharge voltage $U_d$ is the sum of the near-cathode $U_e$ and the near-anode $U_a$ voltage drops, which can be estimated using the assumption that the near-anode field determined by (13) is applied on a characteristic scale of the order of the Debye length $\lambda_D$

$$U_d = U_e + E\lambda_D \tag{14}$$
To calculate the dependences, the main equations of the system (6, 8, and 14) were solved using the method of successive approximations using Minerr function (utilizing the Levenberg-Marquardt algorithm) from the default library of Mathcad software. The results of calculation are given below.

3. Results and Discussion
Figure 2 shows the modeled volt-ampere characteristics of the magnetron at different argon pressure and magnetic field induction.

![Dependence of the discharge current on the magnetron discharge voltage at different gas pressure (a, B = 0.1 T) and magnetic field induction (b, p = 0.1 Pa), Is = 0; Experimental I-V characteristics of magnetron with Cu cathode 115 mm in diameter: c) at B = 0.08 T and pressure I – 0.044 Pa, 2 – 0.1 Pa, 3 – 0.32 Pa, and d) at pressure p = 0.1 Pa and magnetic field strengths B of I – 0.025 T, 2 – 0.05 T, 3 – 0.08 T [12].](image)

As seen from Figure 2 (a), a decrease in the gas pressure leads to an increase of the discharge voltage, because at a lower gas pressure, generation of both gas and metal ions decreases (due to a decreased flux of gas ions to the target). Increasing the induction of the magnetic field at a fixed pressure (Figure
2, b) leads to a more efficient confinement of electrons in the plasma, higher degree of ionization and as a result to a lower discharge voltage at the same discharge current. Calculated experimental curves are in good agreement with experimental data for similar device and experimental conditions (Figure 2, c, d).

The effect of the injected electrons current \( I_s \) on the discharge voltage \( U_d \) is illustrated in Figure 3.

![Figure 3](image.png)

**Figure 3.** Dependence of the discharge voltage on the injected electrons current at different discharge current (a) and working gas pressure (b).

It follows from Figure 3 that increasing the injected electrons current leads to a decrease in the discharge current. Figure 3 (b) shows that the effect of the injected electrons current on the discharge voltage is much stronger than the effect of the gas pressure (Figure 3, b) at a fixed current of the injected electrons. The calculated dependences of the mass fractions of copper and argon ions in the plasma for two different argon pressures are shown in Figure 4.
Figure 4. Calculated fractions of copper and argon ions in the plasma vs. the beam current at a pressure of 0.1 Pa (a) and 0.044 Pa (b). Respective dependences for the concentrations (c, d); e) Influence of the magnetron discharge current $I_{mn}$ on the ion content in plasma at argon pressure $p = 0.1$ Pa [13].

It follows from Figure 4 that, due to the difference in the velocities of copper and argon ions, the concentration of copper ions amounts to the values comparable with the concentration of argon ions, at both elevated (Figure 4, a, c) and lowered (Figure 4, b, d) pressure. This is explained by the fact that the velocity of copper atoms near the cathode is much less than the velocity of argon ions hitting the target. Thus, copper atoms, and therefore their ions, are accumulated near the target, so that their concentration at a steady sputtering coefficient becomes comparable with the concentration of puffed argon. In this
way, the concentration of copper ions in the plasma can reach almost 100% at low argon pressure (Figure 4, b, d). Calculated trends are similar to the experimental data (Figure 4, e). At an increased pressure of the introduced working gas, the discharge is maintained mostly by the ionization of its atoms, while the copper atoms present in the plasma as an impurity. The situation changes with the lowering of pressure and increasing the discharge current, when the plasma ion component is represented mostly by copper ions knocked out of the target. The predominance of copper atoms in the plasma, ionization potential of which is lower than that of argon atoms, causes a decrease in the discharge burning voltage.

4. Conclusion
We have developed a numerical model of a planar magnetron with electron injection from the plasma of an auxiliary discharge with hollow cathode. It is shown that for such a magnetron, the volt-ampere characteristics, depending on the gas pressure and the magnetic field induction, on the whole, are similar to those of a planar magnetron without additional injection. Nevertheless, the current of electrons injected from the plasma of auxiliary discharge, allows the discharge burning voltage to be considerably lowered, which will have a positive effect on energy efficiency of the device. The model explains the main physical processes occurring in this device.

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