EXPERIMENTAL INVESTIGATION AND COMPUTER SIMULATION OF THE MAGNETRON SPUTTERING DEVICE WITH TWO EROSION ZONES

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There was built the self-consistent computer model of the magnetron sputtering device with two erosion zones of cathode-target, based on Monte Carlo algorithm. The magnetron sputtering device is an additional module for the industrial vacuum system VUP-5. The results of computer simulation and the experimental data from test targets sputtering on this magnetron sputtering device demonstrated their compliance in the identical conditions.

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INTRODUCTION

Magnetron sputtering is one of the modern methods of nanomaterials production. One of the ways of improvement the parameters of magnetron sputtering devices (hereinafter – MSD) is to create of a systems with many erosion zones of the cathode-target.

The MSD with two erosion zones of the cathode-target is the additional module for the industrial vacuum system VUP-5 [1]. The device (Fig. 1.) consists of the planar and circular cathode unit (with the diameter 74 mm) and annular anode (diameter is 86 mm and it is made of a copper tube with cross section 6 mm).

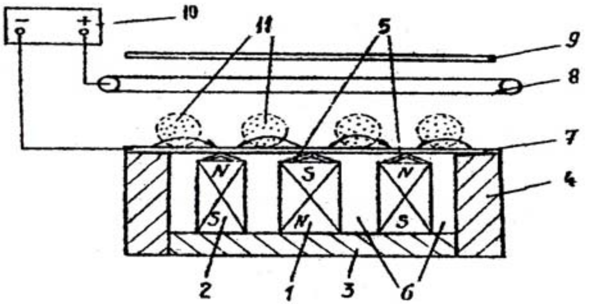

Fig. 1. The scheme of the MSD with two erosion zones [1]: 1 – the cylindrical magnet; 2 – the ring magnet; 3, 4 – the magnetic circuit; 5 – the pads on magnets for amplification of tangential to the cathode magnetic field; 6 – the cavity, which circulates the coolant; 7 – the cathode-target; 8 – the annular anode; 9 – the substrate to be coated; 10 – the power supply; 11 – the plasma of magnetized glow discharge in working gas (usually Ar)

1. ABOUT THE MODEL

For determine the parameters of the simulation the tangential and normal to the cathode components of the magnetic field of the MSD were measured by the magnetic inductometer with Hall probe (Fig. 2). From the measurements it was found, that at increasing of the distance to the cathode surface the magnetic field induction decreases in *e* times on 3.2 mm in the internal discharge zone and on 6.4 mm in the external one [2].

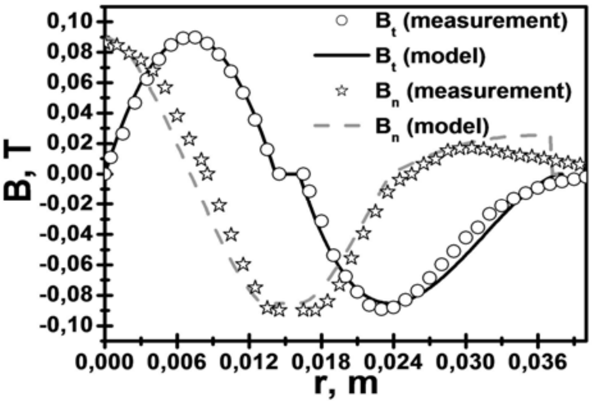

Fig. 2. The components of the magnetic field at the cathode surface along its radius r, (B_t – tangential and B_n – normal components)

The electric field was chosen as one-dimensional and parallel to the axis of the system. As in ordinary glow discharge the electric field intensity in the cathode layer (cathode sheath) is [2]:

$$E_h(h) = -(2V_0/d_E)\cdot(1-(h/d_E)), \qquad (1)$$

where: V_0 – the cathode voltage drop; d_E – the sheath width; h – the vertical coordinate in a cylindrical coordinate system, in which the starting point is at the cathode. Outside the cathode layer was considered that $E_h(h)$ = -25 V/m. To estimate the required width of the cathode layer d_E used reasoning similar to [2].

Based on the current density of ions at the cathode and the cathode voltage drop, obtained from the experiments, the width of the cathode layer was evaluated according to the Child-Langmuir law (according to [3]):

$$d_E = 2,43\cdot10^{-4}\cdot\left(U^{0,75}\Big/\left(M_i^{0,25}\cdot j_i^{0,5}\right)\right)\{cm\}, \qquad (2)$$

where U – the voltage on the cathode layer {V}, M_i – the mass of the ion in atomic mass units (M_i(Ar) = 40), j_i – the ion current density on the cathode surface {A/cm^2}. The discharge current I_d more over the ion current at $(1+\gamma)$ times, which γ – the ratio of secondary ion-electron emission, typically the $\gamma \leq 0{,}1$ [4].

The simulation program, written on C#, based on the integration of the equations of particles motion in crossed electric and magnetic fields [2]. The fourth order Runge-Kutta method used. For electrons, the time step is $\tau = 10^{-11}$ s, that far less than the period of the electron cyclotron rotation in the MSD magnetic fields. The time of the electron motion is limited to 2.5 µs, since under collisions with atoms of the working gas the electrons come out from the system earlier. For ions the time step is about 10^{-8} s, and near the cathode it decreases (also, the magnetic force was neglected).

At the initial time, secondary electrons emitted from random positions on the cathode. The probability of the particle collisions to atoms of the working gas at each time step was accounted by Monte Carlo method. The criterion of collisions is following [2, 5]:

$$Rnd < 1 - \exp\left(-\Delta s n_a \sigma(W)\right), \qquad (3)$$

where Rnd – the random number between 0 and 1, which was generated on each time step; Δs – the path which traced by the particle during the time step; $\sigma(W)$ – the collision cross section, which depends on the particle energy W; n_a – concentration of atoms in the working gas.

At this stage of the study the algorithm for self-consistency of the starting positions of the secondary electrons was introduced. In the self-consistency loop a limited number of electrons (~10^3) started at every step from the random positions on the cathode according to the distribution obtained in the previous step. This limitation allows speeding up the calculations, but also eliminates the direct effect of the coefficient γ. Similar to [6], the secondary electrons positions were considered as self-consistent when the number of created ions in the current step differs from the previous no more than 10 %. Then, the self-consistency cycle stops. Note: the motion and energy of ions are completely calculated only after ending of the self-consistency cycle, during which the positions of ionizations directly projected onto the cathode (with consideration of possible losses).

2. THE EXPERIMENTAL RESULTS AND ITS COMPARISON WITH MODELING

In the previous real experiments there was observed, that variation of discharge voltage within the limits that typically for this magnetron sputtering device, accompanied by the effect of individual ignition of internal and external zones of discharge [2]. This is typically for discharge currents up to I_d = 5…15 mA and for the corresponding voltages (if the pressure of working gas Ar was near p = 1.33 Pa). At the higher pressures (p = 6.65 Pa) both discharge zones are usually ignited. The computer calculation by using of the developed simulation program has showed the similar regimes [2]. At low pressures the cathode plasma sheath can be larger than d_E =3,2 mm. In this case, the electron confinement by magnetic field in the internal zone is less effective than in the external zone. The electrons in internal zone provides less number of ionizations unlike the external zone conditions when they have a good confinement and acceleration in the cathode sheath.

For checking of the modeling results, the test targets for this MSD were produced on it by deposition of the copper thin-film on the thin non-magnetic stainless steel plates (in Ar work gas at pressure p = 1,4 Pa, discharge current I_d = 40 mA, the time of the process was about 1 h). Before the processes, the vacuum chamber was unpressured to the level p = 6,65 mPa.

For the comparison, the two modes of the target sputtering were chosen – the *"low current"* (I_d = 8…10 mA, V_0 = 230 V), in which only the outer zone of discharge was seen clearly (Fig. 3,a), and the *"high current"* (I_d = 70mA, V_0 = 290 V), for which the both zones were ignited (Fig. 3,b). If zone of the discharge was ignited, the copper thin-film on the test target under this zone was completely eroded after the time span equals 30 min at "*low current*" mode and equals 10 min at "*high current*" mode.

When the MSD working at current I_d ~ 10 mA the internal zone is hardly noticeable, but can be included in the results of the targets sputtering. The width of corresponding erosion areas was defined from these experimental results. Then, the current densities were estimated of and the widths of the cathode layer from the expression (2) were calculated (Table). According to (2), the change of the discharge current I_d between 10 mA to 70 mA is accompanied by a decreasing of the cathode layer width by 1.68 times (see Table).

Some data for the cathode sheath evaluation

I_d, mA	*Inner zone radial position, cm*	*External zone radial position, cm*	*Sum area, cm^2*	*d_E, cm*
10 mA	0.6…0.9	2.25…2.85	11.03	0.2
70 mA	0.4…1.05	2.125…3.125	19.45	0.119

The wider cathode layers were used in the simulation due to the need to separate the two modes brighter (d_E = 3.2 mm at *"high current"* and d_E = 5.4 mm for the case of *"low current"* mode), because if the width of the cathode layer is strongly less than 3.2 mm then, both zones can be ignited, by the reason of effective magnetic confinement of electrons in this case. Also the real width of the cathode layer will be uneven along the radius of the cathode region, due to the above reasons [3].

The typical discharge behavior (ignition of the central zone only at high currents) and boundary correspondence of erosion zones in the experiment and in the simulation demonstrates the correctness of chosen approximations (see Fig. 3).

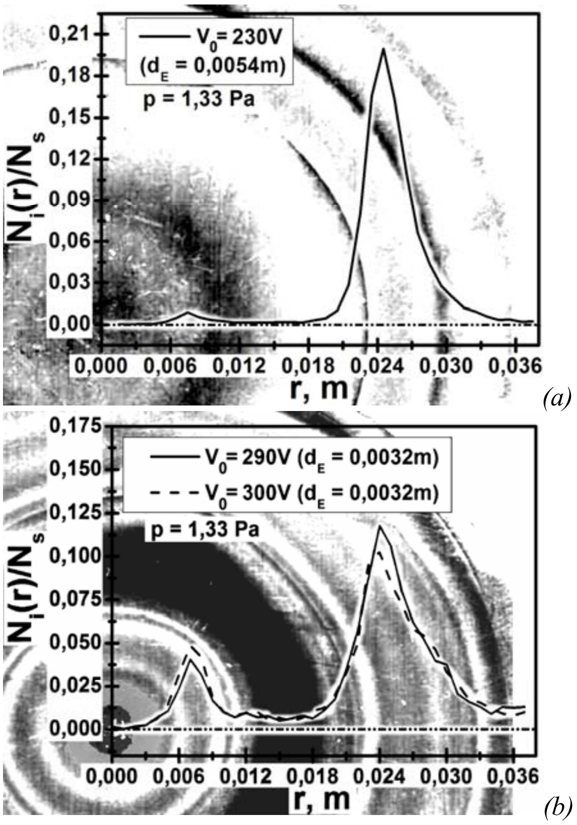

Fig. 3. These are photos of the test targets with the erosion zones under discharge current 8...10 mA (a) and 70 mA (b). The curves – are the simulation results. ($N_i(r)$ – the number of ions, which bombarded the target along its radius r, N_s – the total number of bombarding ions)

CONCLUSIONS

At this stage the computer modeling program of the magnetron sputtering device with two erosion zones takes into account the process of self-maintaining of the discharge. The algorithm of self-consistency of the secondary electrons starting positions on the cathode provides more clearly predict of the discharge modes in the corresponding ranges of voltages and currents. It has been demonstrated that experimentally observed areas of erosion of the test targets are coincidence for the results of the computer simulation.

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ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ И КОМПЬЮТЕРНОЕ МОДЕЛИРОВАНИЕ МАГНЕТРОННОГО РАСПЫЛИТЕЛЬНОГО УСТРОЙСТВА С ДВУМЯ ЗОНАМИ ЭРОЗИИ

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Построена самосогласованная компьютерная модель магнетронного распылительного устройства с двумя зонами эрозии катода-мишени. Использовался алгоритм Монте-Карло. Магнетронное распылительное устройство является дополнительным модулем для промышленной вакуумной установки ВУП-5. Сравнение результатов компьютерного моделирования и экспериментальных данных распыления тестовых мишеней на данном магнетронном распылительном устройстве продемонстрировало их соответствие при одинаковых условиях.

ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ ТА КОМП'ЮТЕРНЕ МОДЕЛЮВАННЯ МАГНЕТРОННОГО РОЗПИЛЮВАЛЬНОГО ПРИСТРОЮ З ДВОМА ЗОНАМИ ЕРОЗІЇ

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Побудована самоузгоджена комп'ютерна модель магнетронного розпилювального пристрою з двома зонами ерозії катода-мішені. Використовувався алгоритм Монте-Карло. Магнетронний розпилювальний пристрій є додатковим модулем для промислової вакуумної установки ВУП-5. Порівняння результатів комп'ютерного моделювання та експериментальних даних розпилення тестових мішеней на даному магнетронному розпилювальному пристрої продемонструвало їх відповідність за однакових умов.