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Study of the effect of argon pressure on the temperature of a hot target

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Abstract. In this work, thermal processes in direct current operating magnetron with hot titanium target are studied in Argon medium. Thermal processes are described by stationary, three-dimensional, heat equation with surface heat source which is the flux of argon ions from the gas discharge. The problem was solved numerically via the Heat Transfer Module in COMSOL Multiphysics Software.

Magnetron sputtering of metal targets in different gaseous media is of constant interest since it is used in many technical applications as a tool for the synthesis of inorganic films with different chemical compositions [1–3]. The progress in this area has led to the arising of magnetron with a hot target where the target surface temperature can be brought up to its melting point. Studies on this topic can be found in [4–7] and references therein.

In hot target magnetron, the sputtering rate is higher compared to the traditional cold target ones. Consequently, in hot target magnetron the growth rate of the film increases by an order of magnitude or more. Another distinguishing feature of hot target magnetron is that the crystalline structure of the thin film could be modified which may be useful in some specific applications. Moreover, the additional heating on the substrate due to the IR radiation from the surface of the hot target [9, 10], affects the film growth process. In this regard, the target temperature appears to be an important parameter for controlling the grow rate and the physical, chemical and electric properties of films. Therefore, the target temperature plays a central role in modeling the physical processes in hot target magnetron sputtering both in inert and reactive media [5, 11].

Boundary conditions for the heat equation are defined by the energy balance of metal heat, radiative heat and gas heat flux densities. The first two mechanisms were taken into account in [7] to study the impact of the target thickness and gas discharge power on the target temperature and it was shown that the second order polynomial fit gives a good agreement for temperature dependence on the discharge power and target thickness.

In the present work, the simulation of the thermal processes in the hot target is carried out by taken into account the gas thermal conductivity. As a result, the pressure of the gas is introduced in the model as new independent variable. The authors pursued two goals in this research: to develop a universal technique for solving the thermal problem for hot target magnetrons and to obtain fundamental knowledge about thermal processes occurring in these systems. Better understanding of thermal processes in hot cathode magnetrons is significant for the deposition of metal films.

Experimental studies were performed in vacuum chamber with a volume of 7.8×⟦10⟧^(-2) m3 and equipped with a flat magnetron. Titanium target with a diameter of 130 mm and thickness of 1 mm is fixed on chrome plate with a thickness of 4 mm. The cooling of the chrome plate is achieved by running water. The 1 mm gap between the target and the cooler filled with Argon gas is achieved by using a titanium ring. This gap reduces heat transfer from the target to the cooler which results an increase in the target temperature. The residual pressure in the chamber did not exceed 10–2 mTorr. Experiment was carried out in an argon atmosphere at (2–7) mTorr pressures and a discharge current of up to 10 A. Effective target temperature (the mean value of the target temperature averaged over the target surface) was measured using spectral method. The spectrum of the electromagnetic waves radiated from the target surface and the gas discharge were measured using a K3600 spectrometer (Research and Development company “Nordinkraft-Sensor”, Russia) with a spectral resolution of no more than 2.0 nm and absolute wavelength measurement error no more than ± 0.5 nm. The spectrometer is equipped with software which allows to analyze the black body radiation of the observed one. The uncertainty provided by this measurement set up is 50 K.

In order to take into account the thermal conductivity of the gas, simulation of thermal processes was carried out for the whole region inside the vacuum chamber. The mechanical designs of the magnetron sputtering system and the vacuum chamber given in figure 1 have been transformed into a 3D model, which is then used for numerical simulations in COMSOL Multiphysics (see figure 1).

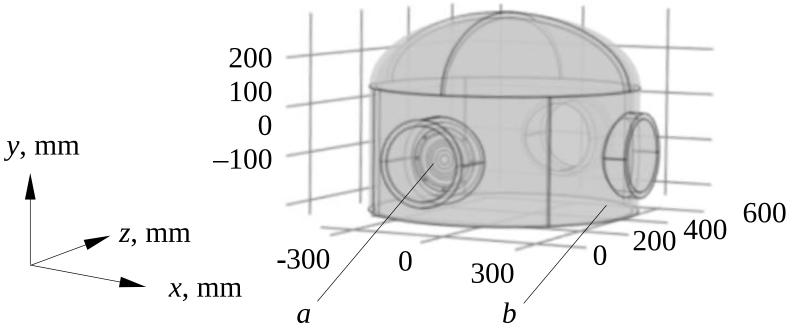

Figure 1. 3D model of the vacuum chamber (*b*) with sputtered unit (*a*).

On the walls of the vacuum chamber, Dirichlet boundary conditions are imposed. The boundary conditions on the magnetron sputtering system are given in [7] which are supplemented by the heat flux densities due to thermal conductivity of the argon gas (see arrows in figure 2). Heat removal process from the target surface (z = 0) due to the gas thermal conductivity is given by the boundary condition on the target surface.

Heat exchange process between the target lower surface ($z = z_1$) and the cooler upper surface ($z = z_2$) is described by the surface balance equation

$$\lambda_{\mathrm{Ar}}\frac{dT_{\mathrm{tag}}(x, y, z)\big|_{z=0}}{dz}=\lambda_{\mathrm{Ar}}\frac{T_{\mathrm{tag}}-T_{\mathrm{w}}}{0.5}, \tag{1}$$

$$\lambda_{\mathrm{Ar}}\frac{dT_{\mathrm{tag}}(x, y, z)\big|_{z=z_1,z_2}}{dz}=\lambda_{\mathrm{Ar}}\left(T_{\mathrm{tag}}-T_{\mathrm{cool}}\right)10^3. \tag{2}$$

where λ_{Ar} is the thermal conductivity of argon; T_w is the temperature of the chamber wall; T_{cool} is the temperature of the refrigerator plate. Condition (1) describes heat removal from a hot target. Conditions (2) – heat removal from the target and heat transfer to the water-cooled plate.

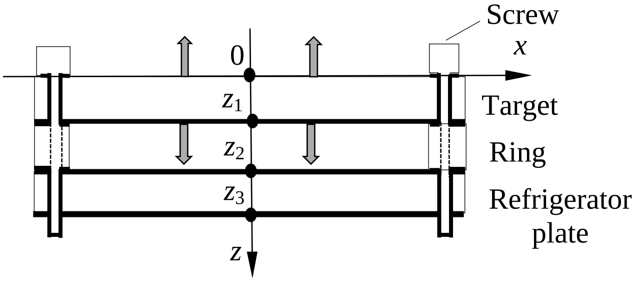

Figure 2. Thermal model of the sputtered unit. The *y* coordinate is perpendicular to the *xz* plane.

The calculation used data on the thermal properties of titanium [7]. The thermal conductivity of argon was obtained from the molecular kinetic theory of gases [12].

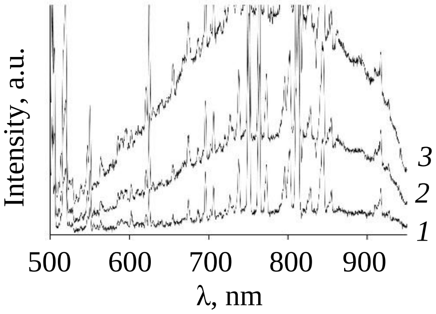

Figure 3. Optical spectra of the discharge at 2 mTorr and discharge current (A): *1* – 2.0; *2* – 4.0; *3* – 6.0.

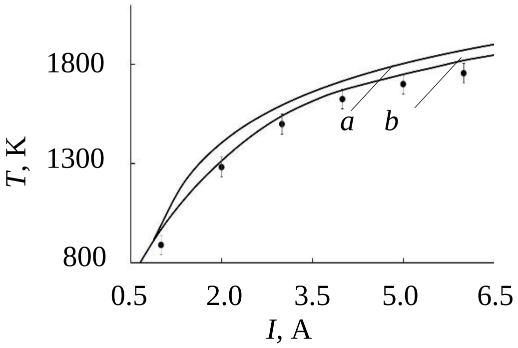

Figure 4. Target temperature at pressure (mTorr): *a* – 0; *b* – 2.0 (black dots – experiment).

In order to validate the modeling, we compare simulation results with the experimental data. The effective target temperature is determined by spectral method. Each spectrum in figure 3 has two components: continuous emission spectrum of the heated target (black body radiation) and emission spectrum line of the gas discharge. Black body radiation curve is used to measure the temperature. The temperature data at a pressure of 2 mTorr is given by black dots in figure 4. The simulation result at 2 mTorr is depicted by the solid curve b the same figure. It is apparent from figure 4 that the model curve is in good agreement with the experimental data within the uncertainty of temperature measurements. Simulation curve a in figure 4 corresponds to the case when thermal conductivity of argon is not taken into account. The target temperature in this case is larger than the one in the presence of the argon. This is due to the fact that the thermal conductivity of gas provides an additional mechanism for heat removal from the target surface.

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