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Coating deposition processes in the gas and vacuum modes of a planar magnetron sputtering system

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The results of comparative studies of the deposition of coatings in the gas and vacuum modes of operation of a planar magnetron sputtering system are presented. Copper was used as the model material of the sputtered target cathode. It is shown that higher deposition rates of coatings are achieved in the vacuum mode, their adhesive properties are improved and their roughness is reduced.

Keywords: magnetron sputtering system, self-sputtering, plasma, vacuum (gassless) mode, magnetron discharge.

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Introduction

Since their appearance in the mid-1970s [1] planar magnetron sputtering systems (MSS) have been actively developing and improving. This development is driven by constantly growing requirements for coating quality and equipment productivity. Reducing the operating pressure of magnetron sputtering systems is one of the main directions of research, since it makes it possible to reduce the number of transport losses of sputtered atoms and thereby increase the energy efficiency of the deposition process, as well as to enhance the energy impact on the substrate during coating deposition. The limiting case of reducing the operating pressure is the vacuum or gasless mode of MSS, in which the magnetron discharge is maintained in the so-called self-sputtering mode [2]. In contrast to the known gasless MSS with a liquid-phase cathode [3, 4], in a vacuum magnetron the temperature of the sputtered target cathode is much lower than the threshold values of the evaporation or sublimation temperature of the cathode material [5]. From magnetrons with

thermal evaporation, the vacuum mode of MSS with a "cold" target features favorably by higher values of the directed energy of sputtered atoms (more than 10 eV versus 0.1 eV) [6], as well as a higher degree of ionization of the atoms of the sputtered target. At the same time, the coating deposition rate in the vacuum mode of MSS is comparable to the vacuum-arc method, but at the same time does not require filtration of the generated flux from the microdroplet fraction.

Our earlier studies [6] were focused predominantly on comparing the parameters of the magnetron discharge and discharge plasma in the gas and vacuum modes of operation. The aim of this work was to compare the deposition processes and a number of coating parameters in these modes at a fixed value of the discharge current.

Methodology and technique of the experiment

A magnetron with a direct water-cooled cathode-target [6] was mounted on a vacuum chamber 60 cm long and 40 cm in diameter

(Fig. 1). Copper was used as the model material of the magnetron cathode-target. The diameter of target 2 was 100 mm. Anode 3 of the magnetron was connected to the grounded walls of the vacuum chamber. The arched magnetic field of the magnetron was provided by a set of NdFeB magnets 1. The body of the magnetron and the vacuum chamber were made of nonmagnetic stainless steel. The vacuum chamber was pumped down to a residual pressure level of 2×10^{-5} Torr by a turbomolecular pump with a capacity of 500 l/s. A specialized power supply APEL-M-20DC-1000SS (Applied Electronics LLC) was used for the electrical supply of the magnetron discharge.

In the gas mode of MSS, argon was used as the working gas. The operating pressure was 3×10^{-3} Torr. To implement the vacuum mode of the magnetron, the initial initiation was carried out in the presence of the working gas at a pressure of 3×10^{-3} Torr, after which the magnetron discharge current was set at a level of 10 A and the admission of the working gas into the chamber was shut off by a mechanical valve installed directly on the vacuum chamber. In this case, the pressure in the vacuum chamber decreased to values close to the residual pressure (2×10^{-5} Torr).

In deposition mode No. 1, a movable holder with a ruler of samples 4 was used to measure the axial and radial distribution of the coating deposition rate, making it possible to change the distance to the target from 20 to 50 cm. Samples with a size of 3×3 cm² were placed at a radial distance R from the axis of the discharge system equal to from 0 to 20 cm with a step of 5 cm. Silicon and glass substrates were used as samples. The thickness of the glass samples was chosen to be at least 4 mm, which ensured sufficient strength of the substrate for measuring the adhesion of coatings by the method of pulling off a glued contact pad.

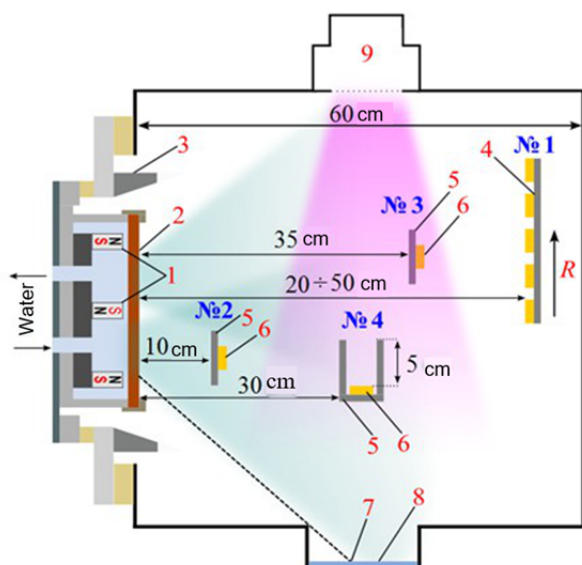
Before being placed in vacuum, the samples were cleaned with the use of an ultrasonic bath in alcohol and distilled water at a temperature of 60 °C for 60 min. Directly in the vacuum chamber, before the deposition process, the samples were subjected to additional ion cleaning

and surface activation using a plasma generator with electron injection [8]. The ion current density in the substrate region was $0.5 \div 1$ mA/cm² at a negative self-bias potential of the substrate of the order of 20–30 V. The duration of the ion treatment stage was 15 min. After that, the samples were covered with a shutter, the magnetron discharge was ignited, the deposition parameters were set, the shutter was opened, and the magnetron deposition process began. After the deposition process, the samples were held in vacuum for at least 60 min.

Experiments on deposition due to backscattering of sputtered atoms [9] were carried out in three modes. For deposition mode No. 2, a glass sample 6 with a size of 3×3 cm² was placed behind a screen 5 with a size of 5×5 cm² at a distance of 10 cm from the magnetron target. An similar experiment for mode No. 3 was carried out at a distance of 35 cm. In deposition mode No. 4, the sample was placed in a tube with an inner diameter of 7 cm at a depth of 5 cm from the end face, while the tube was rotated by 90 degrees relative to the magnetron axis.

The adhesion of coatings was measured by the method of pulling off along the normal to the sample surface on the so-called Sebastian machine, which is a second-class lever. The area of the contact pad was 0.2 cm². If the coating detachment did not occur over the entire surface of the contact pad, the surface area was recalculated to the actual one. The area of the glass samples made it possible to carry out multiple adhesion measurements on a single sample to collect statistics. The ultimate strength of the epoxy adhesive was 150 kg/cm².

An optical profilometer based on the Linnik interferometer (LOMO MII-4) was used to measure the coating deposition rate. A Solver P47 atomic force microscope (NT-MDT, Russia) using a CSG01 cantilever in contact scanning mode was used to study the surface morphology of the deposited coatings. Roughness was measured for three platform sizes: 1×1 μm², 5×5 μm², 15×15 μm². Subsequent image processing was carried out using the software packages Image Analysis 2.0 (NT-MDT) and Gwyddion.

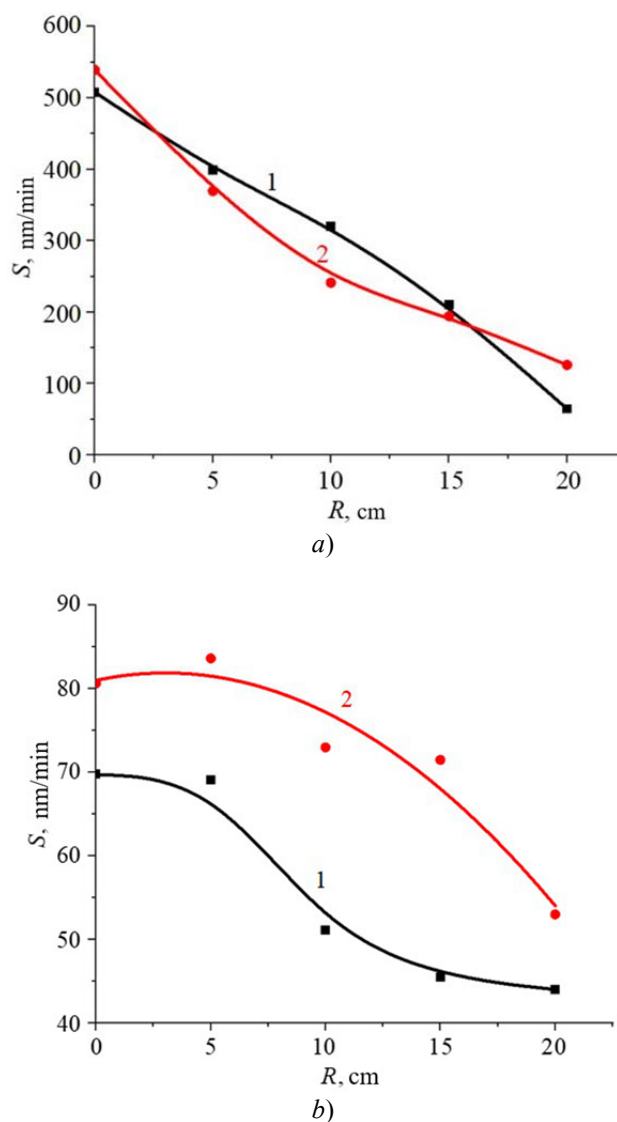


Results of experiments and discussion

Fig. 2 presents the radial distributions of the deposition rate for two values of the distance to the substrate. At distances of the order of two target diameters (20 cm), the deposition rate in the gas and vacuum deposition modes is comparable (Fig. 2a). The difference in the deposition rate in the vacuum and gas modes begins to manifest itself when distance increases. At a distance of 50 cm, the deposition rate in the vacuum mode exceeds the equal values in the gas deposition mode by a factor of 1.2–1.6 (Fig. 2b).

Simple evaluations show that the mean free path of a sputtered atom in the gas mode does not exceed 1 cm. Thus, even for deposition mode No. 2 (10 cm from the target), a sputtered metal atom can experience several collisions with working gas atoms with a change in the initial velocity vector. This conclusion is confirmed by the results of experiments on coating deposition on the back side of the sample. The small (< 100 nm) thickness of the deposited layer did not allow correct measurements using the MII-4 microinterferometer, but visually the dusting of the samples in the gas mode was many times

higher (Fig. 3) both in mode No. 2 and in mode No. 3. An equal effect was obtained for deposition mode No. 4 in the lateral direction at an angle of 90 degrees relative to the axis of the discharge system.



The ballistic deposition mode manifested itself in the vacuum mode of the magnetron as partial dusting of the viewing window with a characteristic sharp boundary 7 (see Fig. 1), determined by the protruding angle of the flange of the vacuum chamber in the path of propagation of the sputtered copper atoms. The part of the viewing window 8 located in the shadow region of the protruding angle of the vacuum chamber remained practically free from dusted even during

continuous operation of the magnetron for several hours. At the same time, in the first few minutes of magnetron operation, two characteristic boundaries of the deposition region were observed on the viewing window. Straight lines drawn from these coating boundaries through the protruding angle of the vacuum chamber pass through the far and near sections of the magnetron racetrack. The distance from the indicated sections of the racetrack to the boundary of the film on the surface of the viewing window was 50 cm. The formation of a sharp boundary 7 (Fig. 4b) of the deposited coating in the vacuum mode indicates the practically collisionless nature of the motion of sputtered atoms at the indicated distances. In the gas mode of the magnetron, the dusting of the

viewing window occurred uniformly over the entire surface, which can be explained by the scattering of the flux of sputtered atoms in collisions with working gas atoms (Fig. 4a).

The results of measuring the adhesion of coatings show that for all the studied values of the distance from the magnetron, the adhesion of coatings obtained in the vacuum mode is higher than for coatings obtained in the gas deposition mode (Table 1). With increasing distance from the magnetron target, the ratio of adhesion values in the vacuum and gas modes increases from 1.2 (at a distance of 20 cm) to 1.9 (at a distance of 50 cm). The decrease in the adhesion of coatings may be due to the loss of directed energy of sputtered atoms in the drift space in collisions with working gas atoms in the gas mode.

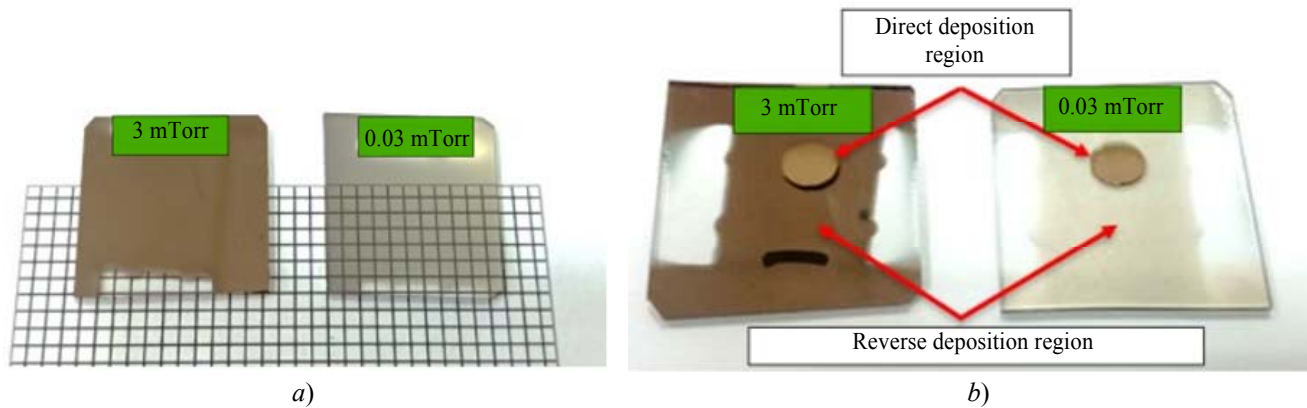


Fig. 3. Photographs of glass samples after deposition in the gas and vacuum modes of the magnetron:
a) $L = 10$ cm; b) $L = 35$ cm

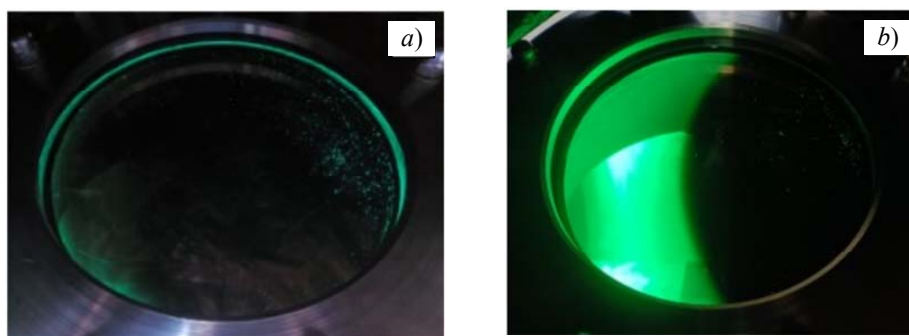


Fig. 4. Photographs of the deposited coatings on the viewing window after 30 min of magnetron discharge operation in the gas (a) and vacuum (b) modes. Discharge current 10 A

Table

Results of measurements of the adhesion of copper coatings for the gas and vacuum deposition modes depending on the distance to the magnetron

Distance from target to substrate	20 cm		30 cm		40 cm		50 cm	
	Gas mode	Vacuum mode	Gas mode	Vacuum mode	Gas mode	Vacuum mode	Gas mode	Vacuum mode
Coating adhesion, kg·f/cm ²	37	46	39	47	45	61	21	40

Coatings obtained in the vacuum mode are characterized by lower (on average by a factor of 1.5–2) values of the mean and root-mean-square coating roughness R_{mean} and R_{rms} , which amounted to 9 and 2.8 nm, respectively. This correlates with the results obtained earlier when reducing the operating pressure in the magnetron deposition process and may be due to the higher energy of the atoms arriving at the substrate and, as a consequence, greater mobility and denser packing of atoms [10].

Conclusion

The results of comparative studies of the coating deposition process in the gas and vacuum modes of operation of a planar magnetron sputtering system with copper as the model cathode material showed that the vacuum mode provides higher coating deposition rates, improves their adhesive properties, and reduces

surface roughness. The achieved parameters are due to the ballistic (collisionless) nature of the motion of the sputtered target atoms in the region from the magnetron cathode to the substrate being deposited. A consequence of this is weak effects of lateral and back scattering of sputtered atoms, which increases the efficiency of the coating deposition process in the vacuum mode of the magnetron using collimators. The obtained results unambiguously testify to the attractiveness of using the vacuum mode of MSS in the technology of creating metal coatings.

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Conflict of interests

The authors declare that they have no conflict of interests.

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