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INFLUENCE OF MAGNETIC FIELD CONFIGURATION AND STRENGTH ON PLASMA PARAMETERS AND EFFICIENCY OF COATINGS DEPOSITION IN MAGNETRON SPUTTERING SYSTEM

A.G. Chunadra[1], K.N. Sereda[1], I.K. Tarasov[2], V.A. Makhlai[1,2], B.M. Kozhukhovskyi[1]

[1]V.N. Karazin Kharkiv National University, Kharkiv, Ukraine;
[2]Institute of Plasma Physics, National Science Center "Kharkov Institute of Physics and Technology", Kharkiv, Ukraine

E-mail: agchunadra@gmail.com

Paper presents results of evaluation of the influence of the parameters of the additional anode electromagnetic trap for discharge electrons in a magnetron sputtering system. The efficiency of ionization processes is also investigated. It has been shown experimentally that a slight increase of the additional anode magnetic field leads to an increase of plasma density in the discharge on several times. The presence of an anode electromagnetic trap causes additional ionization zones. An increase of anode magnetic field leads to an increase of the average energy of charged discharge plasma particles. As the result, it was observed an intensification of the target material sputtering process as well as an increase of coatings deposition rate. In addition, a slight increase in the magnitude of the anode magnetic field has a positive effect on the quality and purity of the deposited coatings.

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INTRODUCTION

Magnetron systems are one type of gas discharge system that uses non-uniform crossed electric and magnetic fields. The electrical parameters of the discharge in the magnetron system largely depend on the operating pressure, the value and configuration of the magnetic field, and the design features of the sputtering system. Magnetron system is one of type the ion sputtering systems with bombarding of the target surface by working gas ions formed in the plasma of an abnormal glow discharge. The high speed of sputtering characteristic of these systems is achieved by increasing the ion current density by localizing the plasma near the sputtering surface of the target with a strong transverse magnetic field [1].

The discharge plasma electrons, which are generated as a result of the ionization of the working gas atoms, and the electrons re-emitted from the cathode under the action of ion bombardment, move along complex trajectories near the target surface. According to the principle of equally independent motion, the trajectories of electrons can be divided into three components.

An integral feature of magnetron systems is a non-uniform magnetic field above the surface of the target. Magnetic field lines have an arched configuration and rests by both ends on the target surface. The amplitude of magnetic field strength relevant to magnetron systems is usually 150...400 Oe. Choose of such value caused by requesting of electron magnetization without significantly influence to the ions motion. Electrons move from the surface of the target cathode along the magnetic field lines along trochoidal trajectories under the influence of an electric field. However, they are returned to the target surface due to the arched configuration of the magnetic field lines. An electric field caused deceleration, stopped and acceleration of electrons in the opposite direction along the line of magnetic field. Thus, electrons are trapped by a magnetic field turning them onto the cathode as well as by a negatively charged target surface push off them.

Other component of the electron motion path is a locked annular current, the so-called Hall current, above the surface of the target cathode, under the influence of the Lorentz force.

The transition of electrons to trajectories more distant from the surface of the target cathode and their movement towards the anode occurs as a result of collisions of electrons with atoms of the plasma-forming gas. An electron is displaced on average during one collision in the direction of the electric field by a distance of the order of the Larmor radius. Thus, in magnetron systems, the Larmor radius begins to play a role similar to the mean free path in discharges without a magnetic field.

So, electrons move over the target surface in an electromagnetic trap during a rather long time before reaching the anode and thus closing the gas discharge current in the magnetron sputtering system. The movement of electrons towards the anode occurs due to numerous ionizing collisions with atoms of the working gas. Thus, the loss of electrons from the discharge plasma as a result, them arrive to the anode does not lead to a decrease of the ionization process efficiency in working gas. Ionization processes lead to an increase of positive ions concentration at the target surface. This causes an increase of ion density which is bombardment of the target and a significant increase of sputtering rate as well as coatings deposition rate.

It should be noted that plasma-forming processes occur mainly in a magnetic trap in the immediate vicinity of the target. The creation of a magnetic trap near the sputtered target surface is a simple but rather effective solution to the problem of increasing the sputtering rate in plasma sputtering systems. Since the magnetic field with high intensity begins to significantly affect the movement of ions, directing them not in the direction of the target surface.

However, there are certain limitations associated with the impossibility of increasing of the magnetic field strength for a more efficient confinement of electrons and intensification of ionization processes. As, a magnetic field with a high strength has been begin to significantly affect the movement of ions, directing them in the direction of the target surface. In addition, a strong magnetic field slows down the movement of electrons towards the anode due to a decrease in the Larmor radius. That is provides electric resistance to the discharge current, reducing its value.

In this paper, we investigate the increase of efficiency of the magnetron sputtering process in order to use this method for the deposition of coatings from heavy materials, such as tungsten. It is proposed to use a modified magnetic configuration in the inter electrode gap by forming an additional magnetic trap for discharge electrons. The so-called magnetic isolation of the anode avoids an increase of magnetic field strength near the target surface. An increase of the magnetron sputtering process efficiency occurs due to the appearance of an additional ionization zone in the near anode region of the discharge gap [2].

1. EXPERIMENTAL EQUIPMENTS

Experiments were carried out using a standard planar MSS of type MAG-5 equipped with a tungsten target of 110 mm in diameter. MSS has an anode magnetic isolation system, which is provided the formation of an additional near-anode magnetic trap for discharge electrons [3].

The near-anode magnetic field was created by permanent neodymium magnets. The number of such magnets actually determines the value of strength and configuration of the near-anode magnetic field. The effect of the additional magnetic field value on the electric parameters of the discharge and the efficiency of spraying the target material was investigated in the experiments. Installation of 24 magnets ensured the generation of the near-anode magnetic field with a strength of 290 Oe.

Any electrodes of the discharge system were not grounded for maximum localization of the discharge area.

The ultimate pressure in the vacuum chamber was approximately $3{\cdot}10^{-3}$ Torr, controlled by varying the working gas (*Ar*) flow directly to the discharge area and pumping speed.

In experiments, tungsten coating was deposited on substrate (glass with very low roughness) at follow stationary magnetron discharge parameters of U_d = 550 V, I_d = 0.5 A during 300 s.

A single voltage pulse was applied between the cathode and the MSS anode additional to a stationary magnetron discharge. A voltage value of U_{pulse} = 1.5 *kV* and duration of τ_{imp} = 1, 2, 3, 4, and 5 ms was applied. Generation of such pulses was provided by means of relaxation generator with discharge of capacitor to inter electrode gap of MSS accompanied by the forced cutoff and short-circuit of capacitor on equivalent load.

The discharge current was measured using the Rogovsky belt during the experiments. Measurements of electron and ion energy distribution functions were carried out using a multi-grid energy analyzer (three-electrode probe), which was located directly above the cathode sputtering zone [4, 5]. Extraction of the analyzed particles was carried out through a screen become under floating potential. The functions of electron and ion energy distribution were calculated from the measured delay curves.

The determination of the mass transfer efficiency of tungsten was carried out by defect masses measurements. The estimation of deposed material mass per unit area (ρ, g·cm^{-2}) was performed on the base of measurement of changing sample mass before and after coatings deposition.

2. RESULTS OF EXPERIMENTS AND DISCUSSION

Measurements of mass transfer efficiency show that tungsten coatings with a weight of 0.87 mg (± 1.5%) deposited at stationary magnetron discharge with parameters U_d = 550 V, I_d = 0.5 A, $3{\cdot}10^{-3}$ Torr and duration of deposition of 300 s. The test sample was placed at a distance of 100 mm from the target. At determining the mass of the coating deposited at pulsed mode, it was taken into account that this fraction of the mass is provided precisely by a stationary discharge with addition of a single high-voltage voltage pulse.

The dependencies of the mean current (*I*, A) and mass transfer (ρ, g·cm^{-2}) on pulse duration are shows in Fig. 1. At the pulsed mode, the coatings were deposited at constant pressure and parameters of a stationary discharge. The value of the maximum pulsed current varied in the range I_{imp} = 0.5…8 A. The duration of the high-voltage voltage pulse was varied in the range τ_{imp} = 1…5 ms.

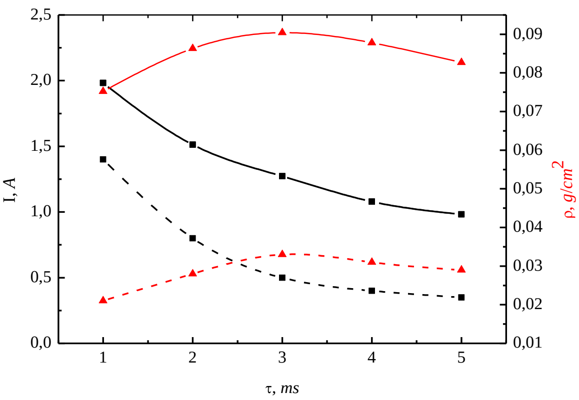

Fig. 1. Average current value (I, A, black line) and mass transfer (ρ, g·cm^{-2}, red line) in depended on pulse duration. Solid line corresponds to near-anode magnetic field of 290 Oe, dashed – 200 Oe

The value of the average discharge current decreases with increasing duration of the voltage pulse. At the same time, the value of mass transfer per unit area of the sample has the greatest value at the voltage pulse duration of 3 ms (see Fig. 1). This is due to the feature of the discharge of the storage capacity in the relaxation generator [6]. However, a comparison of the values of the average discharge current and mass transfer at different near-anode magnetic field shows that a slight increase of the field value leads to an increase of the average current and mass transfer by several times.

Figs. 2, 3 shows the distribution functions of electrons and ions at various values of the near-anode magnetic field in the stationary and combined stationary-pulse modes of magnetron discharge.

The presence of several maxima on the distribution functions indicates on the formation of additional spatially separated ionization zones in the near-anode gap. An increase of anode magnetic field leads to intensification of the ionization processes and increases the density of charged particles in the discharge plasma.

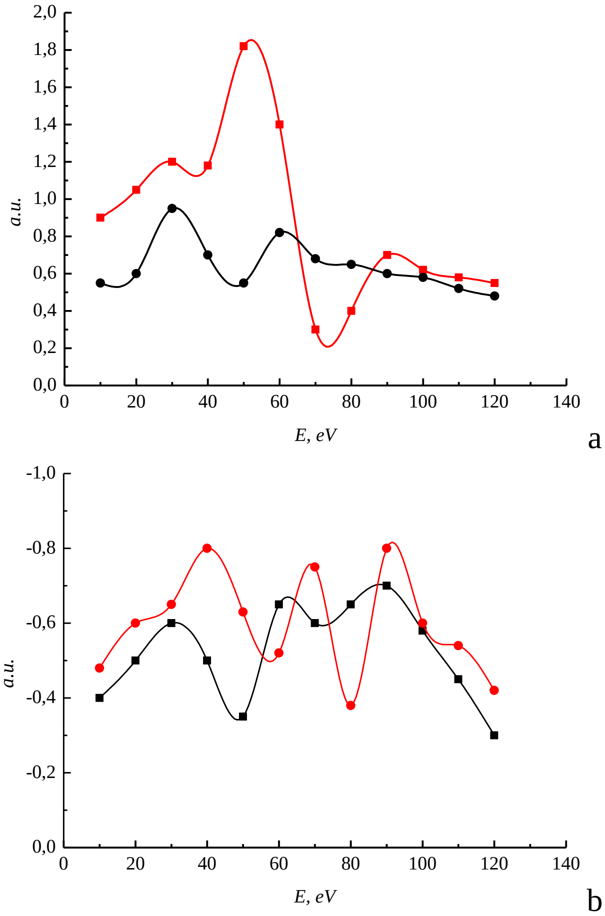

Fig. 2. Ion (a) and electron (b) component of MSS distribution function in stationary discharge combustion mode at cut-off voltage 150 V. The black line corresponds to the case of the intensity value of the near-anode magnetic field 200 Oe, red – 290 Oe

A double probe was used for evaluation of plasma temperature and density. Processing of volt-ampere characteristics of such probe could estimate the following values of the electron temperature $T_e = 2.96$ eV and plasma density of $n_i = 7.86 \cdot 10^{12}$ cm^{-3} for stationary mode of MSS operation. Parameter $T_e = 3.38$ eV and $n_i = 1.71 \cdot 10^{13}$ cm^{-3} was characterized plasma in the combined stationary-pulsed mode of MSS operation with the increase magnetic field near anode. Thus, the value of the plasma density was increasing up to 2.2 times at growth the near-anode magnetic field from 200 to 290 Oe.

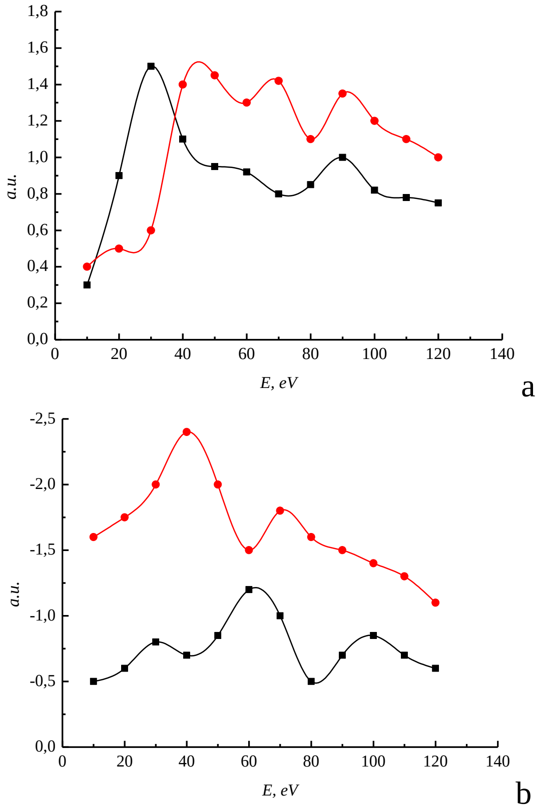

Fig. 3. Ion (a) and electron (b) component of MSS distribution function in combined stationary-pulse mode of discharge combustion at cut-off voltage of 150 V. The black line corresponds to the case of the intensity value of the near-anode magnetic field 200 Oe, red – 290 Oe

Finally, the surface and elemental composition of the applied tungsten coatings were examined using a scanning electron microscope with an energy dispersion X-ray analysis system (JEOL with X-ray analyzer LINK). The obtained results showed that at not so large increase of the near-anode magnetic field value (from 200 to 290 Oe*)* the weight ratio of the obtained tungsten increases from 75 to 90% in the stationary mode of the magnetron discharge as well as from 81 to 95% in the combined stationary-pulsed mode. It should be note the weight ratio of tungsten was 53% for stationary operation and 67% for combined stationary-pulsed mode without magnetic insulation of the anode.

CONCLUSIONS

The paper demonstrates the possibilities of improvement of the magnetron discharge parameters in a standard magnetron sputtering system (MSS) type MAG-5 with an anode magnetic trap. The influence of the parameters of the additional anode electromagnetic trap for discharge electrons in such system on the efficiency of ionization processes is investigated.

It has been shown experimentally that a slight increase of the additional anode magnetic field value leads to an increase of the discharge plasma density up to several times. It is shown that the presence of an anode electromagnetic trap causes additional ionization zones, and an increase of the anode magnetic field leads to an increase of the charged particles average energy in discharge and, consequently, to intensification of target material sputtering and coating rate.

The possibilities of MSS with such a magnetic configuration for the deposition of coatings of materials with a low sputtering coefficient have been investigated.

It is shown that a slight increase of the anode magnetic field magnitude has a positive effect on the quality and purity of the deposited coatings.

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ВПЛИВ КОНФІГУРАЦІЇ І НАПРУЖЕНОСТІ МАГНІТНОГО ПОЛЯ НА ПАРАМЕТРИ ПЛАЗМИ ТА ЕФЕКТИВНІСТЬ ОСАДЖЕННЯ ПОКРИТТІВ В МАГНЕТРОННІЙ РОЗПОРОШУВАЛЬНІЙ СИСТЕМІ

А.Г. Чунадра, К.М. Середа, І.К. Тарасов, В.О. Махлай, Б.М. Кожуховський

Представлені результати оцінки впливу параметрів додаткової анодної електромагнітної пастки для розрядних електронів у системі магнетронного розпилення. Також досліджена ефективність процесів іонізації. Експериментально показано, що незначне збільшення додаткового анодного магнітного поля призводить до збільшення щільності плазми в розряді в кілька разів. Наявність анодної електромагнітної пастки викликає додаткові зони іонізації. Збільшення анодного магнітного поля призводить до збільшення середньої енергії заряджених частинок плазми розряду. У результаті спостерігалося посилення процесу розпилення матеріалу мішені, а також збільшення швидкості нанесення покриттів. Крім того, незначне збільшення величини анодного магнітного поля позитивно впливає на якість і чистоту нанесених покриттів.