Significance of Self-Sputtering Effect for the Magnetron Discharge

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Abstract – The role of the sprayed atoms for physics of the magnetron discharge was studied. For this purpose the following has been made. The phenomenological model of magnetron discharge has been created on basis of probe measurements of cathode potential drop [1]. Ionization rate of operating gas, plasma density depending on discharge current, coordinate distribution of ion and electron components of discharge current, energy distribution of accelerated argon ions on target surface had been calculated. It is shown that cathode potential drop is characteristic of DC magnetron sputtering system and main processes caused material sputtering take place within a several millimeters distance from a target surface.

The operation of a high power density magnetron source in standard and self-sputtering modes are discussed. To understand main properties of the magnetron in self-sputtering mode the light emissive spectra was received and investigated for various conditions of magnetron operation. It is shown that the magnetron based on liquid-metal sputtering process has high rate deposition and able to operate under self-sputtering mode [2]. It is shown, that the mode of self-sputtering plays a main role in the physicist of the category, after the certain level of capacity.

1. Introduction

Electric discharge in a rare gas medium, containing crossed electric and magnetic fields is widely used in a different plasma devices and plants for material sputtering and thin films deposition.

However there is no a generalized model of magnetron discharge, which is able to predicate electrophysical characteristics and sputtering target kinetics. One of a cause of it is a poor idea about spatial distribution of potential within a diode discharge gap.

One of the most perspective technologies of the coating production is the magnetron sputtering of metal from a liquid phase target. It allows combining advantages of two thin film deposition methods as vacuum evaporation and ion sputtering. The films, created by means of the first way are featured by high deposition rate and purity, but have poor adhesive. The magnetron sputtering process is more convenient, allows creating of chemical compounds and ensures the more small fractionating during multicomponent target sputtering [3].

The mode of self-sputtering is very important for the magnetron with a liquid-metal target.

2. Measurement of the electric potential distribution

The dimension of intensive ionization area have less than 3 mm. Our calculations have shown it [4].

Plasma potential measurements in a cathode region of magnetron discharge by means of probe diagnostic are very difficulty that is bound up with a strong magnetic field presence. Therefore we had measured a floating potential of Langmuir probe under the zero current in its circuit. As floating potential is always negative with respect to undisturbed plasma [5, 6], the changing of real plasma potential by floating potential is acceptable.

A probe of 0.3 mm length made from nichrome wire 0.6 mm in diameter was used. Experiments had been operated with titanium target magnetron of 120 to 440 mm dimension. Maximum magnetic induction on the target surface was amount to ~0.08 T.

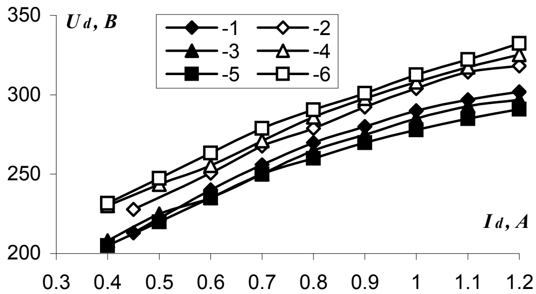

Fig. 1. Volt-ampere characteristics of magnetron and probe potential relative to cathode under different distance from probe to target surface: 1, 2 – 14 mm; 3, 4 – 6 mm; 5, 6 – 4 mm

In Fig. 1 volt-ampere characteristics and probe measurements of discharge potential are presented under different distances from probe to target. Mismatch of curves 2, 4, 6 characterizes inaccuracy introduced into measurement result by the probe (about 10 %).

Distance between pair of curves in potential scale characterizes a voltage dropped in a probe-anode region. This voltage drop is practically constant and does not dependence on discharge current.

On the basis of finding we can conclude that discharge region may be divided into two parts – magnetron discharge from cathode surface to several millimeters and non-self-maintained discharge extending to anode surface.

3. Discharge characteristics

Chamber walls were used as anode of discharge gap. Fig. 2 presents spatial distribution of floating probe potential measured in the center of target erosion zone at different voltage and argon pressure equal to 0.3 Pa ($7 \cdot 10^{19}$ m^{-3}). Location and dimension of probe are shown by line segment in the picture.

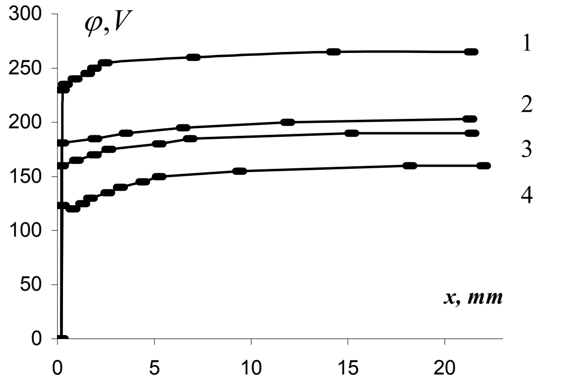

Fig. 2. Floating probe potential, measured to cathode of discharge gap under different voltage: 1 – 285 V; 2 – 225 V; 3 – 215 V; 4 – 195 V

As it is shown in Fig. 2 each curve 1–3 may be conditionally divided into three linear parts with different angels of inclination to abscissa axis. This is presented the dependence of probe floating potential on distance from cathode surface, drawing within a confidence interval.

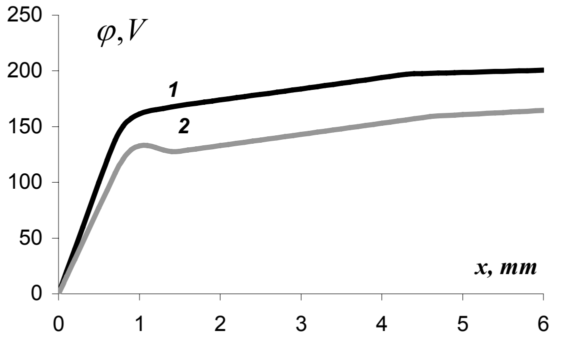

Fig. 3. Floating probe potential constructed within the limits of a confidence interval: 1 – 225 V; 2 – 195 V

Curve 4 more complex owing to presence of the superfluous negative charge area. On Fig. 3 the curves 2, 4 traced within the limits of a confidence interval are presented.

Assumed that probe potential agrees with electric potential within discharge gap. Electric field may be found by differentiation of the electric potential.

On Fig. 4 shows experimentally measured magnetic field and electric field distribution, calculated by differentiation of the electric potential. Using the Poisson's equation the distribution of excess charge may be found.

$$(n_i - n_e), 10^{16} m^{-3}.$$

As one can see in Fig. 5 two regions of increased positive charge density are exist. First region lies in the distance is about 1 mm away from target surface. Excess density of positive ions here is about $3 \cdot 10^{16}$ m^{-3} for voltage equal 225 V. The main part of the fall electric potential takes place in this region. This sheath is responsible for argon ion acceleration.

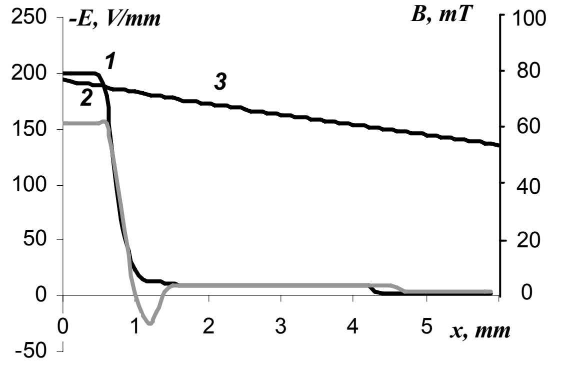

Fig. 4. Spatial distribution of electric (curve 1 – 225 V, curve 2 – 195 V) and magnetic (curve 3) field

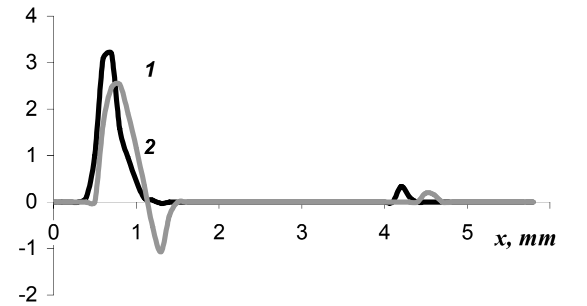

Fig. 5. Spatial distribution of the excess charge for various voltage on the magnetron: 1 – 225 V; 2 – 195 V

Second region lies in 4 mm distance from target. Surplus density of charge supports in this region is about $2.5 \cdot 10^{15}$ m^{-3}. This region promotes extending of electrons from working gas intensive ionization area.

At a low voltage discharge 195 V there is the area of the superfluous negative charge.

When the discharge voltage increases, the function of spatial distribution of the superfluous positive charge moves to the left, the concentration of a positive superfluous charge increases, the magnetron discharge comes nearer to a surface of the target.

4. Structure of magnetron discharge

It is known, that the discharge zone can be divided into two sites conditionally. On the second it is necessary approximately 25 V irrespective of the magnetron voltage $U_c = U_d - U_e$, where U_d – voltage discharge, U_c – voltage of the area discharge with ion and electron current, U_e – voltage of the area discharge with electron current.

We use Chaild – Langmuir equation [7] of the cathode area for calculation of the size of intensive ionization zone

$$J_i = \frac{4}{9}\varepsilon_0 \frac{2e^{0,5}U^{1,5}}{M^{0,5}d^2}, \quad (1)$$

where J_i – ion current, M – ion mass, d – thickness of a zone of the main decline in potential, U – voltage on distance d from the target, e – electron charge, ε_0 – permittivity. It is possible to accept, that $U=U_c$ with a high degree of accuracy.

In the current direct magnetron discharge the basic share of a current in dark cathode space is transferred by ions [8]. In [3] it is shown, that this part makes 0,925 and 0,975 for aluminium and copper targets accordingly. Let's accept its equal 0,95 for the approached calculations. Thus J_i=0.95J_d, where J_d – common current discharge.

The basic part of the decline in potential is concentrated on area of dark cathode space in the classical gas discharge. Our case d it is equal to distance from the target up to external border of a zone of intensive ionization (about 0,8 mm). It is visible from Fig. 2–5.

Thus, for argon

$$J_d = 9{,}16*10^{-9}\frac{U_c^{1,5}}{d^2}. \quad (2)$$

Let's calculate the characteristic sizes of a zone of intensive ionization. We use dependence of the probe potential as function of discharge current (U_d=U_e+U_z) from Fig. 6 and we consider, that U_c=U_z. On Fig. 7 potentials of a probe are presented as function of the voltage discharge for a case when the probe was on distance of 4 mm from the target surface. At the voltage discharge less than 250 V the width of this zone makes some millimeters. Then it decreases in some times in process of its growth.

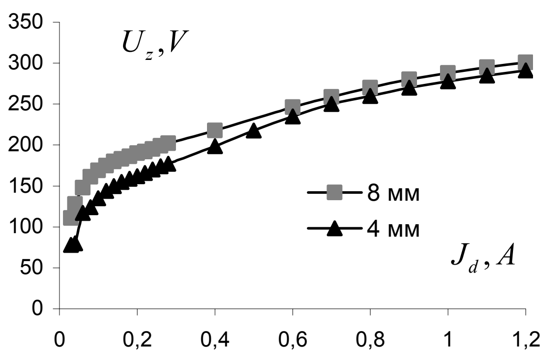

Fig. 6. Probe potential as function of current discharge for different distance from target surface

This fact testifies to spasmodic change of the processes proceeding in the discharge. Let's consider the phenomena caused by increase of voltage discharge to understand an essence of effect.

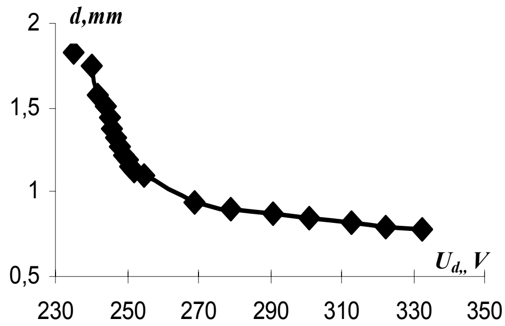

Fig. 7. Thickness of a zone of the main decline in potential as function of the voltage discharge

It is possible to make the following conclusion of the analysis of the presented curves about the mechanism of the magnetron discharge. When voltage discharge is below the certain size (for a case of our pressure and distribution of a magnetic field it lays between 195 V and 225 V), the discharge on the properties is similar on glow discharge. Difference consists that the magnetic field causes Hall current (concerning small on size) which circulates near to a target, does not allow to be generated in a classical kind to the first cathode luminescence and dark space Aston [10]. Instead of four areas – the dark space Aston, the first cathode luminescence, dark cathode space and the second cathode luminescence two zones – dark cathode space and the cathode luminescence are formed.

Electrons of the Hall current have energy, sufficient for ionization of argon, only in the field of the order of 1 mm from a surface of a target. They generate the charge carrier according to the distribution presented in [5].The electric field stretches the charge carrier in the different parties from each other. As a result of it areas with superfluous positive and negative charges (curve 2 on Fig. 5) are formed.

The electrons, are subject to influence of a magnetic field, unlike ions. But mobility all of them equally remains to higher because of the big difference in weights. Therefore they create smaller concentration of a superfluous charge than ions at moving from area of a birth to the anode.

The electrons move to the anode in gradually falling down magnetic field. They again reach the energy necessary for ionization, on distance of the order 5мм from the cathode. As a result of it the small superfluous positive charge is formed. Here process of ionization of the raised atoms, and also the atoms sprayed from a target can play an essential role.

Further electrons move aside the anode in weaker electric field. It does not allow them to reach the energy necessary for ionization.

Growth of a digit pressure leads to increase issue electrons from the target surface. Hence, increases Hall current near to a surface, ionization of working gas amplifies, intensity of dispersion of atoms of a target increases.

The sprayed atoms of a target have lower potential of ionization, unlike atoms of inert gas. For example, for aluminium it makes 5,98 eV. In this connection area of ionization for atoms of a target it will be essential more widely, than to atoms of argon.

Efficiency of dispersion of a target by means of own atoms is more, than argon. On an example, at frontal elastic collision of two atoms of aluminium (when one of them is based) all kinetic energy is transferred the last. In case of dispersion by argon the share of energy equal

$$4M_{Al}M_{Ar}/(M_{Al}+M_{Ar})^2 = 0,96$$

is transferred aluminium. It is more essential to heavy metals. For example, for gold the factor is equal 0,56.

Potential of ionization of own atoms is below, than argon. Therefore they can be ionized on greater distance from the target surface than argon. They are accelerated in higher electric potential, get higher energy. In case of double ionization their energy will be still above.

The increase of capacity discharge leads to growth of concentration of a superfluous positive charge. Its border because of increase in a share of own ions in the discharge moves to the left. Intensity of an electric field on border of the dark cathode space, caused by a superfluous positive charge, increases.

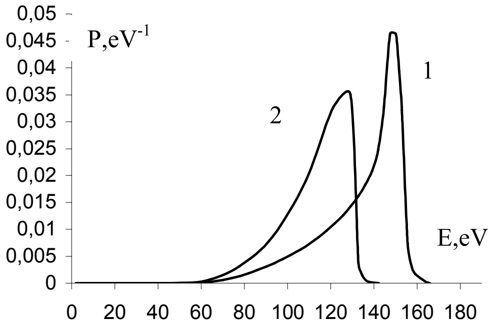

Fig. 8. Energy distribution of accelerated argon ions on the target surface with discharge voltage: 1 – 215 V; 2 – 195 V

Redistribution of a charge carrier in an electric floor leads to increase in intensity of a field near to a surface. It, in turn, "presses" to it a Hall current.

Under certain conditions this process passes a point of balance. The discharge turns in actually the magnetron discharge. Zone of the independent discharge "is pressed" to a surface of the target. This transition it is well visible on Fig. 7 where it is observed at the voltage of the order 250 V.

The similar phenomena are often observed visually Volume of a shone zone sharply decreases, and intensity of a luminescence increases at increase in a voltage discharge.

After that transition active etching a target begins. It is caused by increase of an accelerating voltage. The increase in an accelerating voltage causes increase in energy of the ions bombarding the target.

Absence of a superfluous negative charge on a curve 1 Fig. 5, can be caused by neutralization of ions of a target in this area.

Thus, the sprayed atoms play the important role in the mechanism of the magnetron discharge.

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