Phenomenological Model of Dc Magnetron Discharge

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Abstract — A phenomenological model of DC magnetron discharge has been created on basis of probe measurements of cathode-fall potential. Ionization rate of operating gas, plasma density depending on discharge current, coordinate distribution of ion and electron discharge current, energy distribution of accelerated argon ions on target surface had been calculated. It is shown that cathode-fall potential is characteristic of DC magnetron sputtering system and main processes caused material sputtering take place within a area several millimeters thickness near the target surface.

1. Introduction

Electric discharge in a rare gas medium with 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 universal model of magnetron discharge that is able to predicate electrophysical characteristics and target sputtering kinetics. One of this situation reasons is insufficient imagination of spatial potential distribution within diode discharge gap. Authors [1, 2] suggest that there are three types of DC magnetron discharge: with area of cathode-fall potential, with area of anode-fall potential and with simultaneous presence of both areas. Danilin B.S. and Syirchin V.K. [1] inform that a cathode-fall potential is property of the magnetron with magnetic induction of up to 0.03 T. Moreover, there is no conventional data relatively to the dimension of area with cathode-fall potential. This value changes from 1÷2 mm [2] to 10 mm and more [1].

2. Model Description

The feature of DC magnetron sputtering system is existence of area with crossed magnetic and electric fields in a discharge gap. The magnetic field configuration is closed circuit of electron drift.

Chamber walls are usually used as anode. In the system like this one the area of crossed electric and magnetic fields represents a plasma cathode for anode region not containing a magnetic field and ions emitted (to the area located near the cathode) anode both.

Like usual glow discharge without magnetic field, a spatial charge of ions in the cathode region influences on parameters of electric field and plasma conditions. The secondary electrons emitted from the cathode move according to cycloid path with periodically returning to the cathode. Therefore electron component of discharge current in the diode can exist in the case of electron transition from one to another motion path along direction of electric field. Electron gets energy W_c in the electric field at maximum moving off from target surface equal to cycloid amplitude

$$W_c = e\cdot\varphi_c = e\cdot h_c\cdot E_c. \qquad (1)$$

Here e is electron charge; φ_c – potential in points of discharge gap are located from target surface on distance of h_c away; E_c – electrostatic intensity, which takes place in the gap.

This is desirable to definite the values of free charge density and ion density in the discharge gap.

It is known [1] that cycloid amplitude is described by the expression

$$h_c = \frac{2m_e E}{eB^2},$$

where m_e – electron mass. In view of (1) we can get

$$E_c = B\sqrt{\frac{e\varphi_c}{2m_e}}. \qquad (2)$$

From (2) we have $E_c = 10^5$ V/m and at φ_c equal to ionization potential of argon atom $\varphi_i = 15.7$ eV [2] for typical values of magnetic field induction of DC magnetron $B = 0.05$ T. Therefore, maximum energy of moving electron is less than ionization potential if electrostatic intensity is less than this value. Self-maintained discharge is improbable in this case. Obtained value of h_c specifies the maximum width of dark cathode space d_{DCS}. At discharge voltage equal $U_d = 300$ V in a uniform electric field the dimension of intensive ionization area will be equal

$$d_i \le \frac{U_p}{E} \approx 3 \text{ mm}.$$

We had carried out a probe measurement in the cathode region to verify our assumption about predominant cathode potential drop.

3. Experiments

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 [3], 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. Chamber walls were used as anode of discharge gap. Fig. 1 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.

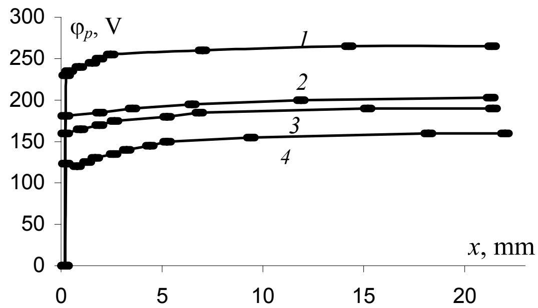

Fig. 1. Floating probe potential measured to cathode of discharge gap under various voltage: *1* – U_d = 285 V; *2* – U_d = 225 V; *3* – U_d = 215 V; *4* – U_d = 195 V

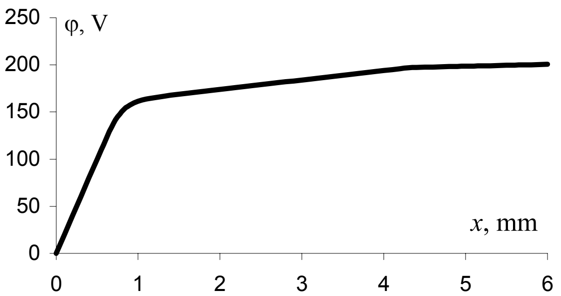

Fig. 2. Distribution of the spatial potential (curve *2* on Fig. 1)

As it is shown in Fig. 2 each curve of Fig. 1 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.

Assumed that probe potential agrees with electric potential within discharge gap, spatial potential distribution may be found from the expression

$$\vec{E} = -\text{grad}\varphi . \quad (3)$$

Figure 3 shows experimentally measured magnetic field and electric field distribution, calculated from (3).

Using the Poisson's equation

$$\text{div}\vec{E} = \frac{e}{\varepsilon_0}(n_i - n_e) , \quad (4)$$

where n_i – ion density and n_e – electron density, the distribution of excess positive charge may be found.

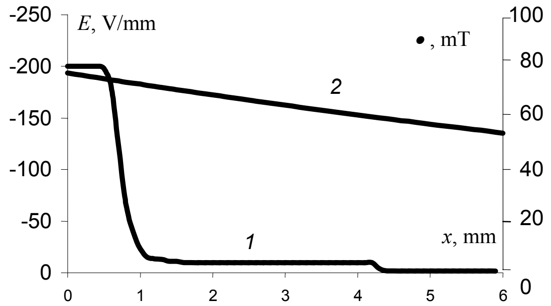

Fig. 3. Spatial distribution of electric (curve *1*) and magnetic (curve *2*) field

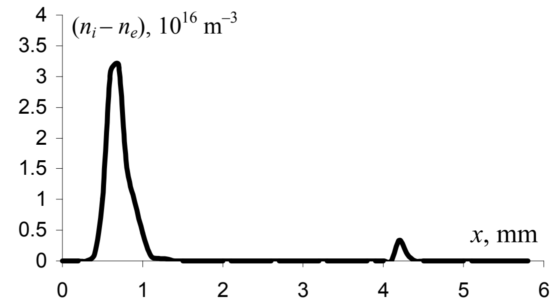

Fig. 4. Spatial distribution of the excess positive charge

As one can see in Fig. 4 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}. The main part of the fall electric potential takes place in this region. This sheath is responsible for argon ion acceleration.

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.

In Fig. 5 electron paths moving in cross electric and magnetic fields (pictured in Fig. 3) calculated by molecular dynamic method are presented.

In calculations it is proposed that electrons leave the target with initial energy equal 1 eV in direction perpendicular to its surface.

From these pictures one can concludes that ionization events carried out by electrons of first and second generations which move away from the cathode surface on distance of not more than 1.5 mm. Only these electrons are able to get energy more than ionization potential.

For ionization probability calculation of argon atoms by electrons of Hall current we were used ionization cross-sections given in [5]. Approximation of ionization ability [6] was used:

$$P = -0.1212 + 8.96 \cdot E^{-\frac{1}{2}} - 4.25 \cdot E^{-1}, \qquad (5)$$

where E – energy in eV.

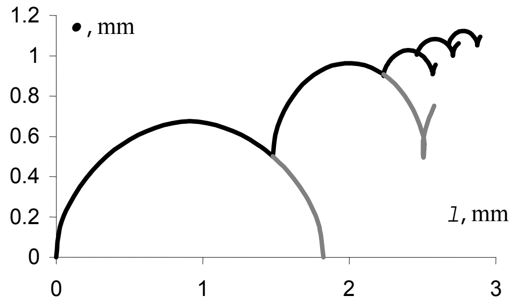

Fig. 5. Electron motion path near the target surface

Expression (5) is correct for electrons energy range from 30 to 4000 eV. The formula (5) was multiplied to correction factor to get an ionization cross-section.

In this calculation electrons of first and second generations had been taken into consideration. Their motion paths, energies, traveling time and so on had been calculated by means of molecular dynamics method. Cycloid height was divided into several tens of equal segments. Ionization probability within each segment was measured by formula

$$P_i = \frac{\sum_i \sigma_i(\overline{E}) n_{\text{Ar}} l_i}{l}, \qquad (6)$$

where $\sigma_i(\overline{E})$ – cross-section of argon atom ionization; $\overline{E}$ – average electron energy within i-segment; l_i – length of i-segment; l – cycloid length.

Electrons of second-generation birth in proportion to probability P_i. Ionization probability by second electrons generation was calculated similarly. Their primary energy was determined as $E = \overline{E} - \varepsilon_i$, where ε_i = 15.7 eV – ionization energy of argon atom.

Figure 6 presents creation rates of ion-electron pairs taken from the calculation in electric and magnetic fields which are given in Fig. 3 and under discharge current density equal to 100 A/m^2.

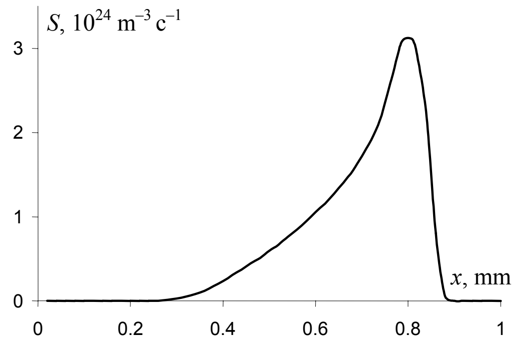

Fig. 6. Creation rate of ion-electron pairs under discharge current density of about 100 A/m^2

As one can see from the picture the maximum part of charge carriers is generated in a zone of main electric potential falling in a distance of 1 mm from target surface.

Argon ions have been accelerated in potential given in Fig. 2 move to cathode. In case of steady-state conditions when number of born particles equal to fallen on cathode one, the argon ions create charge supports density presented in Fig. 7. Near cathode surface where birth of ions takes no place the positive ion charge must be compensated by negative charge of Hall electrons.

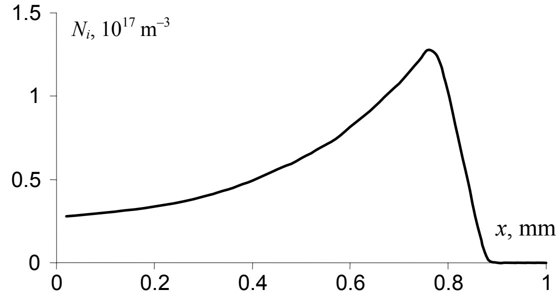

Fig. 7. Spatial distribution of plasma density for discharge urrent density about 100 A/m^2

Hall current value may be evaluated from averaged electron energy along ionization region, magnetron configuration, discharge current value and argon pressure. Free path relatively ionization event was calculated from ionization cross-section for corresponding average electron energy. Then Hall current creating necessary generation rate of charge supports is determined.

In our case the Hall current 2.1 A is required for a discharge current 5.3 A. Real value of Hall current may be bigger because slowed electrons having energy less than ionization potential is not taken into consideration.

Relation of ion and electron components of discharge current is shown in Fig. 8. These dependences are qualitative adjectives and a discharge current part caused by emitted electrons was leaved out of account.

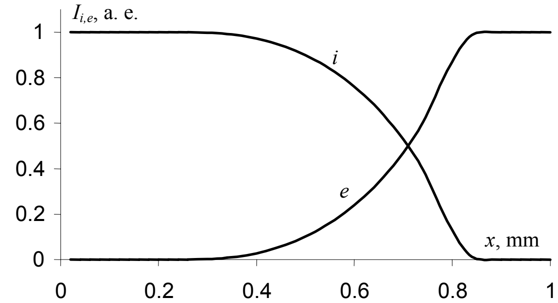

Fig. 8. Relation between the electron and ion discharge urrent components

Energy distribution of accelerated argon ions on the target surface under discharge voltage of 215 V is presented in Fig. 9. The distribution with dislocated maximum to a high-energy region is most favorable for target sputtering process [4].

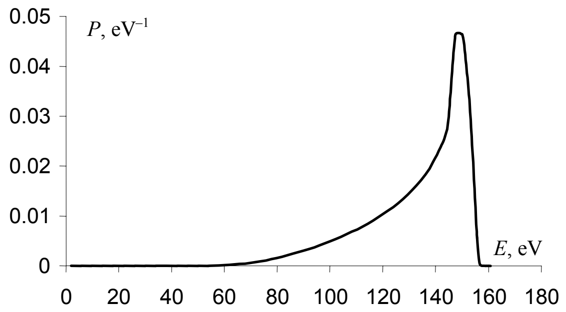

Fig. 9. Energy distribution of accelerated argon ions on the arget surface with discharge voltage equal to 215 V

Electrons are kept in a magnetic trap up to distance of one or several centimeters from target surface. Therefore they can leave the discharge region only in a diffusion regime as a result of deaccelerating to thermal energy or moving along magnetic field lines.

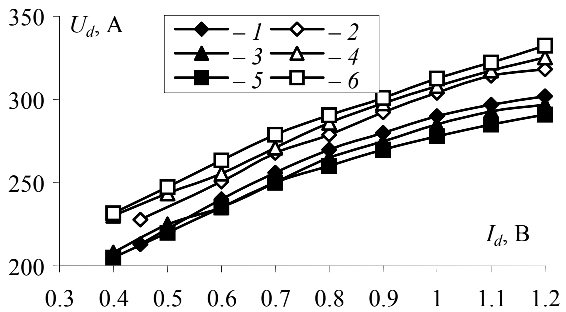

Fig. 10. Volt-ampere characteristics of magnetron (curves *2*, *4*, *6*) and probe potential relatively to cathode (curves *1*, *3*, *5*) under various distances from probe to the target surface: *1*, *2* – 14 mm; *3*, *4* – 6 mm; *5*, *6* – 4 mm

Increasing discharge voltage removes spatial distribution function of charge surplus in left side. Carrier density of positive charge increases and the area of discharge jams to the target surface.

In Fig. 10 volt-ampere characteristics and probe measurements of discharge potential are presented under various 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 fall in a probe-anode region. This fall 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.

4. Conclusion

Results of the work indicate that cathode fall potential is characteristic of DC magnetron sputtering system. About 80% of applied voltage reduced in a distance of 3÷4 mm from target surface under typical value of magnetic flux density and discharge voltage. Region of non-self-maintained discharge lies farther. Argon ions are formed within a distance of 0.1÷1.5 mm from sputtered target. Electrons get energy in electric field not exceeding 60% of maximum possible one, which ion gets passing through discharge gap without interactions with other particles. Argon ion energy is in a range from value equal to ionization potential up to 70% of maximum possible value.

Thus the main physical phenomena those are defining existence of magnetron discharge take place in a near cathode region. The zone of positive surplus charge lies here. This charge forms electrical field that determines a main processes in magnetron discharge.

References

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