

CYLINDRICAL MAGNETRON BASED ON THE PLASMAOPTICAL PRINCIPLES

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The operation of any magnetron-type sputtering system is based on using of anomalous glow discharge in a crossed $E \perp B$ fields. In such systems a principle of magnetic isolation of electrons is realized and idea of magnetic lines equipotentialization for control of ions flow on cathode-target can be applied quite well. In the present work, with consistent taking these principles into account, the sample of axially-symmetric cylindrical sputtering system of magnetron type is proposed, elaborated and tested.

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1. INTRODUCTION

It is hardly possible to imagine the modern plasma technologies of processing of the new exotic materials and functional coatings with given properties without DC and AC magnetron sputtering systems. In spite of the fact that magnetron sputtering systems are known already for a long time and are successfully used in technologies, the sufficient understanding of the physical processes determining their operation is not too clear till now. All such plasmadynamic systems with magnetic isolation of electrons can be divided into two greater classes – planar and cylindrical ones.

Cylindrical magnetrons were proposed by Penfold and Thornton in the mid-1970s. The results of investigations of their properties are presented by a lot of references[1-3]. Both their main advantages and disadvantages are well-known. The operation of any magnetron-type sputtering system is based on use of anomalous glow discharge in a crossed $E \perp B$ fields. It is possible to apply plasmaoptics principles, proposed firstly by A.I. Morozov [4,5], to plasmadynamic systems of such types. In the present work, with consistent taking these principles into account, the sample of axially-symmetric cylindrical sputtering system of magnetron type is proposed, elaborated and tested.

2. EXPERIMENTAL CONDITIONS

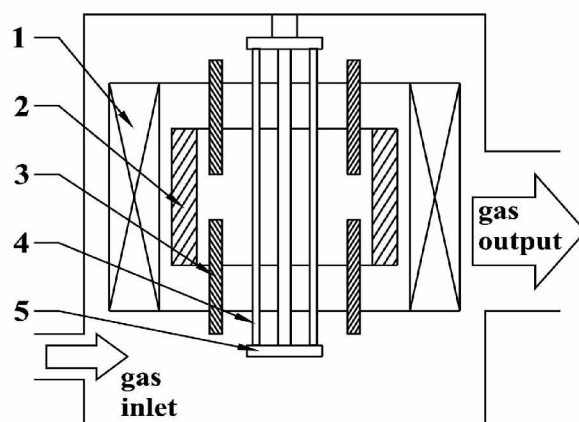
The experiments were carried out at the setup schematically shown in Fig. 1. Cylindrical magnetron sputtering system is placed in the vacuum chamber. There are two opportunities to place samples (4) in the internal magnetron volume: one cylindrical sample directly at the axis or several samples in nosepiece (5). Magnetron has magnetic system (1) assembled on permanent magnets and cooled cathode (2). Cathode is cooled due to thermal contact with reservoir with cold water being pumped through it. Cylindrical cathode made of copper with 59 mm internal diameter, 67 mm outer one and 63 mm height is used. Anode system (3) consists of two moveable units and allows to set different anodes on various depths from outside section of magnetic system at the magnetron axis. It is possible to obtain single anode (when both anode units are connected) or split ones (when there is a gap between the anode units in cathode region localization). Anode electrodes are made of nonmagnetic

steel. Usually anode unit has 6 rods located in parallel to working cathode surface and uniformly along a circle. Distance between the anode and the cathode can be adjusted. Besides, single anode rod can be located exactly at the magnetron axis. Working gas (argon) is supplied directly into the chamber and produces working pressure from 10^{-5} up to 10^{-2} Torr.

Magnetron magnetic system forms axially symmetric magnetic field (see Fig. 2). The magnetic system boundaries are shown by solid parallel line (3) in this figure. Rectangles (1) show cathode localization. Anodes localization are shown by rectangles (2). The configuration of magnetic field lines provides formation of magnetic trap for electrons above the cathode surface and magnetic insulation from the anodes. Magnetic field value at the axis of system is about 0.065 T, and one nearby the cathode surface – 0.075 T. Magnetron magnetic field lines were calculated as lines of equal magnetic flux ($\psi=const$). The magnetic flux values were evaluated from magnitudes of magnetic field B_z accordingly to the following equation:

$$B_z = \frac{1}{2\pi \cdot r} \cdot \frac{\partial \psi}{\partial z}.$$

Photographs of discharges were made in case of absence of bottom anode module by digital camera.



*Fig. 1. Principle scheme of the experiments with magnetron type sputtering system.
1-magnetic system; 2-cathode; 3-anode;
4-sample; 5-samples holder*

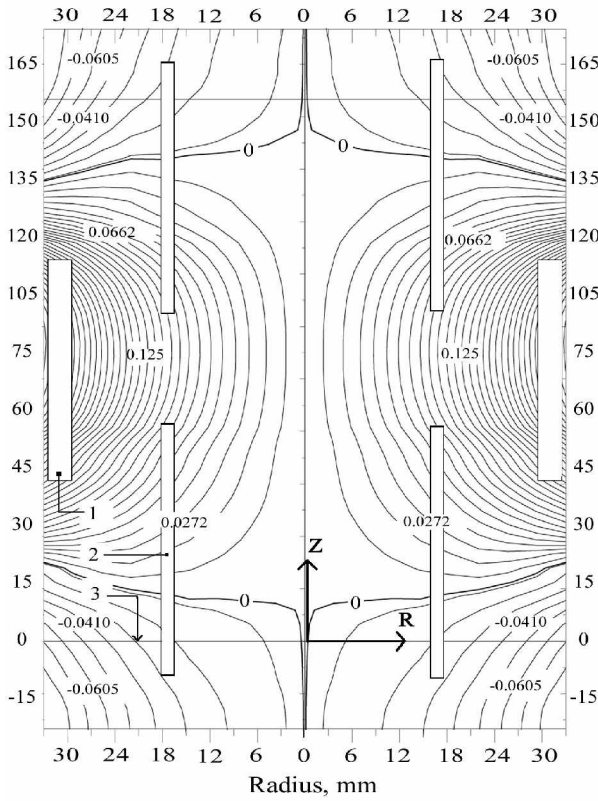


Fig. 2. Magnetron magnetic field lines (μWb)
1-cathodes; 2-anodes; 3-magnetic system boundaries

The physical processes determining behavior of this sputtering system can be close to plasma accelerator with closed electron drift and extended acceleration zone [6].

3. RESULTS

In our experiments plasmaoptical magnetron operated in two modes corresponding to the different types of discharges. The photos of this discharge are shown in Fig.3. It is possible to achieve these regimes by pressure increase. Dependencies of discharge voltage and current via pressure are presented on Fig. 4.

The first discharge mode is characterized by low current (up to 100 mA). The upper limit of existence of this mode is correlated with plasmadynamic and geometric parameters (e.g. breakdown voltage, cathode surface cleanness, cathode-anode distance) and is about $3 \cdot 10^{-3}$ Torr. During pressure increase the current value and the luminescence intensity are growing.

The second discharge mode is characterized by high current (up to 2 A in our experiments) and high luminescence intensity. Switch to this mode occurs in spurts with change of discharge color from blue to green. The bottom limit of existence of this magnetron discharge mode is correlated with plasmadynamic and geometric parameters too and is about $5 \cdot 10^{-3}$ Torr. During pressure increase the current value and the luminescence intensity are growing. As one can see from Fig. 4, curve 1 conforms to the first discharge regime in all pressure range. Thus magnetron discharge regime has both pressure and breakdown voltage limits.

One can see from Fig. 2 that in the central part of the cathode region magnetic field lines extend in parallel enough way to the cathode surface. Use of split anodes leads to formation of virtual ones along these lines. In this

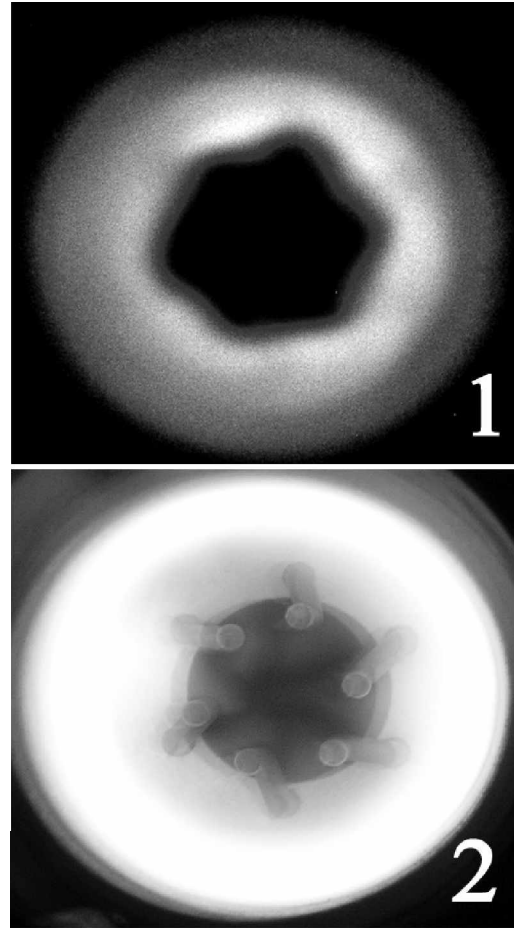


Fig. 3. Photos of discharges in different modes.
1 - $P=3 \cdot 10^{-3}$ Torr, $I_d=40\text{mA}$, $U_d=2000\text{V}$;
2 - $P=6 \cdot 10^{-3}$ Torr, $I_d=1.25\text{A}$, $U_d=400\text{V}$

case we have the treatment of all cathode surface without anode shadows on samples surface. Experiments show that the magnetron continues its normal operation up to virtual anode size of 55 mm. Cathode surface inspection after the sputtering test shows the whole cathode surface etching with more intensive zone in the central plane (about 60% width relatively to total cathode height).

Considering ions arriving to the cathode surface from edge of plasma positive column in accordance with well-known formula we can calculate the density of charged particles for high-current mode the discharge:

$$j_c = (1 + \gamma) \cdot j_i, j_i = 0.4 \cdot e \cdot n_i \cdot \sqrt{\frac{2 \cdot k \cdot T_e}{M_i}},$$

where j_c - current density on cathode ($j_c = \frac{I_d}{S_c}$, S_c - cathode square), j_i - ions current density, γ - secondary electron emission coefficient (is about 0.1), n_i - ions density, M_i - ion mass (Ar), T_e - electron temperature. Thus ions density is about $1.54 \cdot 10^{13} \text{ cm}^{-3}$. Ionization degree in this system is higher than that in typical magnetron and is about 8 %. We suppose that electron temperature is about 20 eV.

Under conditions of our experiments in high-current operation mode deposition rate was about 500 nm/min. Taking into consideration ion current density and deposition rate we can estimate a sputter yield Y:

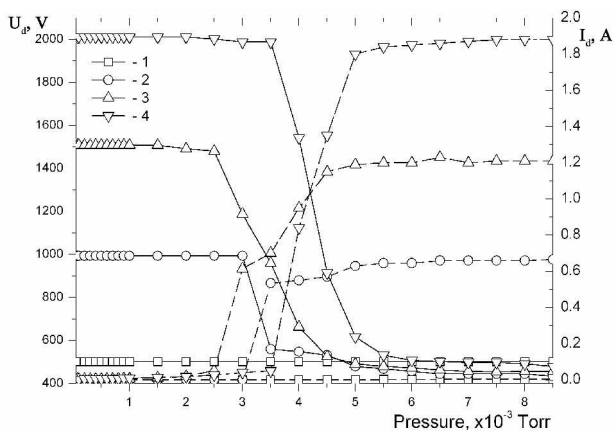


Fig. 4. Dependencies of discharge voltage $[U_d]$ (solid lines) and current $[I_d]$ (dash lines) on pressure at different maximum discharge power: 1 – 0.5 W; 2 – 300W; 3 – 600W; 4 - 900W

$$Y = \frac{D \cdot e}{a^3 \cdot j_i} = 1.17,$$

where D – deposition rate, a - identity parameter (2.2 Å for copper). We can suppose that argon ion energy is about 350 eV [7]. That fact confirms existence of cathode potential drop and plasma positive column in region of the anodes.

Plasmaoptical principles suggest virtual anode existence. These principles require a presence of magnetized electrons and nonmagnetized ions. These criterion can be written as

$$r_e > L, r_i < L,$$

where r_e and r_i – are Larmor radii of electron and ion correspondingly, L – cathode-anode distance (≈ 10 mm). On high-current mode for fast electrons in cathode region ($T_e \approx 350$ eV) and for slow ions in plasma positive column ($T_i \approx 20$ eV) we can write

$$r_e \approx 1 \text{ mm}, r_i \approx 60 \text{ mm}, L \approx 10 \text{ mm}.$$

As one can see the necessary conditions for plasmaoptical principles are created and existence of virtual anode is experimentally confirmed.

CONCLUSIONS

We describe a consistent application of plasmaoptical principles of magnetic isolation and equipotentialization

ЦИЛИНДРИЧЕСКИЙ МАГНЕТРОН НА ПРИНЦИПАХ ПЛАЗМООПТИКИ

А.Н. Добровольский, А.Н. Евсюков, А.А. Гончаров, И.М. Проценко

Использование аномального тлеющего разряда в скрещенных электрических и магнитных полях является основой функционирования любой магнетронной распылительной системы. В таких системах выполняется принцип магнитной изоляции электронов и может быть применена идея эквипотенциализации магнитных силовых линий для управления ионным потоком на катод-мишени. На основе последовательного применения указанных плазмооптических принципов предложен, реализован и исследован вариант аксиально-симметричной цилиндрической распылительной системы магнетронного типа.

ЦИЛИНДРИЧНИЙ МАГНЕТРОН НА ПРИНЦИПАХ ПЛАЗМООПТИКИ

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Використання аномального жевріючого розряду в скрещених електричному та магнітному полях є основою функціонування будь-якої магнетронної розпилюючої системи. В таких системах виконується принцип магнітної ізоляції електронів та може бути застосована ідея еквипотенціалізації магнітних силових ліній з метою керування іонним потоком на катоді-мішені. На основі послідовного використання вказаних плазмооптичних принципів було запропоновано, реалізовано та досліджено варіант аксіально-симетричної циліндричної розпилюючої системи магнетронного типу.

of magnetic field lines for creation of sputtering system magnetron type. We carried out tests and some preliminary investigations of its operation.

Discharge in cylindrical magnetron with strong magnetic field in the whole volume has two main stages. Transition between the discharge stages happens in spurts. High-current stage is characterized by abrupt voltage reduction with current growth in spurts and weak dependence of working voltage on pressure.

Anode to cathode distance and the anode localization determine some peculiarities of the magnetron operation. Efficient high-current discharge glow is possible in the pressure range from 5×10^{-3} Torr. Preliminary sample preparation before sputtering is possible immediately in this magnetron. In our experiments high-current mode allows to achieve sputtering rate from copper target of about 500 nm/min.

REFERENCES

1. J.A.Thornton, A.S. Penfold. *Thin Film Processes*. New York: "Academic Press", 1978.
2. D.A. Glocker, M.M. Romach, V.W. Lindberg. Recent developments in inverted cylindrical magnetron sputtering // *Surface and Coating Technol.* 2001, v.146-147, p. 457-462.
3. M. Amberg, J. Geerk, M. Keller, A. Fischer. Desing, characterisation and operation of an inverted cylindrical magnetron for metal deposition // *Plasma Devices and Operations*. 2004, v.12, N 3, p. 175-186.
4. A.I. Morozov. Focusing of Cold Quasineutral Beams in Electromagnetic Fields // *Soviet Physics – Doklady*. 1966, v10, N8, p.775-777.
5. A. Morozov and S. Lebedev. *Reviews of Plasma Physics* / ed. by M. Leontovich. New York: "Consultants Bureau", 1975.
6. A.I. Morozov, Yu.V. Esinchuk, G.N. Tilinin, A.V.Trofimov, Yu.A.Shchepkin. Plasma Accelerator with Closed Electron Drift and Extended Acceleration Zone // *Soviet Physics Technical Physics*. 1972, v.17, p. 38.
7. H. Coufal, H.F. Winter and H.L. Bay. Energy transfer from noble-gas ions to surfaces: Collision with carbon, silicon, copper, silver, and gold in the range 100-4000 eV // *Phys. Rev. B*. 1991, v.44, N10, p. 4747.