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Magnetron with external magnet to increase the ion content in the flow of deposited atoms

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Magnetrons are widely used for producing protective coatings on the surface of processing tools and for depositing metal and dielectric films in the electronics industry. The properties of the coatings are significantly dependent on ion bombardment of the growing film. At large distances from the magnetron, the part of ions in the flow of deposited atoms is insignificant because the plasma region is concentrated near the magnetron target. The location of the NdFeB ring magnet in front of the magnetron changes the configuration of the total magnetic field. As a result, a magnetic trap forms in which electrons are held in the discharge area. The efficiency of ionization of sputtered atoms increases. This leads to an increase of the ion current by an order of magnitude. The ion current density increases proportionally to the discharge current. The configuration of the plasma boundary and the distribution of the ion current density in the cross section depend on the axial displacement of the external magnet relative to the magnetron. An ion current density of $0.1-0.55\,\mathrm{mA/cm^2}$ was obtained at a distance of $60-90$ mm from the magnetron at the discharge voltage of $320-350$ V and the current of $150-300$ mA. A stable discharge glows in argon, oxygen and argon-nitrogen mixture at a pressure of $0.3-0.5$ Pa.

Keywords:: magnetron, magnetic field, coatings, magnetron sputtering, current density.

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Introduction

Magnetron sputtering is used in commercial technologies for deposition of coatings to obtain thin films with high hardness, thermal resistance, wear resistance, improved anti-frication properties. Microelectronics involves technological processes of metallization on the surface of semiconductor wafers in the manufacture of electronic devices. The structure of the film deposited on the substrate significantly depends on the substrate temperature and the energy of the deposited atoms and ions [1,2]. These parameters impact the mobility of the deposited atoms during the film growth. When the substrate temperature is low, a columnar and porous coating structure may be formed. At a high temperature of the growing film, together with intense ion bombardment of the surface, the mobility of the deposited atoms increases, which leads to improved adhesion and growth of a denser coating.

The energy input of the deposited ions, which move towards the substrate in a flux of atomized atoms, can be increased with a negative electric displacement of the substrate. Deposition of films with high uniformity in thickness over a large area of the substrate is obtained at a relatively large distance of the substrate from the magnetron. However, the number of ions in the flux of deposited atoms will be insignificant, since the ionization of atoms in the gap between the magnetron and the substrate is influenced by a small number of electrons from a magnetron discharge concentrated directly in front of the magnetron target. However, the movement of plasma electrons can be controlled by changing the configuration of the magnetic field lines by choosing the design and size of the magnets of unbalanced magnetrons, or using an electromagnetic coil [3–5].

Magnetic field of the magnetron decreases rapidly with the increasing distance from the target (cathode), so it will have little effect on the movement of plasma electrons in the substrate region and, accordingly, on the ionization process of atoms. To increase the magnetic field, it is proposed to install an additional annular magnet between the magnetron and the substrate. Then a stronger external magnetic field will significantly affect the movement of plasma electrons between the magnetron and the substrate, since the magnetic flux of the external magnet will cross both the substrate and the plasma region of the magnetron, similar to the magnetic flux of an unbalanced magnetron [1]. Accordingly, plasma electrons, rotating around the magnetic field lines, will reach the substrate, ionizing the atomized metal and argon atoms in their path. As a result of more efficient electron ionization, the concentration of ions in the deposited flux of atoms will rise. The purpose of this paper is to experimentally study the effect of the magnetic field of an additional annular magnet located between the magnetron and the substrate on the ion current density and its spatial distribution.

1. Experimental procedure

The diagram of the magnetron with external magnet is shown in Fig. 1,*a*. Copper cathode *1* with a diameter of 40 mm and thickness of 2 mm is cooled by water.

In its center the magnetron has NdFeB magnet *2* with a diameter of 15 mm and thickness of 15 mm. The arched configuration of the magnetron's magnetic field is formed using a central cylindrical magnet and a magnetic core in the form of an external steel ring. The magnetron anode with a 34 mm hole for exit of sputtered atoms has a thickness of 4 mm. The gap between the anode and cathode is 2 mm. A cylindrical anode is installed on the magnetron anode *3* 64 mm in diameter, made of stainless steel. The external annular magnet *4*, located above the magnetron, is made as 12 NdFeB magnets with a diameter of 15 mm and

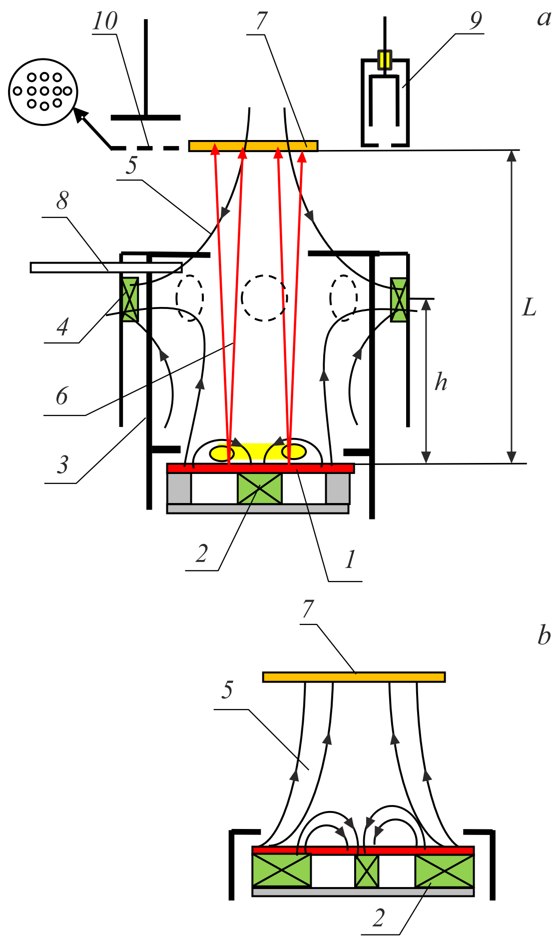

Figure 1. Magnetron diagrams: *a* — with external annular magnet above the magnetron, *b* — magnetron with unbalanced magnets: *1* — cathode, *2* — magnetron magnetic system, *3* — cylindrical anode, *4* — external annular magnet, *5* — magnetic field lines, *6* — trajectories of atomized atoms, *7* — substrate, *8* — gas tube, *9* — ion probe, *10* — collimator.

a thickness of 5 mm, which are evenly spaced around the perimeter of the external anode cylinder *4*.

To avoid overheating of magnets, there is a vacuum gap between them and the cylindrical anode. At a low operating pressure of about 0.5–1 Pa, the thermal conductivity of the discharged gas in the gap between the anode and the magnets is negligible, therefore, to ensure long-term (about 1 h) operation of the magnetron, a thermally insulating fluoroplastic strip with a thickness of 2 mm and a width of about 20 mm was provided to reliably protect the magnets from overheating. No demagnetization of magnets was observed in the experiments.

The same poles of all magnets are directed inside the sputtering system. They coincide with the pole of the central cylindrical magnet of the magnetron. As a result, the magnetic lines of force of the external magnet and magnetron create a magnetic trap of a plug configuration in which the magnetic field in the central part of the anode is weaker than in the periphery. Therefore, the magnetic field limits the escape of electrons from the plasma across the magnetic field lines to the walls of the anode, providing more intense ionization of atoms in the center of the magnetic trap. The distance *h* between the cathode and external annular magnet significantly affects the magnitude of the ion current. The sputtered atoms *6* are deposited on the substrate *7*.

Argon, oxygen, and a mixture of argon and nitrogen were used as the operating gases (40 %/60 %). Argon was used to obtain metal coatings of Cu and Al. A mixture of argon and nitrogen was used to fabricate films of metal nitrides [6–8]. The operating gases were injected near the substrate in order to increase the concentration of oxygen and nitrogen for more efficient formation of nitrides and metal oxides on the surface of the growing film. Gas *8* was injected into the cylindrical anode through an opening located above the annular magnet. A gas shower in the form of an annular tube with six holes with a diameter of 2 mm located along its perimeter was also used to evenly supply gas to the discharge area.

To measure the ion current density at a distance of *L* from the cathode, a probe *9* was installed with a diameter of 14 mm and having a form of Faraday cylinder with negative displacement of −50 V, at which the ion saturation current was detected. The inlet hole of the probe was 4 mm in diameter. The inner cylindrical current collector had an inner diameter of 10 mm and a length of 50 mm. The thickness of the deposited coating and, accordingly, the deposition rate were measured using Alpha-Step 200 profilometer based on the height of the film step on thin glass or silicon wafers, when its part was covered with a screen made of the same material. The angular divergence of the flow of atoms deposited on the substrate was measured by the imprint size of copper atoms passing through a mesh collimator with holes 2 mm in diameter and spacing of 10 mm in a stainless steel plate. The imprint of the copper coating was recorded on the metal plate at a distance of 20 mm from the holes of the collimator.

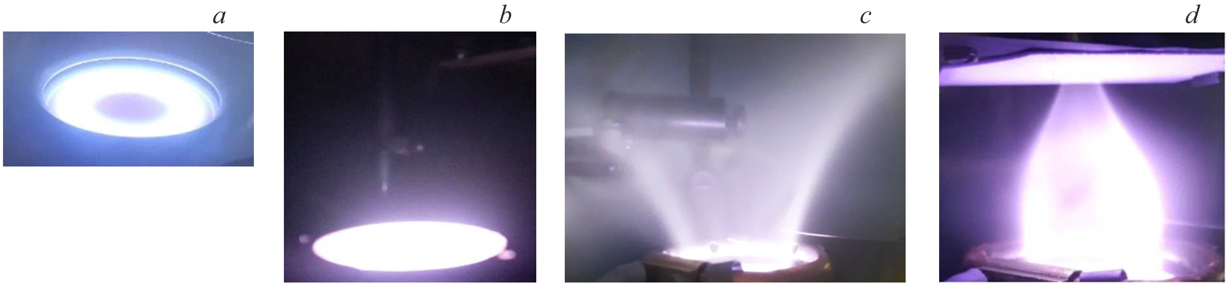

Figure 2. Types of plasma discharge: *a* — view of the plasma ring in the magnetron's anode hole without cylindrical anode and external magnet, *b* — photo of the same high-brightness plasma ring in the anode hole and the dark area above it, *c* — plasma glow over the cylindrical anode with external magnet, *d* — plasma glow between the cylindrical anode with the external magnet and the substrate after installation of additional permanent magnet on it.

The substrate was grounded. Since plasma has a positive potential relative to the grounded substrate, the ion flux got additional energy upon deposition onto the substrate.

The magnetron was powered by a 80–100 W power supply. The movement of the permanent magnet had no effect on the discharge current and voltage. During operation of the magnetron, the discharge current was maintained unchanged, which was usually 160 mA. The discharge voltage 320–350 V varied during the change of cathodes made of various metals. The results of the experiments were not related to the discharge power variation.

2. Experimental results and discussion

The magnetic field of the external magnet changes configuration of the magnetron's magnetic field. Depending on the distance between the magnet and the magnetron, the shape and size of plasma boundary near the substrate changes, as well as the density of the ion current.

2.1. Effect of the external magnet on plasma configuration near the substrate

Experiments have shown that annular magnet above the magnetron affects the flow of plasma electrons ionizing the sputtered atoms of metal and operating gas. When the film is deposited when there's no cylindrical anode with external magnet, a bright plasma glow is observed inside the magnetron anode *3* hole directly above the cathode surface (Fig. 2, *a*). The edge of the anode hole is depicted as a rim around a bright plasma ring. Through the glass window of vacuum chamber, the plasma ring is clearly visible when the magnetron is operating with metal cathodes made of various materials. Its diameter corresponds to the diameter of the groove on the cathode, which gradually fades away during long operation of the magnetron. Without external magnet, plasma practically does not go beyond the anode (Fig. 2, *b*), since there is no glow of plasma coming out of the magnetron.

In experiments, the substrate was usually placed at a distance of 60–90 mm from the magnetron, where a uniform coating was deposited [9]. However, the plasma density is low at such distances (Fig. 2, *b*). After installing cylindrical anode with external annular magnet, the area of luminous plasma spreads beyond the anode of the magnetron, reaching the substrate (Fig. 2, *c*). Magnetic field of the annular magnet, combined with magnetic field of the magnetron, changes the shape of magnetic field lines near the substrate. The electrons, moving along the magnetic field lines along a spiral trajectory, create additional plasma ionization in the substrate area. As a result, the current density of ions falling on the substrate rises at large distances from the cathode. If you change the pole of external magnets to the opposite pole relative to the pole of the magnetron central magnet, switching them to 180°, the pressure at which the discharge is glowing increases by an order of magnitude, and the effect of the external magnet becomes insignificant.

The magnetron magnetic system is aimed at creating a gas-discharge plasma above the cathode surface. The arched magnetic field of the magnetron is transverse relative to the direction to the substrate. It greatly subsides near the magnetron surface. The value of the magnetron's magnetic field at a distance of 70-90 mm will be insignificant, so it will not affect the film deposition on the substrate. External annular magnet is located closer to the substrate, so it will have a significant effect on the movement of charged particles towards the substrate compared to the magnetron magnet.

In a magnetron that has external magnet, the operating pressure of gas discharge goes down to 0.2 Pa due to a more efficient process of electron ionization of atoms. Without external magnet, the operating pressure of the magnetron was 2.5 Pa. The benefit of a magnetron that has an external magnet is that it operates at a lower discharge pressure 0.2–0.5 Pa, when the free path of atoms is commensurate with the size of the vacuum chamber. Collisions with gas atoms occur less frequently than when operating at higher pressure. The quality of the coating on the substrate is improved, as the scattering of deposited particles on the atoms of the operating gas is reduced.

The effect of the magnetic field configuration on the movement of electrons is confirmed by Fig. 2, *d*, which shows the shape of a luminous plasma when a cylindrical permanent magnet with a diameter of 10 mm is mounted on the upper side of the substrate in the form of a thin stainless steel plate. The permanent magnet concentrates the magnetic flux of the external annular magnet. When the substrate with the magnet is displaced horizontally away from the axis of the magnetron, the area of the luminous plasma becomes distorted, following the displacement of the magnet over long distances.

Further experiments showed that changing the configuration of the magnetic field has little effect on the trajectory of ions formed from sputtered metal atoms due to their large mass compared to the mass of electrons. It was seen that the shape and size of the copper imprint on the substrate changes slightly with axial displacement of the external annular magnet. Thus, using permanent magnet located directly on the substrate, it is possible to increase the density of ionizing electrons near the substrate, provided that the substrate does not heat up above the demagnetization temperature of the magnet during the technological process.

2.2. Configuration of magnetic field of the magnetron with external magnet

The total magnetic field of the a „cork" configuration between the magnetron and the substrate is formed by the magnetron's magnetic system and annular magnet located above the magnetron. The magnetron discharge creates plasma near the surface of the cathode, and the annular magnet serves to efficiently transport electrons to a substrate to ionize the flux of the sputtered atoms.

The magnetic system of the magnetron creates magnetic field of an arched configuration (Fig. 1, *a*). From the plasma ring above the cathode, heavy argon ions are accelerated going towards the cathode, knocking out metal atoms and electrons from its surface, which, after acceleration in the cathode layer, ionize the atoms of the operating gas in the region of the bright plasma ring. The azimuthal drift of electrons over the cathode occurs in crossed electric and magnetic fields. The electrons, moving along a cycloidal trajectory, drift in a circular trajectory over the cathode, ionizing the argon atoms. The cycloidal trajectory gradually rises above the cathode due to the loss of electron energy because of ionization. Metal atoms, sputtered with argon ions, move along rectilinear trajectories from the cathode to the substrate, forming a thin-film coating on it. In this case, an annular groove is produced on the metal cathode in the area of intense atomization of metal atoms. The number of deposited atoms and the quality of the applied coating are significantly affected by their losses as a result of scattering on the operating gas atoms. At high operating gas pressure, atomized atoms can lose energy due to repeated collisions with gas atoms before they reach the substrate. At a large distance to the substrate and at high gas pressure, metal atoms mixed with operating gas atoms may not reach the substrate. Therefore, a decrease in operating pressure affects the density of the deposited film and its adhesion.

The external annular magnet mounted on the anode of the magnetron changes the magnetic field configuration, enhancing the peripheral magnetic field at the walls of the anode. Magnetic trap prevents the electrons leaving this region [10]. As a result, the efficiency of electron ionization of sputtered atoms increases at a great distance from the magnetron.

Figure 1 also shows lateral lines of the external magnet field oriented towards the cathode of the magnetron and simultaneously intersecting the cylindrical anode and the cathode of the magnetron. Along the edge lines of the magnetic field, electrons can move towards the cylindrical anode, but these magnetic field lines intersect the cathode at its periphery outside the plasma ring. At the edges of the cathode, plasma density and, consequently, the electron density is low, since plasma is concentrated in the central ring area. From the edge region of the cathode, electrons move to the cylindrical anode along the magnetic field lines, but their number is insignificant.

Similarly, magnetic field is formed near the substrate in the unbalanced magnetron with a weak central cylindrical magnet of small diameter and a strong external annular magnet when part of the peripheral magnetic flux crosses the substrate (Fig. 1, *b*) [11–13]. The lateral magnetic field lines crossing the magnetron cathode and the substrate prevent the transverse escape of electrons from the discharge area. This results in higher ion current density on the substrate. The proposed magnetic system with an annular magnet above the magnetron is more efficient, since it is possible to form an optimal configuration of the magnetic field by moving the annular magnet vertically.

2.3. Ion current density on substrate

The increase in ion current density is confirmed by measurements made using ion probe in the form of a Faraday cylinder with a negative electric displacement of −50 V. Fig. 3 illustrates the curves of ion current density versus central axis without magnet and with external magnet

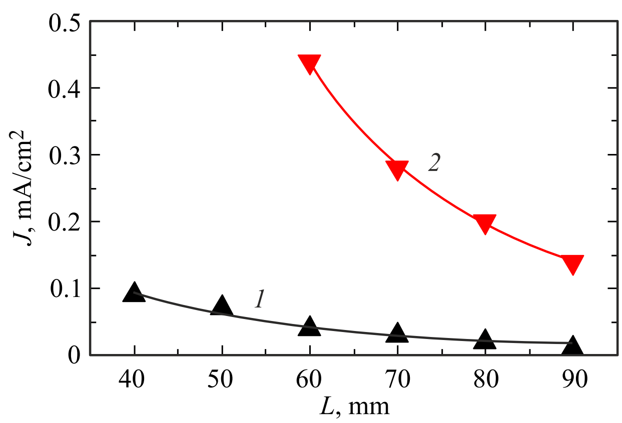

Figure 3. Densities of ion current versus various distances from the cathode. *1* — magnetron without external magnet, *2* — magnetron with external magnet.

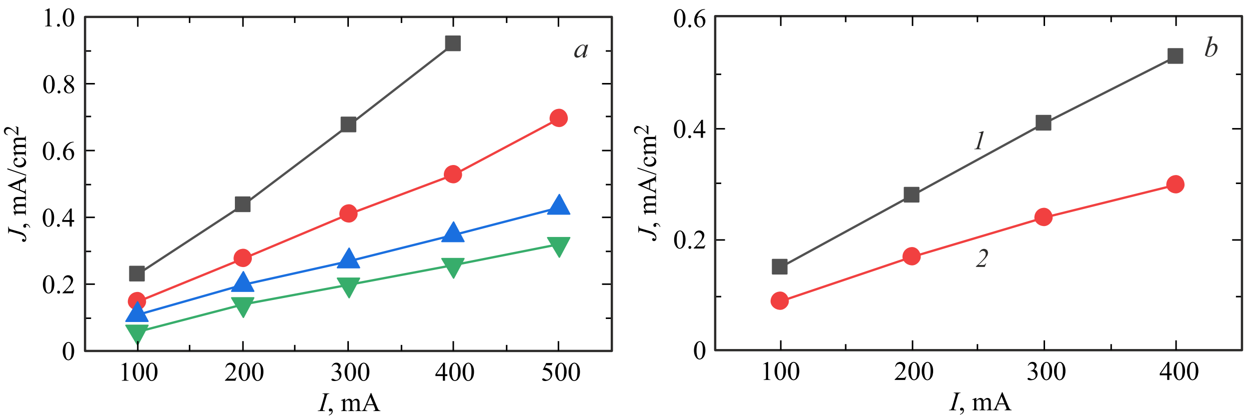

Figure 4. Densities of ion current versus magnetron discharge current: *a* — at different distances *L* from the cathode to the substrate: ■ — 60 mm, • — 70 mm, ▲ — 80 mm, ▼ — 90 mm; *b* — discharge with a copper target in a medium of various gases: *1* — argon, *2* — oxygen.

located at a height of $h = 24$ mm from the cathode. Fig. 3 shows that with external magnet, the ion current density increases by an order of magnitude at a distance of 70 mm from the magnetron. Due to divergence of the ion flux at a distance from the magnetron and the recharge of ions on gas atoms, the intensity of the ion flux goes down with increasing distance from the magnetron.

The ion current density (Fig. 4, *a*) increases linearly depending on the magnetron current at the discharge voltage 320–350 V, since plasma density generated by magnetron rises with the growing discharge power.

The magnetron with external magnet demonstrated stable operation at a pressure of 0.4–0.5,Pa with various operating gases: argon, oxygen, and a mixture of argon and nitrogen to fabricate the films of metals (Cu, Al, Ti, Mo, Pt), metal oxides, and nitrides. Oxygen was used instead of argon to compare the deposition rates of copper and copper oxide films [14].

The ion current density on the substrate for these films also increased with the rise of discharge current (Fig. 4, *b*). The deposition rate of copper was 52 nm/min when sputtering the cathode with argon atoms. The magnetron discharge in oxygen environment was stable at oxygen pressure of 0.5 Pa. The thickness of deposited oxide coating was 320 nm at a deposition rate of 7 nm/min. The deposition rate of copper oxide was several times lower than that of copper due to the low sputtering rate of the copper cathode with lighter oxygen ions, as well as due formation of an oxide film on the cathode surface, which changed the sputtering coefficient. Similar dependencies were obtained when depositing AlN film using aluminum cathode and a mixture of argon with nitrogen.

The advantage of a magnetron fitted with external magnet compared to a magnetron without a magnet is its stable operation when using oxygen as an operating gas. Typically, a mixture of argon and oxygen is used to precipitate metal oxide films. If only oxygen without argon is used for magnetron discharge, then when discharged at direct current, the metal target is oxidized to form an oxide layer on its surface. Due to accumulation of surface charge on the oxide layer, sparking and frequent electrical breakdowns may occur. The dielectric layer also prevents the flow of the discharge direct current. The film sputtering rate goes down. The magnetron stops its stable operation. In the oxygen/argon mixture, argon ions bombard the target surface, clean it from oxides by sputtering the atoms of dielectric film. As a result, the magnetron discharge becomes stable, but part of the discharge power is spent on ionization of argon atoms, which reduces its efficiency.

In the proposed magnetron fitted with external magnet, the discharge was burning stably when oxygen was supplied to the vacuum chamber. There is no complete coating of the target with an oxide film on its surface. The magnetron also worked stably with an argon/nitrogen mixture to produce films of copper nitride and aluminum nitride.

2.4. Spatial distributions of the ion flux during displacement of external annular magnet

The shape of the glowing plasma changed when the external annular magnet was removed from the magnetron cathode (Fig. 5).

As the distance h between the magnet and the magnetron increases, the cross-section of the luminous plasma flux is reduced. To measure the density distribution of the ion current in the cross section, a probe in the form of a Faraday cylinder with an electric displacement was used, which could move across the plasma flux. The anode didn't change its position relative to the substrate. The external magnet was moving vertically.

It can be seen from Fig. 5, *a* that at $h = 20$ mm, a plasma ring about 25 mm in diameter with a low ion flux intensity in the center is formed. The diameter of the ring is almost equal to the diameter of the plasma ring at the cathode, which corresponds to the diameter of the annular groove on the magnetron cathode. When the external magnet is displaced from the magnetron, the force lines of magnetic trap with a „cork“ configuration

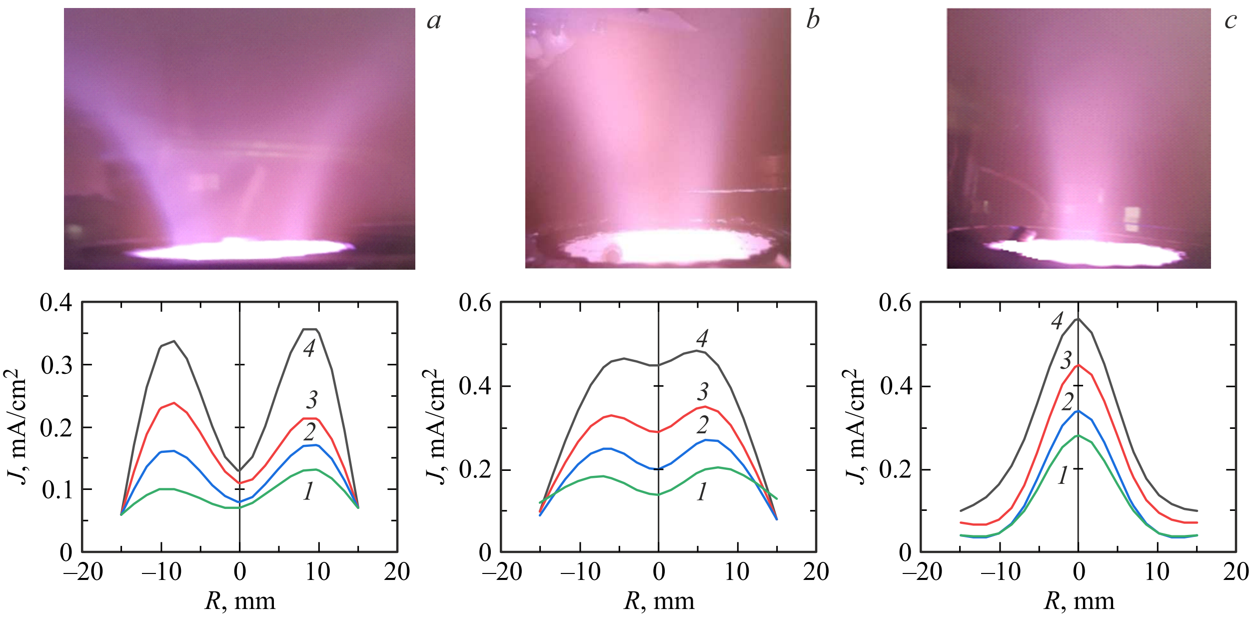

Figure 5. Plasma glow between the magnetron and substrate and distribution of ions density in plasma cross-section at different distances h of external magnet from the cathode: a — 20 mm, b — 24 mm, c — 34 mm at a distance of L from the magnetron to the substrate: *1* — 60 mm, *2* — 70 mm, *3* — 80 mm, *4* — 90 mm.

in the center of the cylindrical anode start to change their shape. At a distance of $h = 24$ mm from the external magnet to the cathode (Fig. 5, b), the plasma cross-section decreases, plasma is formed along the magnetron axis, and the uniformity of the cylindrical ion flux in the cross-section improves. When the external magnet is further removed from the magnetron, the ion flux becomes narrow (Fig. 5, c). The maximum value of the ion current density increases to 0.55 mA/cm^2. Probably, when permanent magnet is located not far from the magnetron (Fig. 5, a), the ionization of ions is significantly influenced by the magnetic field of the magnetron. It can be seen that the cross-section size of the ion flux at the substrate at a distance of 60–90 mm coincides with the size of the plasma ring above the magnetron cathode. With external magnet is significantly displaced from the magnetron (Fig. 5, c), the ion flux near the substrate is affected by the magnetic field of external magnet, since the plasma flux jet is compressed towards the axis of the magnetron in accordance with the magnetic field lines.

Another feature of a magnetron with external magnet is the increased ion current density on the substrate at a fixed distance from the magnetron when external magnet is significantly moved away from the magnetron (Fig. 6). An increase in the ion current density occurs simultaneously with a narrowing of the plasma region relative to the magnetron axis. It is likely that the flux of plasma electrons is concentrated near the magnetron axis, which leads to ionization of a large number of atoms in the gap between the magnet and the magnetron.

As the distance from the external magnet to the cathode increases from 20 to 34 mm, the annular ion flux transforms into an axial cylindrical ion flux. At that, the ion current density in the center rises from 0.12 to 0.45 mA/cm^2. Thus, by changing the configuration of the magnetron magnetic field using the external magnet, the cross section and density of the ion current can be adjusted.

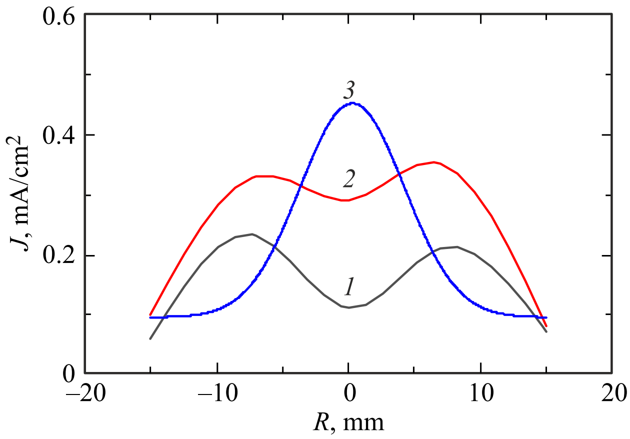

Figure 6. Dependences of the ion current density in plasma cross-section at the same distance of 80 mm from the cathode and different displacement h of external magnet: *1* — 20 mm, *2* — 24 mm, *3* — 34 mm.

3. Angular divergence of sputtered atoms

It could have been also assumed that the decreased diameter of the glowing plasma leads to lower angular divergence of the ion flux going to the substrate. To determine the trajectories of sputtered atoms, a bright

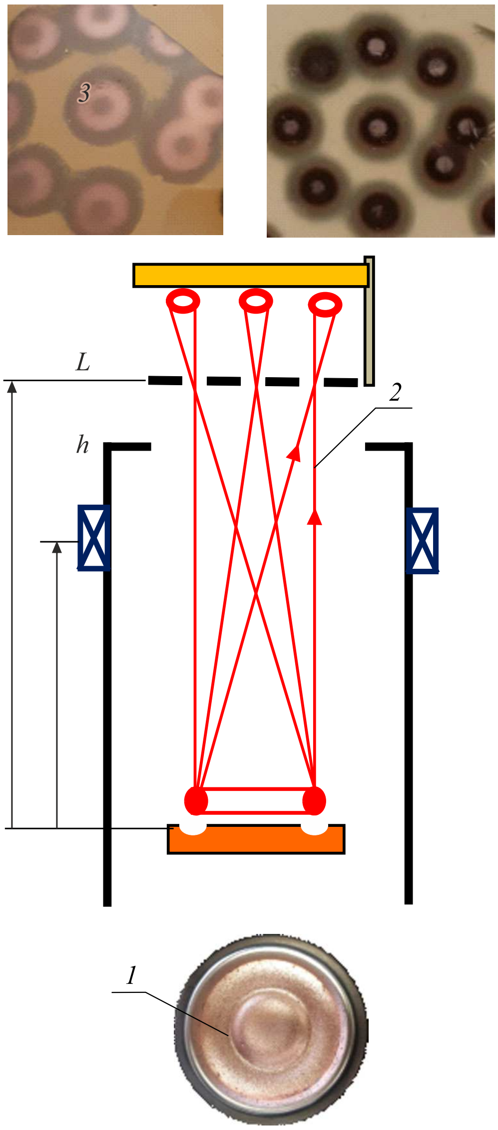

Figure 7. Diagram to measure the angular divergence of sputtered atoms: *1* — copper cathode of the magnetron, *2* — trajectories of sputtered copper atoms, *3* — an imprint on the substrate of dark-colored copper and copper oxide atoms and ions passing through the holes of the collimator.

imprint of copper atoms on a polycrystalline glass substrate was used, obtained over a short time interval during coating deposition. The angular distribution of the sputtered copper atoms was measured using a collimator based on the imprint on the substrate (Fig. 7). The diameter of the small annular copper imprints on the substrate decreased as the collimator was removed from the magnetron. The lines drawn through the collimator hole from the annular copper imprint on the substrate towards the magnetron passed through the cathode groove, above which a plasma ring was formed. This correlates with a rectilinear motion of the sputtered atoms from the target to the substrate. The same ring-shaped oxide imprints were obtained by using oxygen as an operating gas (Fig. 7). The size of the copper imprints did not change when the external magnet was displaced relative to the magnetron.

Thus, when a magnetron operates with an external magnet, electron ionization of the atomized atoms occurs along the trajectory of their movement to the substrate. The magnetic field has little effect on the rectilinear motion of ions due to their large mass compared to the mass of electrons.

Conclusion

An external permanent magnet placed above the magnetron changes the configuration of the magnetron's magnetic field. The electrons ionize the atomized atoms along the trajectory of their movement from the magnetron to the substrate. At a large distance from the substrate, the ion density in the flux of deposited atoms increases. By installing external magnet on the anodes of magnetrons of various designs, it is possible to increase the ion component of the current in the sputtered atoms flow, if the growing film requires additional bombardment by ions. The energy of the incident ions is regulated by changing the negative bias voltage of the substrate.

As a result of electron confinement in the combined magnetic field of an external magnet and magnetron, a discharge in the environment of argon, oxygen, and a mixture of argon and nitrogen glows steadily at a pressure of about $0.3-0.5$,Pa. A decrease in the operating pressure leads to less scattering of the deposited atoms on the atoms of the operating gas. With an external magnet installed in front of the magnetron, the ion current density on the substrate is an order of magnitude higher than without an external magnet. The ion current density is proportional to the magnetron discharge current. This is due to an increase in the density of plasma generated by it. The axial displacement of external magnet relative to the magnetron significantly impacts the ion current density and the cross section of the intense ion flux onto the substrate. Magnetic field of external magnet increases the efficiency of electron ionization of atoms and does not impact the rectilinear trajectory of the ions moving to the substrate due to significant difference in the masses of ions and electrons.

Conflict of interest

The authors declare that they have no conflict of interest.

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