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Improvement of coating deposition and target erosion uniformity in rotating cylindrical magnetrons

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Abstract

Cylindrical magnetrons with rotating cathodes have found wide application in the thin-film coating deposition technologies owing to a higher degree of the target utilization and used power level as compared with planar magnetrons. The aim of this work was to increase the efficiency of cylindrical magnetrons. It is known that the region of uniform coatings deposition with extended magnetrons is essentially lower than the sputtered cathode length. The actual achievable cathode utilization degree is limited, with the regions at cathode ends having a higher wear rate than the central part. To eliminate these shortcomings, experiments were carried out on the creation of a magnetic system to allow an increase of the coating deposition uniformity and target utilization. Resulting from the investigations that were carried out, a magnetic system design with an increased magnetic field at its ends (by 5–15%) and modified turn-around parts has been developed. This magnetic system design allows extending the coating deposition region with the uniformity of ±1% by 12.5 cm and completely eliminating accelerated erosion of the end cathode parts. The obtained results are promising for use in technologies of deposition of thin-film coatings with a high degree of uniformity (no worse than ±1%) onto large-area substrates.

Keywords: Large-area substrate; Magnetron sputtering; Target erosion; Uniform deposition

1. INTRODUCTION

There exist many applications for film coatings deposited by a magnetron sputtering method. Some coatings, for example, low-emissive, optical ones, are deposited mainly onto large-area substrates and require a high degree of thickness uniformity along the whole substrate surface. Cylindrical magnetrons with rotating cathodes are suitable for depositing these coatings in industrial scales in the best way (Kukla, 1997). In comparison with flat magnetrons, they have a higher degree of target utilization, used power level, and operation stability in the processes of reactive coating deposition. However, cylindrical magnetrons with rotating cathodes have some shortcomings due to their characteristic geometry. The first shortcoming typical of all extended magnetrons irrespective of the target form is that the region of uniform coating deposition is essentially less than the sputtered cathode length (Ananyin *et al.*, 1998). This occurs due to the lower coating deposition rate at the substrate ends than at its central part because of a nonsymmetrical sputtering diagram. Therefore, depending on the required uniformity, we have to fabricate magnetrons with cathode dimensions that are 30–60 cm larger than the dimensions of the processed substrates. This results in a cost increase for both magnetrons and the vacuum setup as a whole. The second shortcoming is the accelerated erosion of the end cathode parts (Vanderstraeten *et al.*, 1998; De Bosscher & Lievens, 2002). The magnetic system creates a magnetic trap for electrons over the cathode surface that determines the erosion zone often called a "race track." The race track consists of two parallel erosion grooves closed at the ends with U-bend parts. The top of the U-bend presents a length of the plasma race track that remains at the same longitudinal position as the target rotates. This leaves a circular groove around the target tube at both ends. Target life is limited by the depth of this groove. To decrease erosion at the cathode ends, an increase in its thickness or of the sputtered groove width in the places with accelerated erosion is sometimes used (Hartig *et al.*, 1994; Vanderstraeten *et al.*, 1998). However, the shortcoming of these methods is a magnetic field decrease at the target surface, resulting in electron losses and instabilities in magnetron discharge plasma. Application of cathodes with the end parts made of a material with a low sputtering rate is undesirable as well since ingress of this material onto the substrate is inevitable.

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This article presents results of the experiments directed to creation of a magnetic system design allowing increasing the coating deposition and target erosion uniformity in a cylindrical magnetrons with a rotating cathode.

2. EXPERIMENTAL

2.1. Sputtering system

Figure 1 presents the schematic of the setup of the experiments. A vacuum chamber (1) has the dimensions of 600 × 600 × 600 mm^3 and is pumped off with a diffusion pump. A cylindrical magnetron with a rotating cathode (2) is placed vertically inside the vacuum chamber. The 80-mm outer diameter and 600-mm long cylindrical cathode of the magnetron can rotate around the magnetic system with the speed of up to 50 rpm. Cathode rotation is realized with a motor (3) by means of the belt drive (4). In the experiments aluminum and titanic targets were used. A magnetic system shown in Figure 2 is placed inside the cathode. It consists of linear (1) and turn-around (2) parts forming a closed sputtering race track on the target surface. The linear part consists of three lines of permanent magnets placed at a core (3). The lines of the outer magnets (4) are connected with each other with the end magnets (5). Between the end magnets and the line of the central magnets (6) there is a gap ΔX.

The vacuum chamber walls served as the discharge anode. Coating deposition was realized at the pressure of 1 mTorr and sputtering power of 3 kW. The substrate (5) movement 4 cm from the sputtered cathode surface was performed for the uniform coating deposition along the substrate width.

2.2. Measurements

Magnetic field value at the cathode surface was determined with a magnetic induction meter RSH1-10 (Izmeritel, St. Petersburg, Russia) that has a standard measurement error of ±1%. The deposited film thickness was measured with an interferometer MII-4 (LOMO, St. Petersburg, Russia). Measurement error in these cases was no higher than ±0.5%. Homogeneity of target erosion along its length was determined by means of the cathode erosion depth measurement with an error of ±0.01 mm and further evaluation of the cross-sectional area of the erosion groove that was formed at a stationary cathode several hours after continuous magnetron operation.

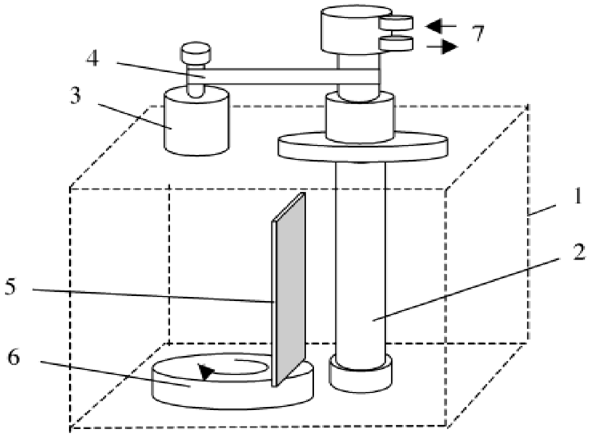

Fig. 1. Sputtering system: 1: vacuum chamber, 2: rotating cathode, 3: motor, 4: belt gearing, 5: substrate, 6: rotating table, 7: cooling water.

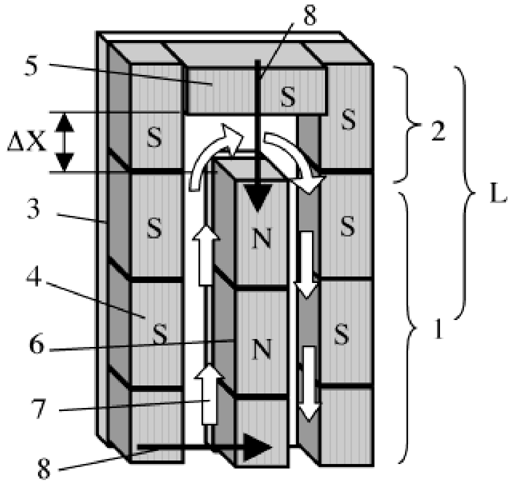

Fig. 2. Magnetic system scheme: 1: linear part, 2: turn-around part, 3: core, 4: outer magnets, 5: end magnets, 6: central magnets, 7: direction of electron $E \times B$ drift, 8: direction of magnetic field measurement.

3. RESULTS AND DISCUSSION

The first series of experiments was devoted to investigation of the width of the uniform coating deposition region formed with extended magnetrons. A lower rate of coating deposition at the end cathode parts is characteristic of extended magnetrons. The reason is solely geometrical. In the central part of substrate, the fluxes of sputtered atoms from both sides from the deposition point are summarized while the end parts are deposited from one side only. The experiment carried out with a 52-cm-long magnetic system providing a traditionally used uniform magnetic field (Shidoji *et al.*, 2000) confirmed this fact. Magnetic field distributions over the cathode surface in the regions of linear and turn-around parts of the magnetic system for this case are shown in Figure 3. Magnetic field measurement was carried out in the directions indicated with black arrows in Figure 2.

Figure 4, curve 1, shows the measured distribution of the coating thickness along the substrate length for this type of magnetic system. It is seen from the diagram that the region of coating deposition with the uniformity of ±1% makes up only 21.5 cm. Thus, the end cathode parts with a dimension of about 15 cm are used ineffectively from the point of view of the coating deposition uniformity.

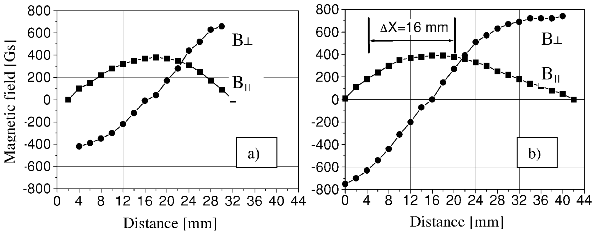

Fig. 3. Distributions of a longitudinal $B_{\|}$ and normal $B_{\perp}$ components of the magnetic field between the magnets: (a) on the linear part; (b) on the turn-around part of the magnetic system.

A uniform coating deposition region can be extended without increasing magnetron dimensions by means of a sputtering rate increase at the target ends to compensate for the lower sputtering rate at the substrate ends. This can be achieved by increasing the magnetic field at turn-around parts of the magnetic system (Ananyin *et al.*, 1998). However, this local increase of magnetic field results in very fast wear of the cathode end parts. So, it is more preferable to use a relatively lower magnetic field increase but at the extended by the length parts of the magnetic system. This magnetic system design is realized by replacement of the outer magnets at magnetic system ends (Fig. 2) by magnets with 5–15% higher magnetic field induction. Varying the number of these magnets in the magnetic system, one can change the length of the regions with increased magnetic field L. Figure 3, curve 2, presents the coating thickness distribution along the substrate length deposited with the use of magnetic system having $L = 10$ cm. It is seen from the diagram that the coating deposition region with the uniformity of ±1% increased from 21.5 cm to 30 cm. Increase of L up to the value higher than 10 cm gives no positive effect since the sputtering rate increase no longer takes place at the target ends.

In parallel with the experiments investigating the coating deposition uniformity investigations were carried out on the target sputtering uniformity along its length using different magnetic system designs. In the first experiment, the magnetic system provided a magnetic field with a uniformity no less than ±5% along its length and had a gap between the end and central magnets $\Delta X = 16$ mm. Figure 5 presents distributions of the depths and cross-sectional areas of erosion grooves along the race track length in the region of a magnetic field linear part. For the given magnetic system design, these distributions are very similar. It is seen from the diagrams that the sputtering rate at each erosion groove is changing by its length from one cathode end to another. Moreover, at the first groove the sputtering rate is higher at the upper cathode part, while at the second groove, it is higher at the lower cathode part. This cathode sputtering asymmetry is related to the drift electron motion over the cathode surface in the crossed electrical E and magnetic B fields (Wendt *et al.*, 1988; Sheridan *et al.*, 1990). For a magnetic system with a north pole placed in the center, electrons drift in the direction indicated with the arrows in Fig. 2. With the electron motion from one end of the race track to the other, concentration of electrons, and, hence, the cathode sputtering rate, are increased. In the region of a turn-around part of the magnetic system, electrons are forced to realize a sufficiently sharp transition from one sputtered groove to another and therefore some part of them is inevitably lost. However, most of the electrons after a turn continue their drift motion and the gradual increase of their concentration again results in the sputtering rate increase. Since after the turn electrons move in the opposite direction relative to the previous one, this results in the appearance of a region with a higher sputtering rate at the other cathode end (Chairev, 1999).

Figure 6 presents the distribution of the summary cross-sectional area of the erosion zone along the magnetron length, including the region over the turn-around part of the magnetic system. Curve 1 corresponds to the magnetic system with the uniform magnetic field along its whole length. In the curve, on the left, there is a region with the cross section exceeding the average one by 20%. The similar region is at the other end of the race track, but it is not shown in the

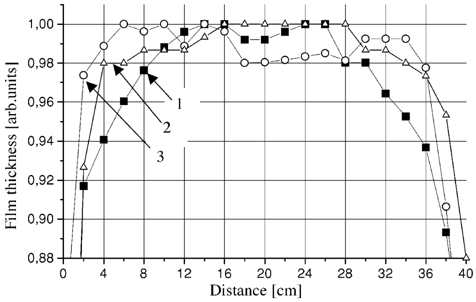

Fig. 4. Distribution of film thickness along substrate length: 1: magnetic system with uniform magnetic field; 2: magnetic system with the magnetic field increased at the ends; 3: magnetic system with the magnetic field increased at the ends and modified turn-around parts.

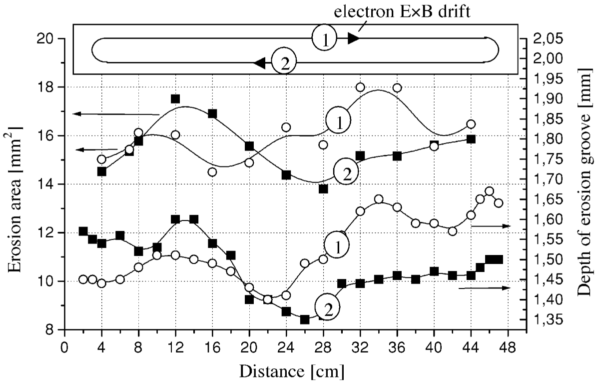

Fig. 5. Distribution of erosion grooves depth and cross-sectional area along the race track length for magnetic system with uniform magnetic field; 1,2: numbers of erosion grooves.

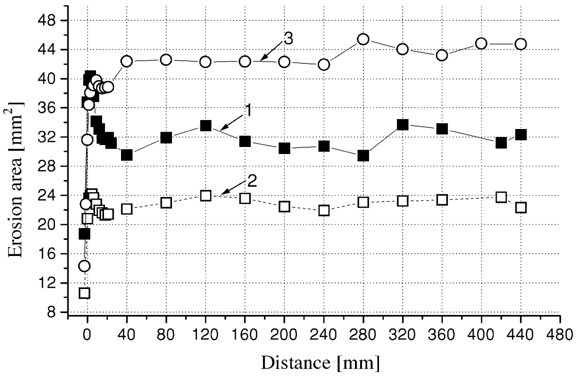

Fig. 6. Distribution of total erosion area along the magnetron length: 1: initial magnetic system (with uniform magnetic field); 2: magnetic system with modified turn-around parts; 3: magnetic system with the magnetic field increased at the ends and modified turn-around parts.

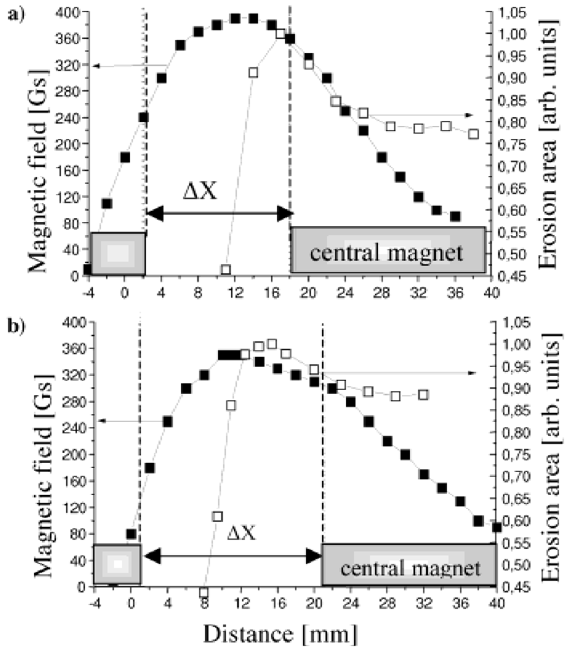

Fig. 7. Distribution of magnetic field and erosion area above turn-around part of the magnetic system: initial (a) and modified (b) constructions of magnetic system turn-around parts.

figure. These regions with accelerated erosion are at the cathode ends over the turn-around part of the magnetic system. Nonuniformities of the cathode sputtering at its linear part are caused by nonuniform sputtering along each race track side owing to the drift electron motion mentioned above.

To find the reasons for accelerated erosion, measurements were made of the magnetic field component $B_{\parallel}$ parallel to the sputtered target surface in the region of the turn-around magnetic system part. The measurements were made in the direction from the end magnet to the central one, as is shown with the arrow in Figure 2. Results of measurements of magnetic field and areas of erosion profiles in the accelerated eroding zone are joined in Figure 7a. Dotted lines show the boundaries of the gap ΔX. It is seen from the diagrams that the magnetic field maximum is shifted to the central magnet side due to the magnetic system geometrical features. This magnetic field distribution results in locating the erosion maximum in the immediate vicinity of the central magnet edge.

The turn-around part design of the magnetic system was modified with the gap ΔX extension and introduction of an additional magnet into it. This allowed shifting both magnetic field maximum and erosion maximum to the gap ΔX center (Fig. 7b). Target sputtering uniformity along the length of a magnetic system with modified turn-around parts is shown in Figure 6, curve 2. The sputtering rate at the target ends exceeds the average by only 5%.

Use of a modified turn-around part in the magnetic system with the magnetic field increased at the ends (L = 12 cm) completely eliminated the accelerated erosion at the cathode ends. In this case, the sputtering rate at the target ends is even less than at its linear part (Fig. 6, curve 3).

Distribution of the erosion groove depths and cross-sectional areas along the race track length for this magnetron system design are shown in Figure 8. Dotted lines indicate the boundaries of the regions with increased magnetic field. In this case, distribution of the depths and erosion areas along the cathode length have one important distinction. It is seen from the erosion depth diagrams that at both cathode ends there are parts with larger erosion depth that correspond to the regions with increased magnetic field in the magnetic system. However, these parts are unnoticeable in the diagrams of erosion area distribution along the cathode length. For a cylindrical magnetron with a rotating cathode, the target utilization degree is determined not with

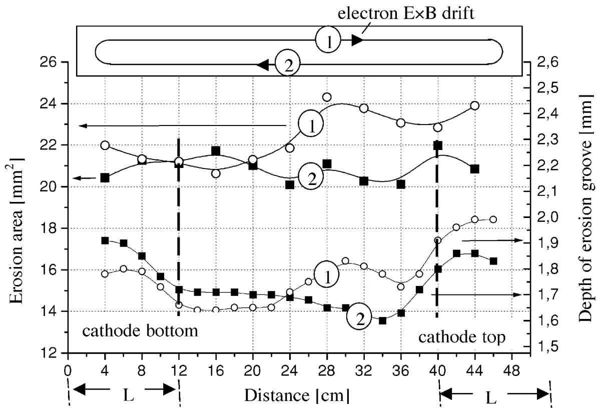

Fig. 8. Distribution of erosion grooves depth and cross-sectional area along race track length for magnetic system with the magnetic field increased at the ends and modified turn-around parts; 1,2: numbers of erosion grooves; L = 12 cm—areas with increased magnetic field.

the erosion depth but with its area. This gives us reason to believe that the presence of the parts with a 5–15% magnetic field increase in the magnetic system will not adversely affect the cylindrical target utilization.

It is interesting that a magnetic system with an increased magnetic field at the ends and modified turn-around parts has an advantage from the point of view of the coating deposition uniformity as well. Curve 3 in Figure 4 shows that the region of coating deposition with the uniformity of ±1% is extended from 21.5 cm to 33 cm when this magnetic system is used.

4. CONCLUSIONS

This article presents the results of the investigation of a magnetic system design influence on the coating deposition and target erosion uniformity in a rotating cylindrical magnetron. It has been shown experimentally that use of a magnetic system with the magnetic field increased at its ends (by 5–15%) and modified turn-around parts allowed decreasing dimensions of ineffectively used cathode regions and increasing the coating deposition region with the uniformity of ±1%. Measurements of the erosion area along the target length have shown that there was no noticeable increase in the erosion rate at the parts with an increased magnetic field, and accelerated erosion at the cathode ends is eliminated completely. Modifications made in the magnetic system design allow increasing possibilities for cylindrical magnetrons with rotating cathodes in achieving coating uniformity at large-area substrates and in the target utilization degree increasing.

ACKNOWLEDGMENTS

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