

**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 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. Really achievable cathode utilization degree is limited with the regions at cathode ends having higher wear rate than at the central part. In order to eliminate these shortcomings, there were carried out experiments on creation of a magnetic system allowing increasing the coating deposition uniformity and target utilization. Resulting from the investigations that were carried out, a magnetic system design with 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 $\pm 1\%$ by 12.5 cm and completely eliminating accelerated erosion of the end cathode parts. The obtained results are promising for using in technologies of deposition of thin-film coatings with high degree of uniformity (no worse than $\pm 1\%$) onto large-area substrates.

KEYWORDS: magnetron sputtering, target erosion, uniform deposition, large-area substrate

1. INTRODUCTION

There exist many applications of film coatings deposited by a magnetron sputtering method. Some coatings, e.g., low-emissive, optical ones, are deposited mainly onto large-area substrates and require 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 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, 1998). This occurs due to the less coating deposition rate at the substrate ends than at its central part because of nonsymmetrical sputtering diagram. Therefore, depending on the required uniformity, we have to fabricate magnetrons with cathode dimensions being 30-60 cm larger than dimensions of the processed substrates. This results in the cost increase of both magnetrons and a vacuum setup as a whole. The second shortcoming is the accelerated erosion of the end cathode parts (De Bosscher & Lievens, 2002; Vanderstraeten et al., 1998). Magnetic system creates a magnetic trap for electrons over the cathode surface that determines the erosion zone often called as 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 round the target tube at both ends. Target life is limited with the depth of this groove. To decrease erosion at the cathode ends, increase of its thickness or of the sputtered groove width in the places with accelerated erosion is used sometimes (Vanderstraeten et al., 1998; Hartig

et al., 1994). However, the shortcoming of these methods is 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 low sputtering rate is undesirable as well since ingress of this material onto the substrate is inevitable.

This paper 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.

Fig. 1 presents the schematic of the setup at which the experiments were carried out. A vacuum chamber 1 has the dimensions of $600 \times 600 \times 600$ mm³ and is pumped-off with a diffusion pump. A cylindrical magnetron with a rotating cathode 2 is placed vertically inside the vacuum chamber. A 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 there were used aluminum and titanic targets. A magnetic system shown in Fig. 2 is placed inside the cathode. It consists of a 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 at

a 4-cm distance 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 standard measurement error of $\pm 1\%$. The deposited film thickness was measured with an interferometer MII-4 (LOMO, St.-Petersburg, Russia). Measurement error in these cases was no higher than $\pm 0.5\%$. Uniformity of target erosion along its length was determined by means of the cathode erosion depth measurement with error of ± 0.01 mm and further evaluation of cross-section area of the erosion groove that was formed at a stationary cathode several hours after continuous magnetron operation.

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. Less rate of coating deposition at the end cathode parts is characteristic of extended magnetrons. The reason is only geometrical. In the central substrate part 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 Fig. 3. Magnetic field measurement was carried out in the directions indicated with black arrows in Fig. 2.

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

A uniform coating deposition region can be extended without increasing magnetron dimensions by means of the sputtering rate increase at the target ends in order to compensate less sputtering rate at the substrate ends. This can be achieved increasing 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 preferably to use relatively less magnetic field increase but at the extended by the length parts of the magnetic system. This magnetic system design is realized by replacement of outer magnets at magnetic system ends (Fig. 2) for the 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 . Fig. 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 $\pm 1\%$ 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 on investigation of the coating deposition uniformity there were carried out investigations of the target sputtering uniformity along its length at different magnetic system designs. In the first experiment, magnetic system provided a magnetic field with the uniformity no less than $\pm 5\%$ along its length and had the gap between

the end and central magnets $\Delta X = 16$ mm. Fig. 5 presents distributions of the depths and cross-section 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 much 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 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 make drift motion in the direction indicated with the arrows in Fig. 2. At the electron motion from one end of the race track to another, concentration of electrons, and hence, cathode sputtering rate are increased. In the region of a turn-around part of the magnetic system electrons are forced to realize sufficiently sharp transition from one sputtered groove to another and therefore some part of them is lost inevitably. However, most of electrons after a turn continue their drift motion and 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 appearance of a region with higher sputtering rate at the other cathode end (Chairev, 1999).

Fig. 6 presents distribution of the summary cross-section area of 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 figure. These regions with accelerated erosion are at the cathode ends over the turn-around part of the magnetic system. Non-uniformities of the cathode sputtering at its linear part are

caused with non-uniform sputtering along each race track side owing to drift electron motion mentioned above.

To find the reasons of accelerated erosion, there were made measurements of the magnetic field component $B_{||}$ 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 it is shown with the arrow in Fig. 2. Results of measurements of magnetic field and areas of erosion profiles in the accelerated eroding zone are joined in Fig. 7a. Dotted lines show the boundaries of the gap ΔX . It is seen from the diagrams that 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 from the central magnet edge.

The turn-around part design of the magnetic system was modified with the gap ΔX extension and introducing 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 Fig. 6, curve 2. Sputtering rate at the target ends exceeds the average one by 5% only.

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

Distributions of the erosion groove depths and cross-section areas along the race track length for this magnetron system design are shown in Fig. 8. Dotted lines indicate the boundaries of the regions with increased magnetic field. In this case distributions of the depths and erosion areas along the cathode length have one important distinction. It is seen from the erosion depth diagrams that at the 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 at 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 the erosion depth but with its area. This gives the reason to believe that presence of the parts with increased by 5-15% magnetic field in the magnetic system will not adversely affect the cylindrical target utilization.

It is interesting that magnetic system with increased magnetic field at the ends and modified turn-around parts has advantage from the point of view of the coating deposition uniformity as well. Curve 3 in Fig. 4 shows that the region of coating deposition with the uniformity of $\pm 1\%$ is extended from 21.5 cm to 33 cm in case of using this magnetic system.

4. CONCLUSIONS

This paper presents the results of 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 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 $\pm 1\%$. Measurements of erosion area along the target length have shown that there was no any noticeable increase of erosion rate at the parts with increased magnetic field and accelerated erosion at the cathode ends is eliminated completely. Modifications made in the magnetic system design allow increasing possibilities of cylindrical magnetrons with rotating cathodes in achieving coating uniformity at large-area substrates and in the target utilization degree increasing.

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FIGURE LEGENDS

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.

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.

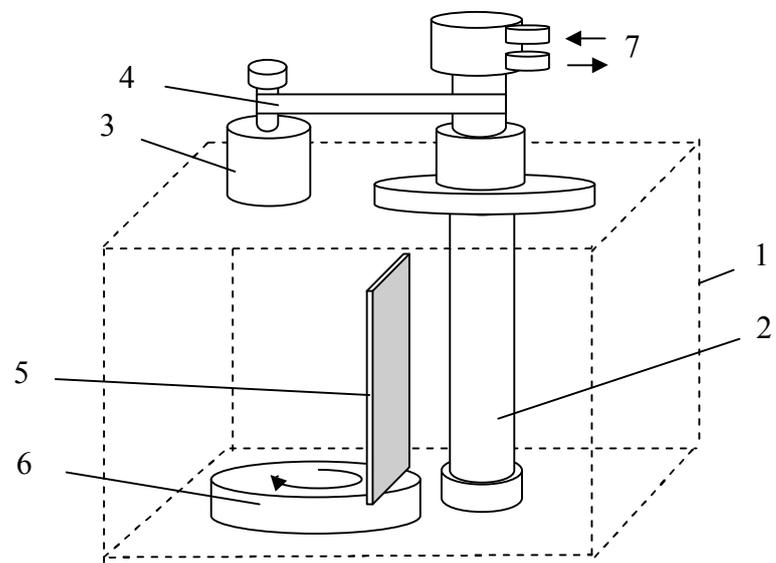
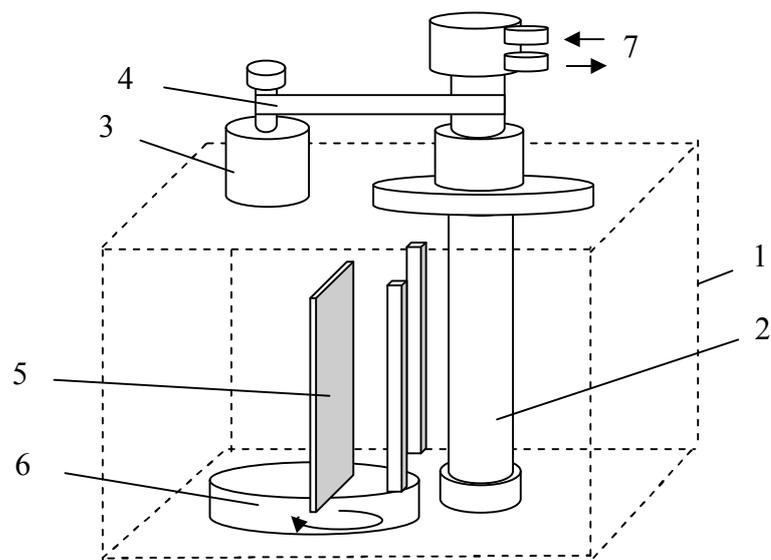
Fig. 4. Distribution of film thickness along substrate length: 1- magnetic system with uniform magnetic field; 2- magnetic system with increased at the ends magnetic field; 3- magnetic system with increased at the ends magnetic field and modified turn-around parts.

Fig. 5. Distributions of erosion grooves depth and cross section area along 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 increased at the ends magnetic field 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.

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

**Fig. 1**

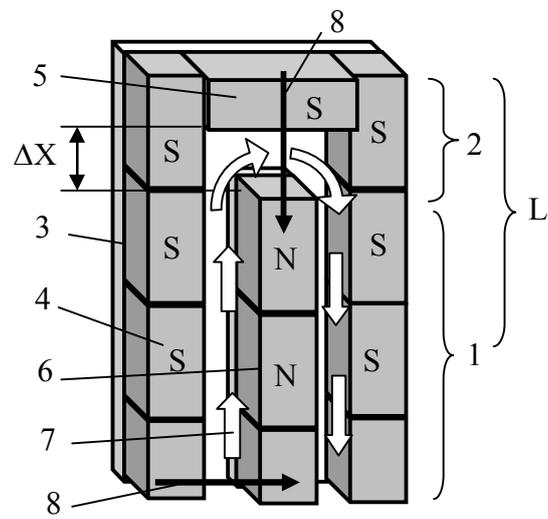


Fig. 2

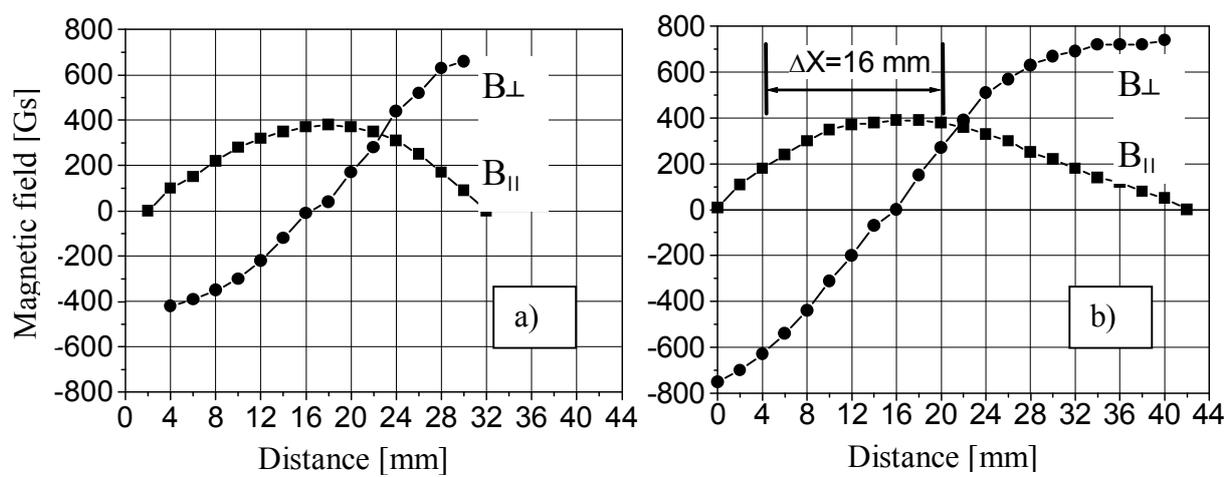
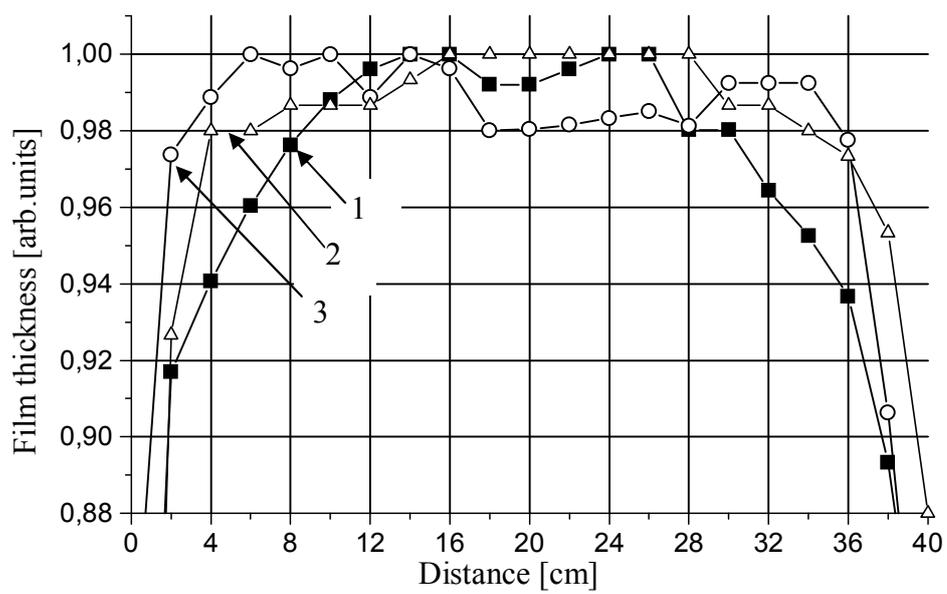


Fig. 3

**Fig. 4**

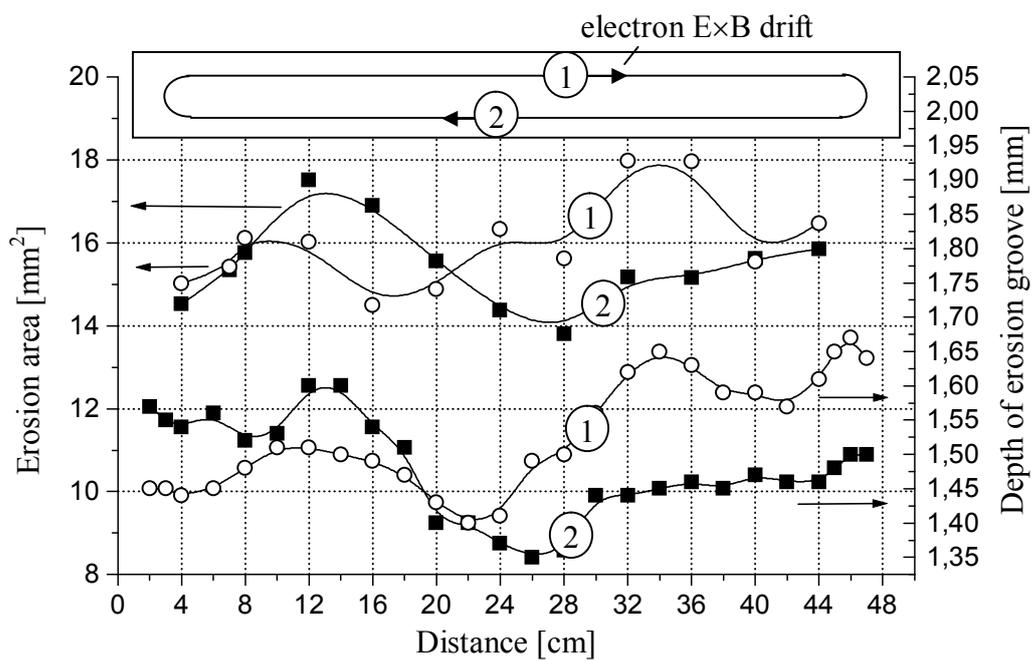
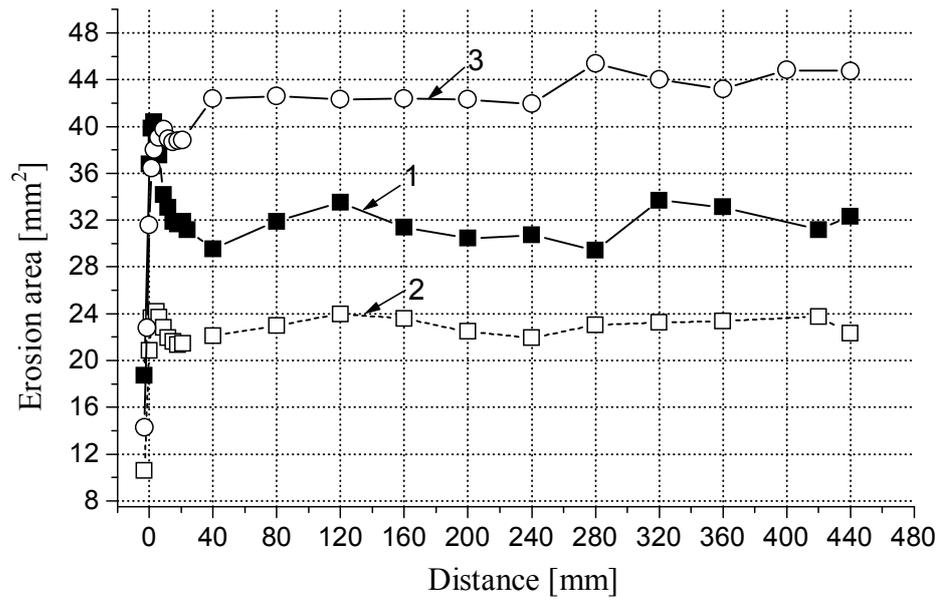


Fig. 5

**Fig. 6**

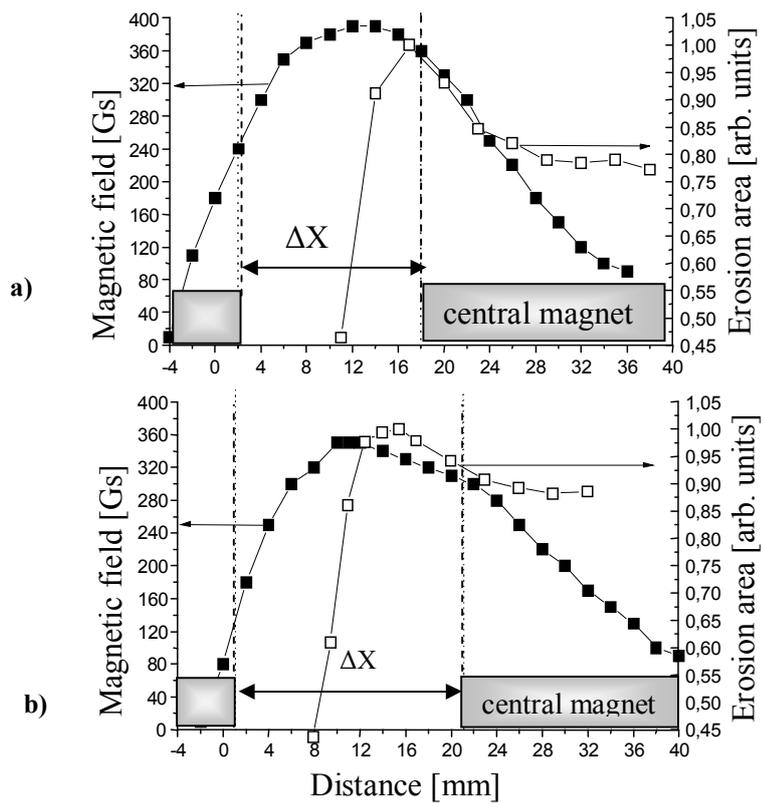


Fig. 7.

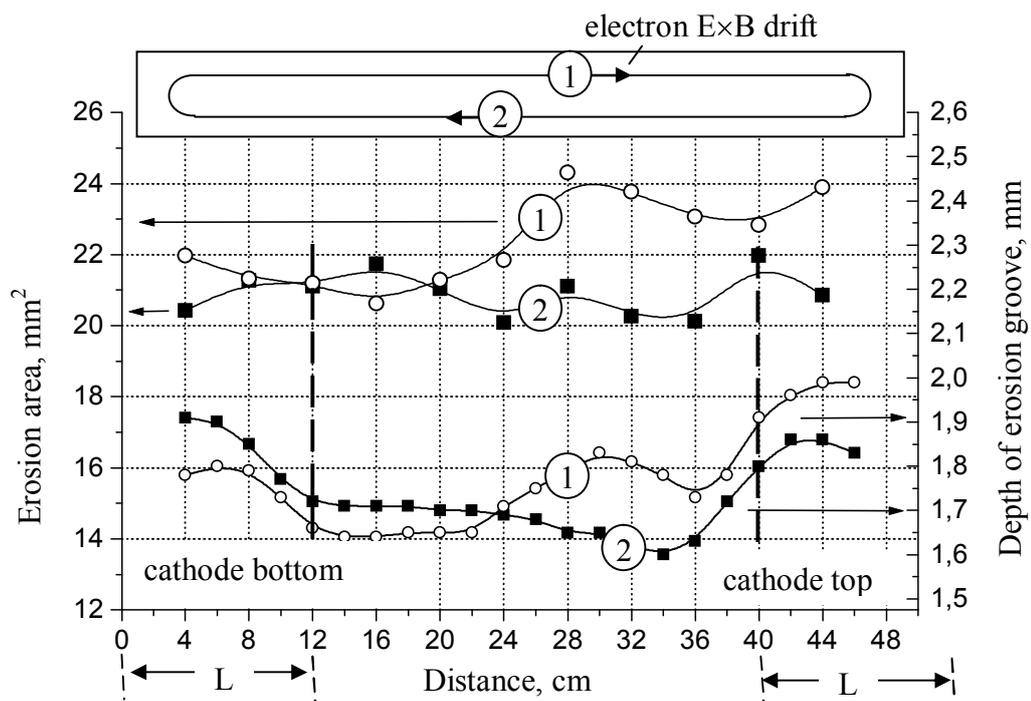


Fig. 8.