The influence of the discharge current axial component on the magnetic field distribution in the cathode region of magnetron sputtering system

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Abstract. The paper includes the description of the mathematical model, which simulates magnetic field distribution in the cathode area of the sputtering system discharge considering the current created by electrons moving along the surface of cathode-target. Presented results of the numerical modeling were received using the developed model. It is also shown that the current component, directed along the cathode surface significantly impacts total magnetic field distribution in the magnetron discharge.

1. Introduction
The properties of the discharge ignited in the crossed electric and magnetic fields depend on the complicated character of the electron motion in the cathode area of this discharge. Special conditions in the area are created in the way to force the electrons overcome the distance between cathode and anode couple thousand times. As a result of low pressure (meaning longer free path for electrons and ions) a significant energy flow might be reached on the surface of the cathode. It allows using the discharge to sputter the target more effectively. This principle is the main idea of magnetron sputtering systems [1]. These systems are widely used in manufacturing, though a number of the problems of maintaining such type of discharge is still unsolved. First problem is the mechanisms of forming the current density on the surface of the cathode, especially at high-power pulsed sputtering [2]. Another problem is the possibility of decreasing the operating pressure in the system lower than 0.1 Pa [3]. Such a decrease improves the flexibility of the system, allows controlling the coatings thickness, modifying the sputtering process with ion bombardment of the growing coating [4]. It all opens the new perspectives for applying magnetron sputtering systems for creating protective coatings and coatings with special properties [5].

In general, to simulate the processes in magnetron sputtering system the expressions describing electric and magnetic field distribution with free electrons and their motion for every moment of the simulation must be solved. Also we have to consider the expressions describing the electrons incidents with gas molecules, expressions of the ion component drifting, etc. This problem is very complicated, but it might be solved in a number of separate steps.

And the first one in our opinion is the description of the magnetic field distribution near the sputtering system target. This paper is dedicated to calculating this field.
2. Model description

The most common construction of magnetron system is taken into consideration in the paper. This model includes the plane target (with electric field directed normal to the surface) and “arc” type of the magnetic field distribution.

To maintain such form of glowing discharge [6] the emitted from the cathode electrons get trapped by crossed electric and magnetic fields. Being trapped the electron moves along the cycloid trajectory until the collision with gas molecule happens (figure 1). The cycloid radius should be enough to make the electron reach a certain energy level to make the gas molecules ionization possible (condition defining the longitudinal component of the magnetic field) [7]. After inelastic (with energy loss) or elastic (only direction of movement changes) collision with molecule, the electron accelerated by electric field moves away from the cathode surface to a distance equal to Larmor radius. In the area where electron drifted the field decreases and the cycloid radius increases. It lasts until electron gets “trapped”, so before it reaches anode it moves along the surface of the target. Such motion causes axially directed current, which exceeds the discharge current many times (figure 1).

![Figure 1](image1.png)

**Figure 1.** The scheme of the cathode processes of the magnetron sputtering system, forming the most of discharge.

The ratio between these currents is equal to the ratio of the distances, which electron passes between cathode and anode. This ratio might be equal from couple hundreds to couple thousands. For example, when the discharge current is 5 A, the axial one is 10 000 A. The direction of the current is so that it’s magnetic field decreases the field of the permanent magnets at the target and increases it when moving away from it. Studying the summary of distribution of the magnetic field in the cathode area experimentally is very complicated. That’s why we made theoretical researches. The paper is dedicated to this mathematical model.

The geometry of the studied area and qualitative distribution of the lines of the magnetic field are presented in the figure 2. The half of the section of the studied area is presented. Permanent magnetic field is created by SmCo magnet 1. The lines of the magnetic field are commutated through the magnetic core made of electrotechnical steel 2. The vector of the magnetic field might be presented as vector sum of longitudinal ($H_r$) and transversal ($H_z$) 3. Over the target surface the current loop is placed 4, where the axial current flows. It’s width was defined experimentally according to a sputtering zone on the target surface.

Simulation of magnetic field distribution [8, 9] requires very complicated calculations, and the problem doesn’t have any particular analytical solution (especially considering real magnetic materials characteristics). That’s why this simulation was provided numerically using mathematical model created in ANSYS. The geometry of the model copied a real device. The field distribution was defined
by fourth Maxwell equation solution \( \text{div} \vec{B} = 0 \). Current loop with magnet fields were defined by solving first Maxwell equation solution \( \text{rot} \vec{H} = \vec{J} \), where \( \vec{H} \) is a vector of a magnetic field, \( \vec{J} \) is a current density in the loop. We presumed the axial current to fill the loop evenly.

![Diagram](image)

**Figure 2.** The geometry of studied area and qualitative character of magnetic field distribution.

Also in the figure 2 the boundary conditions are shown: I, II – zero magnetic field on a significant distance from the studied area; III, IV – no normal component of the magnetic field.

The results of the simulation for clarity are presented in 2-dimentional simplified plots. In the figure 3 two images of magnetic field simulation are presented (left is a case when there’s no axial current, right one is a case when axial loop current is 1 kA).

![Images](image)

**Figure 3.** Magnetic field distribution (left) without axial current and (right) with axial current influence on field.

However, in simulating the magnetic field of the sputtering system, the highest interest is in tangent component of \( \vec{H} \), directed along the target. In the figure 4 the tangent component of the magnetic field is presented, calculated for different distances from the magnetic system section. These results allow defining Larmor radius and choose the right target thickness for the magnetic system configuration.

The less gas pressure, the more free path distance of the electron hence the higher axial current. That’s why the results received when increasing \( I_a \) might be treated as field distribution when the gas pressure decreases with the same other conditions.

Consideration the axial current component influences the field distribution dramatically. So, in the figure 5 depicted the results of calculating the tangent component of the magnetic field on the surface...
of the target for different cases: without the axial current, with $I_a = 1$ kA (200 times more than discharge current) and with $I_a = 2.5$ kA (500 times more than discharge current). Wherein the maximal $H$ value decreases when axial current increases, the zone, where this value exists becomes wider.

**Figure 4.** The results of calculating the tangent component of magnetic field at different distances from the magnetic system.

**Figure 5.** Calculation results of tangent component of $H$ on the surface of the target (7 mm from the magnet system) for the cases without axial current, with $I_a = 1$ kA (200 times more than discharge current) and with $I_a = 2.5$ kA (500 times more than discharge current).

Another important plot (figure 6) is tangent component of the magnetic field distribution at different distances from the magnetic system at 1 kA axial current. It appeared to be that considering this
current allows aligning the tangent component of magnetic field at different distances from the target. In other words, the cyclotron radius doesn’t change at the distances up to the 5 mm above the target. This is the area of localization of the cathode area of magnetron discharge. Beyond this area the tangent component decreases significantly. It causes the cyclothrone radius increase and electron emission from the cathode area.

![Figure 6](image_url)

**Figure 6.** The results of tangent magnetic field calculation at different distances from the magnetic system. The current $I_a = 1$ kA.

3. Conclusions
1. The axial component of current influences the magnetic field in the area of the discharge dramatically.
2. The value of the magnetic field on the surface of the target decreases in the discharge area.
3. Increasing the magnetic field at the boundaries of the discharge might cause the forming additional “magnetic traps” there, preventing electrons from leaving the cathode area.

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