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Balanced magnetic field in magnetron sputtering systems

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ABSTRACT

Discharge characteristics of the planar axial magnetron sputtering systems (MSS) with different dimensions and level of unbalance of their magnetic systems were investigated. Additional coils were used to change the level of the magnetron unbalance (the configuration of the magnetic field over the target surface). For these configurations of the magnetrons, the dependencies of the discharge voltage, substrate ion current density, deposition rate, minimal working pressure on MSS geometrical unbalance (K_G) were received.

Based on the data obtained it was determined that for all MSS, independent of the dimensions of magnetic system, the magnetic field of balanced configuration is formed at $K_G = 1.235–1.27$, and the discharge voltage has maximal conductivity. If K_G is decreased the magnetic field with unbalanced configuration of second type is formed, at greater K_G the magnetic field of the first type is developed.

For all investigated configurations of the magnetrons the minimal working pressure can be reached at a lower level of the geometric unbalance ($K_G = 1.02–1.125$) compared to the minimal discharge voltage, and it is independent of the dimensions of magnetron's magnetic system.

1. Introduction

The magnetron sputtering method has undergone a tremendous growth during the latest three decades, when it became a dominating technique in the process of ion-plasma deposition of thin films for various purposes [1,2]. Initially applied for deposition of metal and alloy films, this technique has been ever-evolving. The configurations of magnetrons with a planar, cone, and cylindrical target were designed, as well as extended magnetron sputtering systems (MSS). The techniques of reactive, pulsed, and radio frequency magnetron sputtering were devised for compound film deposition.

The unbalanced magnetron (UBM) sputtering systems emerged during the ‘80s and were widely used for deposition of wear-resistant, low-friction, anti-corrosive, and decorative coatings. The term “unbalanced magnetron” was firstly used by *Window* and *Savvides* [3–5] when they studied seven planar magnetrons with different magnetic field configurations. Those configurations were divided into three groups (Fig. 1). The first one (Fig. 1 a) included a conventional or balanced magnetron (CM) with the inner and outer magnets placed in a way what all the magnetic lines coming out of one pole of at the target surface, were closed at another pole over the target surface. Compared to the conventional magnetron, the unbalanced one has only several lines of the magnetic field that are “closed” between the inner and outer poles in the magnetic system (Fig. 1 b, c). In the UBM of the type-1 (Fig. 1 b) the inner pole of the magnetic system is intensified in comparison with the outer pole. While the “unclosed” magnetic field lines from the inner pole tip are directed radially towards the chamber walls. The axial component of the magnetic field is practically eliminated, yielding low-density plasma in the substrate area. In case of the type-2 UBM (Fig. 1 c), the outer pole of the magnetic system was intensified as compared to the inner pole. In this case the “unclosed” magnetic-field lines from the cathode periphery were directed towards the substrate, and the ions could reach the substrate. Then ion currents of substantial density could be extracted from plasma, even without the additional substrate bias.

Initially it was proved by *Window* and *Savvides*, and by others afterwards, that for type-2 UBM the ion current density on the substrate can reach 5.0 mA/cm^2, being an order of magnitude higher than that in case of conventional magnetrons, and 5–100 times exceeded the ion current density obtained with the UBM of the type-1 [4–10]. It was also mentioned that the ion-to-atom ratio for the type-2 configuration was 2:1, whereas for the type-1 it was 0.00025:1 [4,6,7]. The conventional magnetron was defined as an ideal case of the magnetron, in which the inner and outer magnets are completely balanced, thus providing the maximal ionization in

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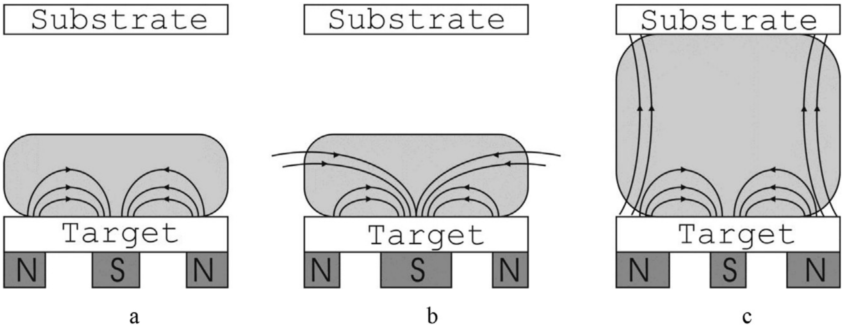

Fig. 1. Types of the magnetron configurations: *a* – conventional magnetron, *b* – unbalanced magnetron of the type-1, *c* – unbalanced magnetron of the type-2.

the vicinity of the target and minimizing the electron and ion heating of the substrate [1]. However, in practice all of the "balanced" magnetrons have some level of unbalance in their magnetic system, thus they can be referred to as UBMs of either the first or the second type.

It was further shown that other plasma parameters, such as electron temperature, plasma potential, plasma density, substrate-directed ions energy, and substrate bias voltage depended on magnetic system unbalance [11,12]. As a result, the properties of the deposed films (their structure, phase composition, and stoichiometry) were also directly related to the level of unbalance [13–17]. For characterizing the level of magnetron's magnetic system unbalance in these articles they used the magnetic field configuration, relation of volumes or magnetic flows of inner and outer magnets, the position of the line where the vector of magnetic field's vertical component was zero [11–23]. It is worth to mention that neither those, nor subsequent papers by different authors, devoted to this topic, contain precise criteria to refer a magnetron sputtering system to one of the three types presented above, which makes it impossible to compare various UBMs, and magnetron deposition conditions, presented by different authors. Therefore, this paper analyzes and compares discharge characteristics of a series of magnetron sputtering systems with different level of unbalance in order to set the MSS balance criteria, the correlation between the level of unbalance and the discharge characteristics, and to devise the procedure for identifying the MSS level of unbalance.

2. Experimental

Planar axial magnetron sputtering systems using targets of 40, 80, 100 and 160 mm in diameter were studied. Parameters of the magnetrons under investigation are rendered in Table 1. In each case, except for the MAC-160 magnetron, the main magnetic trap was formed by permanent magnets. An electromagnet was used as the source of the magnetic field for the main magnetic trap in MAC-160 with the target of 160 mm in diameter. Additional coils (see Table 1) were used for all types of the magnetrons to vary the ratio of the outer magnetic flux to inner magnetic flux (the level of unbalance), as previously proposed in the articles [24,25].

Fig. 2 shows a scheme of the experimental setup used to study the characteristics of the magnetron sputtering systems. The setup was based on a VU-2MP exhaust cart. During the experiment the magnetron sputtering systems were installed into the vacuum chamber one by one. Discs of Ti (99.5% purity) 3–8 mm thick, were used as the magnetron targets. A substrate of stainless steel, 300 cm^2 in area, was placed at a distance of 50–150 mm from the magnetron's target surface. At the substrate level the probes were mounted on a holder, moved by an electric motor. The Faraday cup probe was used to measure the ion current density. To measure the ion current, the probe was supplied with a negative bias potential $U_b = -90$ V enough to repel the electron flux. The voltage from the probe proportionate to the ion current density was converted through the ADC. A water-cooled quartz sensor was mounted next to the point probe to measure the deposition rate distribution. Variations in the quartz frequency were recorded by the Micron-5 quartz thin-film thickness controller. To prevent the influence of high-energy electron on the quartz generating frequency, the probe was equipped with a specialized magnetic system. The probes were moved along the sputtering area to form the deposition rate and ion current density distribution profiles. Data including the quartz frequency, ion current density and positions of the probes were processed using original software.

During the experiments, the vacuum chamber was pumped down to the residual pressure of 10^{-3} Pa. The target surface was cleaned of impurities before the experiments. For this purpose, the substrate with the probes was taken away from the sputtering area. Argon was supplied into the magnetron gas distribution system. The Ar flow rate depended on the type of the magnetron under investigation and ranged at 20–70 sccm. Whereas, the Ar flow was controlled by a RRG-1 mass flow controller. A 3.0 kW DC power supply, capable of operating either in discharge current or power stabilization modes, was used to supply power to the MSS. The

Table 1
Specifications of the magnetrons under study.

Magnetron	Main magnetic system		Additional coil	
	Magnets	Size of magnetic systems, $d_1/d_2/d_3 \times H$, mm (Fig. 3)	Size $D_1/D_2 \times H_c$, mm[a]	Wire diameter, mm/number of windings
RIF-040	Nd–Fe–B	13/28/34 × 10	65/88 × 24	0.6/550
MAC-80	Inner magnet – SmCo, outer magnet – strontium ferrite	18/52/70 × 30	*S1* 124/156 × 65 *S2* 127/153 × 45	0.7/2024 1.0/585
MAC-100	Nd–Fe–B	30/76/96 × 11	140/168 × 45	1.0/480
MAC-160	Coil 1200 winds ⌀ 1.5 mm	58/128 × 87[b]	206/235 × 39.5	1.5/220

[a] D_1, D_2 and H_c are internal and external diameters, and the height of the additional coil.
[b] For MAC-160 the main coil dimensions are given.