Magnetron with a sputtering unit for deposition of binary alloy films and solid solutions of two compounds

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Abstract. In this work, for the first time we present a magnetron with a sputtering unit used to deposit films of two metal alloys and binary solid solutions of simple compounds (oxides and nitrides). This unit contains two metal targets located on the same axis. The inner (cold) target is effectively cooled by running water, the outer (hot) target is cooled through the fastening elements and by radiation. The inner target is sputtered through slots in the outer target. Current voltage characteristics of a new magnetron working on direct current in inert and reactive environments have been studied. In pure argon with a low current, the V-I characteristics correspond to the mode of abnormal glow discharge, when the current increases, a maximum appears. In the reactive Ar + N₂ environment, the V-I characteristics have a maximum and three sections corresponding to the nitride, transition and metal modes of operation of the sputtering unit.

1. Introduction
An increasing interest was observed for inorganic coatings in the form of binary solid solutions of transition metal nitrides in the world. In 2010–2017 over 5000 articles were devoted to this topic (according to the Scopus database).

Presently, many leading world research centers synthesize these coatings. The greatest attention is paid to the TiAlN (figure 1) [1, 2]. Besides, TiTaN [3], TiCrN [4], TiVN [5, 6], TiMoN [7], TiZrN [8], AlCrN [9] are in the focus of the scientific community.

![Figure 1. Publications about coatings of different types (numbers indicate the percentage of articles published on the nitride film in 2010–2017).](image-url)
A variety of sputtering devices are used to deposit above films. They include, first of all, the devices containing two magnetrons with targets from different metals [10] or one magnetron with a compound target [11]. Usually the target is effectively cooled in these devices. At the same time, the magnetrons with targets that can be heated up to the melting temperature and higher are studied [12], [13]. The hot target mode is provided by removing heat from it through a gap of up to 1-mm-width and by fastening elements [14].

![Figure 2](image)

**Figure 2.** Magnetron with a sandwich–target: (a) – general view (1 – inner target, 2 – outer target); (b) and (c) are the photos of discharge with an external titanium target at low (heating is not noticeable) and medium (weak heating) power, respectively.

In this paper, we study a new type of magnetron with a sputtering unit, which was called a “sandwich–target”. The unit contains two targets of different metals located on the same axis (figure 2(a)). The inner target 1 is sputtered through the gaps of the outer target 2 and operates in a cold mode. The external target is set at a distance of 1 mm from the internal target and operates in hot mode. Obviously, in order to deposit films by the new device, it is necessary to study it thoroughly. In this paper, we focused on the study of the magnetron V-I characteristics in different gas environment.

2. Experimental
The experiments were performed on a balanced dc magnetron with a diameter of 130 mm. The magnetron is installed in a high-vacuum system equipped with oil-diffusion and mechanical pumps having a nominal operating speed of 0.3 m³/s and 0.005 m³/s, respectively. The volume of the vacuum chamber is 0.076 m³, its residual pressure did not exceed 5·10⁻⁵ mTorr. We studied the V-I characteristics of a magnetron equipped with:
- a hot titanium target of 2-mm-thick (without gaps) cooled through an aluminum board;
- the sputtering unit with targets:
  - inner one with thickness of 4 mm, made of aluminum;
  - outer one with thickness of 2 mm, made of titanium. Its gaps occupied 50% of the area of the sputtered ring region.
The V-I characteristic of each magnetron is measured in two media:
- Ar at a partial pressure in the range 2-7 mTorr;
- Ar + N₂ at a partial argon pressure of 2 mTorr and nitrogen flow in the range of 4-6 cm³/min. Argon and nitrogen of high purity were used to create gas environment.

3. Results and discussion
Figures 2(b), (c) show the photos of the sputtered unit made during the operation of the magnetron in different modes. In figure 2(c), the sputtered ring region is clearly visible, which is heated up more strongly than other target surface. Figure 3 shows the V-I characteristics of a magnetron with a sandwich–target operating in an argon environment (curves 1 and 2). These curves, same as for a magnetron with a single hot target (figure 3, curves 3 and 4), have extrema. And the discharge voltage of a magnetron with a sandwich–target is higher by 10–17 %. We assume that this result relates to an in-
ternal aluminum target. It is sputtered under 50% discharge current. The lower coefficient of ion-electron emission of aluminum compared to the titanium one requires a higher voltage for providing a given current (see [15] for relevant references). It should be kept in mind that an additional increase in the discharge voltage can be caused by the known effect of pressure reduction in the target region caused by the heating of the gas layers adjacent to it and called a “sputtering wind” [15].

In the initial section (up to about 50 mA/cm²), the V-I characteristic in figure 3 corresponds to an abnormal glow discharge, which is typical of a magnetron with a cold target. But for the above reasons, they grow with a larger derivative than the ones of the magnetron with cold and hot targets. In figure 3 there is another feature characteristic of an abnormal discharge. When the pressure increases, the invariance of the current density on the target is due to a decrease in the discharge voltage.

At a current of more than 50–60 mA/cm², the current-voltage characteristic of the studied magnetron has a form of the dependence, which is usually observed in the transition to the arc discharge. It can result from an increase in ion-electron emission when an external titanium target heats up to a temperature corresponding to the discharge current densities to the right of the maxima.

Figure 3. V-I characteristics of a magnetron with an Al + Ti (1 and 2) sandwich target and a single hot titanium target (3 and 4) at argon pressure (mTorr): 2 – solid lines; 7 – dashed lines.

Figure 4. V-I characteristics of a magnetron with an Al + Ti (1 and 2) sandwich target and a single hot titanium target (3 and 4) in Ar + N₂ at an argon pressure of 2 mTorr and nitrogen flow rate (cm³/min): 4 – solid lines; 6 – dashed lines.

Figure 5. Dependence of the total pressure on the discharge current density for the Al + Ti sandwich–target in Ar + N₂ at a nitrogen flow rate (cm³/min): 1–4; 2–6

Figure 4 shows the V-I characteristic of a magnetron with a sandwich–target operating in a mixture of argon and nitrogen (curves 1 and 2). These dependencies with extrema are similar to the V-I characteristic of a magnetron with a single hot target (figure 4, curves 3 and 4). Everything related to the emis-
sion of electrons in this case also has an effect, so the curves in figure 4 qualitatively do not differ from the dependencies in figure 3. The observed difference in the form of inflection points on the left sections, a larger discharge voltage and a shift to the right of the extremum position are determined by other physical processes. At low discharge current the sputtering unit operates in a reactive mode, when both targets are coated by a film of the corresponding nitride. In the region \( j > 100 \text{ mA/cm}^2 \), the targets operate in the metal mode. These features affect the emission in other way, and hence they have a different effect on the V-I characteristics of the discharge.

More precisely, the mode boundaries can be found based on the dependence of the total pressure \( P_2 \) on the current density (see figure 5). Figure 5 shows that at a nitrogen flow rate of 4 cm\(^3\)/min the exit from the nitride mode begins at \( j = 50 \text{ mA/cm}^2 \) and ends at \( j = 70 \text{ mA/cm}^2 \). An increase in the nitrogen flow rate to 6 cm\(^3\)/min results in a shift of the complete transition point of the target into the metal mode to \( j = 85 \text{ mA/cm}^2 \).

4. Conclusions
The study of the magnetron with a sandwich–target (Al + Ti) allowed revealing the individual physical features of the discharge in inert and reactive environment. The study was based on the analysis of the V-I characteristics.

In the argon environment, the current-voltage characteristics in the low-current region are similar to the dependences observed in a magnetron with a cold target. When the current increases, the voltage of the discharge increases smoothly, but with a larger derivative than the one of the magnetron with a cold and hot target. The curves reach an extremum, and then behave similar to the arc discharge.

In a mixture of argon and nitrogen, the V-I characteristics qualitatively are similar to the dependences obtained in pure argon. They differ by inflection points in areas to the left of the extrema, by a large discharge voltage and by shifting the extreme positions to the right.

All the revealed features are likely to be resulted from variations in the coefficient of ion-electron emission under different conditions and for different materials. Additionally, the effect of pressure reduction in the target region may influence the discharge.

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