Current-voltage characteristics of magnetron with hot target

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Abstract. In this paper, the discharge characteristics of the magnetron with a hot titanium target in inert and reactive environments have been experimentally studied for the first time. It is established that the current-voltage characteristics of the magnetron operating in the argon environment correspond to the abnormal glow discharge mode with a low current. When the current increases, they reach a maximum and depend on the pressure in the same way as in the case of a cold target. When the magnetron operates in the Ar+O₂ environment, the current-voltage characteristics have three sections corresponding to the oxide, transition and metallic target operation modes. In the transition mode, an increase in current leads to a significant decrease in voltage (by about 80 V or by 17%). In the region of higher currents, the target operates in stationary metallic mode, and the discharge voltage decreases, when the current increases. In this case, the transition from the oxide mode starts at the current density, which is approximately four times smaller than for a magnetron with a cold target. The V-I characteristics of a magnetron with a hot target are changed in Ar+N₂ environment at any nitrogen flow similarly to the V-I characteristics in the Ar+O₂. However, in this case the transition from the nitride mode to the metallic mode is observed at a current density, which is about twice as less as for a magnetron with a cold target.

1. Introduction
Films of metals and their compounds are deposited by magnetron sputtering, laser ablation and other methods [1–3]. The use of DC sputtering systems with hot targets is considered promising. In these systems, the magnetron is designed so that the surface temperature of the target can be increased up to the melting point. The results of the research of this topic can be found in [4–7], which include the extended reference list. In addition, the operations of magnetrons with liquid targets are investigated [8].

However, such systems have not yet found industrial application, since physical processes during the sputtering of hot targets have not been completely investigated. In particular, the concept of the current-voltage characteristic is very ambiguous. Even for a magnetron with a cold target, there is no single point of view on this issue. Many specialists recognize the equivalence between a vacuum diode and a gas discharge in a diode system and believe that the so-called «low 3/2» is valid for a gas discharge [9]:

\[ I \sim U^{3/2}. \] (1)

It should be noted that the recording of the current-voltage characteristic of a gas-discharge device in the form (1) can not be accepted as correct, since the current in the gas discharge is an independent variable. Using here (1), the authors of this paper follow the notations of the cited publications.

Strictly speaking, the law (1) is indeed valid, but only for a collisionless layer [10]. In a more general form, the relationship between the current \( I \) and the voltage \( U \) is described as [11, 12]
\[ I = kU^n. \]  

where \( k \) and \( n \) are constants that are adjustable parameters, when expression (2) is used to approximate the experimental results.

The influence of the target temperature on the magnetron V-I characteristics has not been discussed in the literature. In this paper, the distinctive features of the magnetron discharge with a hot titanium target in the inert and reactive environments have been experimentally studied for the first time.

2. Details of the experiment
The investigations were carried out in a high-vacuum system equipped with an oil-diffusion and mechanical pumps with a nominal operating speed of 0.3 m\(^3\)/s and 0.005 m\(^3\)/s, respectively. The volume of the vacuum chamber is 0.076 m\(^3\), its residual pressure did not exceed \( 5 \times 10^{-2} \) mTorr. The experiments are performed on a balanced magnetron with a diameter of 130 mm, equipped with titanium targets:

- 6 mm thick with typical cooling by running water (cold target);
- 1 mm thick with cooling through a vacuum gap of 1 mm from a cooper water-cooled board and by fastening elements (hot target).

The processes of magnetron sputtering in three environments are studied:

- Ar at a partial pressure in the range 2, 3 and 7 mTorr;
- Ar + O\(_2\) at a partial argon pressure of 2 mTorr and oxygen consumption of 4, 5 and 6 cm\(^3\)/min;
- Ar + N\(_2\) at a partial argon pressure of 2 mTorr and a flow rate of nitrogen of 4, 5 and 6 cm\(^3\)/min.

Argon, oxygen and nitrogen of high purity were used to create working gas.

In all cases, the magnetron operated at a constant current from 0.5 to 4.0 A at a voltage of 200–500 V.

3. Results and discussion
Figure 1 shows the V-I characteristics of magnetrons operating in argon. For a magnetron with a cold target, the result is typical: as the pressure is increased, the current density on the target remains unchanged by decreasing the discharge voltage. A similar pressure effect is also observed for a magnetron with a hot target. But there is a significant difference between them: the V-I characteristics of a magnetron with a hot target in the region of \( \sim 90 \text{ mA/cm}^2 \) have extremes, which can be caused by an increase in ion-electron emission from a target heated to a temperature corresponding to a discharge current density higher than 90 mA/cm\(^2\).

![Figure 1](image1.png)

Figure 1. In Ar, discharge V-I characteristics of a magnetron with cold (solid lines) and hot (dashed lines) targets at argon pressure of 2, 3 and 7 mTorr.

Figure 2 shows the V-I characteristics of a magnetron operating in the Ar + O\(_2\) environment. The measurements were performed at an oxygen flow rate of 4, 5 and 6 cm\(^3\)/min. The curves for a magnetron with a cold target fit the well-known concepts of processes in a reactive sputtering system [12]. In the first section of the V-I characteristics, when the discharge current is increased, the voltage gradual-
ly increases up to the critical value of the current, at which it abruptly decreases by approximately 60 V or 15 %. This jump reflects the transition of the target from the oxide mode to the metallic mode.

The V-I characteristics of a magnetron with a hot target in figure 2 at any oxygen consumption have three sections:

- in the field of low currents, there is a similarity to the magnetron with a cold target. The target operates in the oxide mode, and the discharge voltage increases proportionally to the current density, but at a higher rate than for the cold target. This effect can be attributed to the known rarefaction of gas (a decrease in density) in the target region due to its heating during sputtering [13]. When the magnetron is operated with a hot target, the heating occurs not only due to the elastic interaction of ions with neutral particles, but also comes from a strongly heated target. The mode exists until the conditions for the transition of the target to the metallic mode of operation arise. The transition from the oxide regime begins at a current density approximately 4–5 times smaller than for a magnetron with a cold target (figure 3, curve 1). One of the reasons for this shift becomes more obvious if we consider the reactive sputtering model [4]. The mode changes when the oxide film growth rates on the target surface are equal to its sputtering with argon ions. The latter value is proportional to the sputtering coefficient, which, in turn, is approximately proportional to the ion energy or discharge voltage. Figure 2 shows that with a current density of 30 mA/cm², the discharge voltage for a magnetron with cold and hot targets is approximately 350 and 480 V, respectively;

- in the region of higher currents, the target operates in a stationary metal mode, but as compared with the cold target, the voltage decreases with increasing current density;

- between these extreme states, there is a transient mode, in which an increase in the current density leads to a significant decrease in voltage (by about 80 V or by 17 %). Most likely, this is due to the equilibrium purification of the target surface from titanium oxide, which leads to an increase in the coefficient of ion-electron emission. For a titanium target, this value increases from 0.078 for an oxide to 0.113 for a pure metal [14]. The current density at which this process terminates depends on the consumption of oxygen (figure 3, curve 3).

![Figure 3](image1.png)

**Figure 3.** Influence of oxygen consumption on the V-I characteristics transition points from oxide to metallic modes for the target: 1 - cold; 2 - hot.

![Figure 4](image2.png)

**Figure 4.** In Ar + N₂, discharge V-I characteristics of a magnetron with cold (solid lines) and hot (dashed lines) targets.

The results of the experiments carried out in the Ar + N₂ environment are given in figure 4. The measurements were fulfilled at a flow rate of nitrogen of 4, 5 and 6 cm³/min. The character of the curves for a magnetron with a cold target differs from the analogous dependences in Fig. 2 only by the magnitude of the voltage jump, when the target operation mode changes, which does not exceed 5 V (1.5 %). Such a slight decrease in discharge voltage is associated with a slight difference in the coefficients of ion-electron emission of titanium nitride (0.110) and titanium (0.113).

The character of the change in the V-I characteristics of a magnetron with a hot target in figure 4 at any nitrogen flow is slightly different from what is reflected in figure 2. Only in the transition from the
nitride mode to the metallic mode in this case begins at a current density about 2 times smaller than for a magnetron with a cold target.

4. Conclusions
The study of magnetrons with a cold and hot titanium target allowed to determine that:

- The V-I characteristics of a magnetron with a hot target operating in an argon environment in the pressure range of 2-7 mTorr at a low current density correspond to the abnormal glow discharge mode; have a maximum, when the current increases; depend on the pressure typically for the magnetron discharge: with increasing pressure, the current on the target is provided by a decrease in discharge voltage;
- in the Ar + O₂:
  - in the V-I characteristics of the magnetron with a cold target, a characteristic jump-like decrease of about 60 V or 15% is observed, reflecting the transition of the target from the oxide mode to the metallic mode;
  - the V-I characteristics of a magnetron with a hot target contain 3 sections corresponding to the oxide, transition, and metallic modes of operation of the target;
  - in the oxide regime, the voltage on the discharge increases approximately in proportion to the current density, but at a higher rate than for the cold target;
  - the transition from the oxide mode starts at a current density approximately four times smaller than for a magnetron with a cold target;
  - in the transition mode, the current increase leads to a significant decrease in voltage (by about 80 V or by 17%);
  - in the region of higher currents, the target operates in a stationary metallic mode, but the voltage decreases with increasing current;
- in the Ar+N₂:
  - in the V-I characteristics of a magnetron with a cold target, the magnitude of the voltage jump when the mode of its operation changes does not exceed 5 V (1.5%); a characteristic jump-like decrease of about 60 V or 15% is observed, reflecting the transition of the target from the oxide mode to the metallic mode;
  - the character of the change in the V-I characteristics of a magnetron with a hot target is slightly different from that obtained in the Ar + O₂. However, the transition from the nitride mode to the metallic mode occurs at the current density about 2 times smaller than for a magnetron with a cold target.

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