Characteristics of magnetron sputtering of hot titanium target in argon

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Abstract. In this work, the discharge characteristics of 130 mm diameter planar balanced magnetrons equipped with cold and hot titanium targets were studied. It is found that these devices operating in argon have significantly different I-V characteristics measured in the current density range of $10^{-100}$ mA/cm$^2$. At different argon pressures, a hot target magnetron provided a given current at a higher voltage, and its I-V characteristics had maxima. The observed characteristics can be caused by gas heating and its rarefaction near the target, as well as by thermionic emission of the heated target.

1. Introduction
Magnetron sputtering with an effectively cooled (cold) target is a reliable and well-studied method of the deposition of metal and compound films [1–3]. Along with this, the number of publications on the study of dc sputtering systems with hot targets increases [4–9]. Despite the long history of magnetron sputtering studies, many experts use erroneous models of these processes. In particular, the ideas about the current-voltage characteristics of a magnetron discharge [10] are rather ambiguous, as it was noted in our previous work [9]. Thus, when modeling I-V characteristics of the cold target magnetron, some experts believe that a vacuum diode and a gas discharge in a diode system are similar [11, 12]. Strictly speaking, this is indeed true, but only for the collisionless layer [13]. The discharge characteristics of the hot target magnetron in the inert or reactive environments have not been discussed in the literature, yet. We presented the selected experimental results in [9]. In this work, our goal was to develop a physical model of I-V characteristics of the magnetron with a hot titanium target operating in argon. To this end, we carefully performed new experiments, the results of which differ from those presented in [9].

2. Experimental details
The study was performed in a high-vacuum system equipped with oil-diffusion and mechanical pumps having a nominal speed of 0.3 m$^3$/s and 0.005 m$^3$/s, respectively. The volume of the vacuum chamber was 0.076 m$^3$, the residual pressure did not exceed $5 \cdot 10^{-2}$ mTorr. The experiments were performed on a 130 mm diameter balanced magnetron equipped with titanium targets:
- 6 mm thick, typically cooled by running water (a cold target);
- 1 mm thick, cooled through a vacuum gap of 1 mm by a 4 mm thick copper water-cooled board and through fastening elements (a hot target).

The magnetron sputtering processes in a high-purity argon environment at a partial pressure in the
range of (2–7) mTorr were studied. In all cases, the magnetrons operated on direct current with a density $j = 10–100$ mA/cm$^2$ at a discharge voltage of 200–500 V.

3. Results and discussion

Figure 1(a) presents the I-V characteristics of both types of magnetrons. Our study showed that there are both a difference and a similarity between the sputtering processes of a cold target and a hot target.

![Figure 1. I-V characteristics of the magnetron discharge for hot (1, 2, 3) and cold (4, 5, 6) titanium targets in argon (a) and the difference between them (b) at a pressure (mTorr): 1, 4 – 2; 2, 5 – 3; 3, 6 – 7.](image)

Firstly, we describe the observed difference. In order to maintain a given current density, a hot target magnetron requires a higher discharge voltage $U_{\text{hot}}$ than a cold target magnetron $U_{\text{cold}}$. This is demonstrated by Figure 1(b), where the points show the values of $\Delta U = U_{\text{hot}} - U_{\text{cold}}$ calculated at each current density for pressures 2, 3 and 7 mTorr (points 1, 2 and 3, respectively). The solid line represents averaging over pressure, i.e., it shows the relationship only between $\Delta U$ and the current density. An increase in the current density up to ~80 mA/cm$^2$ leads to the appearance of maxima on the I-V characteristics of the hot target magnetron. In this case, as figure 1(b) shows, the difference of $\Delta U$ reaches a maximum value of ~30 V. To the left of the extremum of the I-V characteristics of the hot target magnetron, as figure 1(a) demonstrates, the derivative of $dU/dj$ is greater than for a cold target. Further we indicate the possible cause of the observed effect.

It is found that during cold target sputtering the working gas density decreases significantly (to 50–60%) [14]. Gas heating near the target caused by collisions between sputtered atoms and gas particles is recognized to be the cause of this effect. The gas density decrease is equivalent to the pressure decrease, therefore this effect is called gas rarefaction.

![Figure 2. The maximum target temperature (a) (black points – melting temperature) and $\delta$ (b) at $p_{Ar}$ (mTorr): 1 – 2; 2 – 3; 3 – 7.](image)

Hot target sputtering initiates additional gas heating. This is due to the fact that the material flux generated by the hot target carries more energy. An additional contribution comes from an
exponentially increasing flux of the evaporated particles with an average power of up to 0.2 eV. Figure 2(a) shows target heating. Figure 1(b) shows the increase of $\Delta U = U_{\text{hot}} - U_{\text{cold}}$ up to ~70 mA/cm$^2$ caused by the above reason.

We conclude the analysis of difference in the I-V characteristics by identifying the possible cause of the maxima appearance on curves 1, 2 and 3 (figure 1(a)). In the physicochemical model of reactive sputtering of a hot target with a temperature $T_t$, described in [8], we took into account the thermionic emission, which is described by the Richardson-Dushman equation. At the low discharge current density, heating of the target does not initiate significant emission. Under these conditions, the main source of electrons is ion induced electron emission of the target.

Figure 2 shows the relation between the currents of thermionic $I_T^-$ and ion-electron emission $I_{sp}^-$ as a dependency of $\delta = I_T^- + I_{sp}^- / I_{sp}^-$ on the discharge current density. These results demonstrate that at the pressure of $(2, 3, 7)$ mTorr, the contribution of the thermionic current becomes noticeable at the points $j_{1.0e} = (63.0, 66.4, 71.1)$ mA/cm$^2$, respectively (white points). They have the value of $\delta$ up to 1.02. The black points show the increase of $\delta$ up to 1.10 at $j_{1.10} = (72.1, 76.1, 81.1)$ mA/cm$^2$. The obtained values of the discharge current density approximately correspond to the maxima of the I-V characteristics in figure 1(a).

Now we turn our attention to the general features of the gas pressure influence on the sputtering processes of hot and cold targets. The discussed quantitative difference in the current-voltage characteristics inevitably influenced the discharge voltage dependences on the pressure $U(p)$.

![Figure 3. Dependence of discharge voltage on argon pressure for a magnetron with a target: (a) – cold; (b) – hot. Points – experiment, lines – approximation.](image)

Points in figure 3 show these dependences obtained from the experimental I-V characteristics in figure 1(a). In order to avoid overloading the figure 3(b), we show there only dependences for the parts of the I-V characteristics, which are located to the left of the extrema. The solid lines in figure 3 reflect the results of approximation by an exponential function with an accuracy of 0.999:

$$U_j(p) \approx U_{0j} + U_{1j} e^{-p/p_{0j}}, \tag{1}$$

where $U_{0j}, U_{0j}$ and $p_{0j}$ are parameters depending on the discharge current density.

The similarity of the expressions describing the dependences $U(p)$ in the form (1) confirms the generality of the given processes. We study this problem in more detail using the derivatives $dU/dp$:

$$\frac{dU_j(p)}{dp} = -\frac{U_{1j}}{p_{0j}} e^{-p/p_{0j}}, \tag{2}$$

where $j$ – the density of the discharge current.

Analysis of the processes with different targets was performed according to expression (2). The mean values of $\bar{U}_\text{cold}$, $\bar{U}_\text{hot}$, $\bar{p}_\text{cold}$ and $\bar{p}_\text{hot}$ applied in constructing the curves in figure 3 were used in (2). The error of the dependence (1) for each target in the form of an average curve is defined
as the standard deviation of \( \frac{dU}{dp} = f(p) \) at \( p = (2, 3, 4, 5, 6, 7) \) mTorr from the corresponding mean values. It defines the region where all eight dependences \( U(p) \) for a target of this type are located. Figure 4(a) shows an example: the width of this region decreases, when the pressure increases.

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\begin{align*}
\text{Figure 4.} & \text{ Dependences on argon pressure: (a) – derivatives (2) for a magnetron with a hot target (solid line – average, dashed lines – eight dependencies for different current densities); (b) – averaged derivatives } \frac{dU}{dp} \text{ for a magnetron with a cold (dashed line) and hot (solid line) target.}
\end{align*}
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Figure 4(b) ultimately confirms the equivalence of the sputtering processes of hot and cold targets. It shows that the difference between the corresponding derivatives \( \frac{dU}{dp} = f(p) \) is within the limits of measurement errors. It means that in both cases the decrease of the discharge voltage, when the pressure of the working gas increases, is caused by the well-known physical effect in the gas discharge. Namely, it is the increase in the argon ionization cross section, when the pressure increases [13].

4. Conclusions
In conclusion, we outline the discovered difference and similarity of the sputtering processes of cold and hot targets. The difference appeared in the current-voltage characteristics is associated with an increased gas rarefaction and the thermionic emission of a hot target. The similarity found in the dependence of the discharge voltage on temperature is caused by the variations in the argon ionization cross section when pressure changes.

References
[1] Anders A 2011 Sur. Coat. Technol. 205 S1–9
[2] Komlev A E, Shapovalov V I and Shutova N S 2012 Techn. Phys. 57 1030
[3] Ferreira F, Sousa C, Cavaleiro A et al. 2017 Sur. Coat. Technol. 314 97
[4] Shapovalov V I, Karzin V V and Bondarenko A 2017 Phys. Lett. A. 381 472
[5] Lapshin A E, Levitskii V S, Shapovalov V I et al. 2016 Glass Phys. Chem. 42 359
[6] Cormier P-A, Thomann A-L, Doliwe V et al. 2013 Thin Solid Films 545 44–9
[7] Bondarenko A S, Kolomiitsev A A and Shapovalov V I 2016 J. Phys.: Confer. Ser. 729 012006
[8] Goncharov A O, Minzhulina E A and Shapovalov V I 2018 IOP Conf. Ser.: Mater. Sci. Eng. 387 012020
[9] Shapovalov V I, Minzhulina E A and Smirnov V V 2018 IOP Conf. Ser.: Mater. Sci. Eng. 387 012069
[10] Maniv S, Westwood W D and Scanlon P J 1982 J. Appl. Phys. 53 856
[11] Westwood W D, Maniv S and Scanlon P J 1983 J. Appl. Phys. 54 6841
[12] Depla D, Haemers J and De Gryse R 2013 Sur. Coat. Technol. 235 62–7
[13] Raizer Yu P 1991 Gas Discharge Physics (Springer, Berlin, New York) 449
[14] Gudmundsson J T, Brenning N, Lundin D et al. 2012 J. Vac. Sci. Technol. A. 30 030801
[15] Kozin A A and Shapovalov V I 2019 Sur. Coat. Technol. 359 451–8