Estimation of the influence of the parameters of magnetron sputtering processes on its energy efficiency

V V Tlyavlin, P B Petukhov, Zaw Phyo Aung and L L Kolesnik
Bauman Moscow State Technical University, Department of “Electronic engineering technologies”, 2nd Baumanskaya str. 5, bld. 1, 105005, Moscow, Russia
E-mail: kolesnik@bmstu.ru, tliavlin.vladislav@yandex.ru, ppetukhov95@yandex.ru, zpaung89@gmail.com

Abstract. In this paper was researched the thermal processes in DC magnetron sputtering system when sputtering a titanium target, depending on parameters such as discharge power, pressure and gas flow. Physical model of sputtering processes and the part of energy balance equation were investigated and the powers of various heat fluxes that occur during the magnetron sputtering process were determined. As a parameter of energy efficiency, the value of power heat flow to the substrate is ration to the discharge power were proposed. The influence of the change in sputtering parameters on the energy efficiency of the process was investigated.

During the work of magnetron sputtering process target is under the action of gas discharge plasma. The energy supplied to the target and consists of the following components [1]:

- energy of ions accelerated in the dark cathode space (ion components of discharge current);
- energy transmitted from the plasma cloud by neutral particles;
- plasma radiation;
- energy of the electrons (electronic components of discharge current);
- energy released by the passage of electric currents.

Estimates show that the main source of energy at the cathode assembly is the ionic component of the discharge current and the other components can be neglected when building the physical model [1]. According to [1, 2], the kinetic energy of ions entered from the plasma to the target surface, and the current of ion energy equal to 0.6U_d and 0.95I_d respectively (I_d – discharge current, U_d – discharge voltage).

Consequently, ion current power on the target surface P_i is calculated by the formula:

\[ P_i \approx 0.6U_d \cdot 0.95I_d = 0.57P_d \]  

where \( P_d \) – discharge power of the magnetron; \( P_i \) – ion current power.

The outflow of energy from the target consists of the following components [4]:

- energy of the reflected ions;
- energy radiated or emitted by the target surface;
- energy released by the magnetron cooling system;
- energy transferred from the target surface by sputtered atoms.

After starting of DC magnetron with the target in some time at the cathode node is established a stationary temperature regime [1, 3].
For this steady state, the energy balance at the cathode node can be described the value of the ion current power on the target surface $P_i$:

$$P_i = \sum_k Q_k = Q_{cool} + Q_{sp} + Q_{rad}$$  \hspace{1cm} (2)

where; $Q_{cool}$ – power of the heat flow removing by the magnetron cooling system; $Q_{sp}$ – power of heat flux is caused by sputtering of the target; $Q_{rad}$ – power of the heat flux radiated by the target surface.

For a cold target, $Q_{rad}$ is insignificant and practically independent of power [1, 3, 4]. Then the ion current power $P_i$ can be described by the expression:

$$P_i = Q_{cool} + Q_{sp}$$  \hspace{1cm} (3)

According to [5], the quantity of heat $Q_{cool}$ removed by the cooling water is equal to (4):

$$Q_{cool} = Gc_p (t) \Delta t$$  \hspace{1cm} (4)

where $\Delta t$ – temperature difference between incoming and outgoing flows; $c_p$ – specific heat capacity of water depending on temperature; $G$ – water flow rate.

During the experiment was measured every second the temperature difference on the pipes of the magnetron cooling system.

By using the formula (4) have received dependence the quantity of heat removing during the magnetron sputtering process for different discharge powers on the sputtering time of the magnetron. This dependence describes in the following graph.

![Figure 1](image)

**Figure 1.** Dynamics the heat removing changes when the magnetron sputtering process at different discharge power.

The horizontal sections in figure 1 correspond to the stationary mode and then the power of the heat flow removed by the cooling system of the magnetron sputtering system $Q_{cool}$ can be calculated with the following formula:

$$Q_{cool} = \frac{\sum Q_{in}}{n}$$  \hspace{1cm} (5)

where $n$ – number of measurements during establish the stationary mode; $Q_{cool}$ – power of the heat flow removing by the magnetron water cooling system.

During the magnetron sputtering thermocouple sensors was used to measure the heat flow to the substrate $Q_{sp}$ as a basics data for the calculation of the results of heating kinetics.
In paper [6, 7] describes the kinetic equations of substrate is given as temperature dependence:

\[ \frac{dT_i}{dt} = A_i - BT_i^4 - CT_i \]  

(6)

where \( A_i \) – value of proportional to the power emitted to the sensitive element; \( B \) – coefficient the radiation of sensitive element; \( C \) – thermal conduction of gas and element of the substrate holder.

The radiation of the sensitive element can be neglected at temperatures below 200 °C, so the coefficient \( B = 0 \) and the expression (6) takes the following form:

\[ \frac{dT_i}{dt} \approx A_i - CT_i \]  

(7)

The value \( A_i \) can be calculated by using experimental kinetic heating curves. Below is the kinetic curve of substrate heating at a discharge power of 580 W, obtained by approximating the polynomial of the first degree of experimental data (figure 2).

![Figure 2. The kinetic curve of substrate heating at a discharge power of 580 W.](image)

As indicated in [6, 7], the power of the heat flow to the substrate can be calculated by the formula:

\[ (Q_{sp}^{sub})_i = mcA_i \]  

(8)

where \( m \) – mass of the substrate; \( c \) – specific heat capacity of the substrate.

Substituting (8) into (5) we obtain the following formula for the power of the heat flux to the substrate \( Q_{sp}^{sub} \).

\[ Q_{sp}^{sub} = \sum_{i=1}^{n} (Q_{sp}^{sub})_i \]  

(9)

where \( n \) – number of measurements during the magnetron sputtering processes.

So \( Q_{sp}^{sub} \) includes the flux of sputtered atoms from the target, then the ration can be described as an energy efficiency parameter of the sputtering process, \( \epsilon = Q_{sp}^{sub} / P_d \) where, \( P_d \) – discharge power of the magnetron.

The experiments were performed in a vacuum chamber with a volume 0.01 m³, equipped with the flat target of DC magnetron. Diameter of magnetron is 75 mm. Titanium target with DC mode from power source was used for conducting the experiments which was fixed on a water-cooled plate (figure 3). Pure argon was used as a sputtering gas. Discharge power \( P_d \) was controlled from the power supply of magnetron. Gursu Grs 150 chiller with a flow rate of 0.097 kg/s was used for cooling system of magnetron sputtering processes.
Patap-03 thermocouple sensor was used for the research of the thermal processes occurring on the substrate. The sensitive element of the thermocouple is Chromel-Copel was fixed at a copper plate as a substrate with an area of 28 cm²; a thickness of 1 mm and the distance from the target to the element is 70 mm.

![Figure 3. Scheme of fixing the target with water-cooled plate.](image)

As a results of measurements the $Q_{\text{sub}}$, $Q_{\text{ext}}$ and $Q_{\text{abc}}$ was calculated by using the formula (3). In the following table 1 was shown the experimental results with the changing of inlet working pressure to the vacuum chamber at a constant discharge power.

**Table 1. The results of experiments at a constant discharge power.**

| Pressure (Pa) | Inlet gas flow (sccm) | $P_d$ (Watt) | $P_i$ (Batt) | $Q_{\text{ext}}$ (Watt) | $Q_{\text{abc}}$ (Watt) | $\varepsilon = Q_{\text{abc}} / P_d$ |
|--------------|-----------------------|--------------|--------------|-------------------------|-------------------------|----------------------------------|
| 11           | 15                    | 580          | 330,6        | 290,9                   | 39,6                    | 7,09                             | 0,0122                           |
| 11           | 25                    | 580          | 330,6        | 296,57                  | 34,02                   | 7,115                            | 0,0122                           |
| 11           | 35                    | 580          | 330,6        | 306,43                  | 24,17                   | 8,91                             | 0,015                            |
| 11           | 45                    | 580          | 330,6        | 287,28                  | 42,72                   | 4,46                             | 0,007                            |
| 2            | 15                    | 580          | 330,6        | 269,30                  | 61,29                   | 8,86                             | 0,0153                           |
| 2            | 25                    | 580          | 330,6        | 292,41                  | 38,19                   | 9,64                             | 0,01664                          |
| 2            | 45                    | 580          | 330,6        | 274,2                   | 56,43                   | 7,77                             | 0,01342                          |

![Figure 4. The dependence of the energy efficiency parameter on the inlet (gas flow rate) at various pressures.](image)

**Figure 5. The dependence of the value $Q_{\text{abc}}$ on the inlet (gas flow rate) at various pressures.**
According to the results presented in table 1, it was possible to find the dependence of energy efficiency parameter $\varepsilon$ of the magnetron sputtering processes on the inlet (gas flow rate) at various pressures (figure 4), as well as the dependence of the value $Q_{sp}^{tag}$ on the inlet (gas flow rate) at various pressures (figure 5).

In the following table 2 show the results of measurements $Q_{sp}^{sub}$, $Q_{cool}$, $Q_{sp}^{tag}$, $\varepsilon$ with the changing of discharge power $P_d$ (400, 580, 800 Watt) at constant values of working pressure and the inlet (gas flow rate).

Table 2. Experimental results at constant values of working pressure and the inlet (gas flow rate).

| Pressure (Pa) | Inlet gas flow (sccm) | $P_d$ (Watt) | $P_i$ (Watt) | $Q_{cool}$ (Watt) | $Q_{sp}^{tag}$ (Watt) | $Q_{sp}^{sub}$ (Watt) | $\varepsilon = Q_{sp}^{sub} / P_d$ |
|--------------|-----------------------|--------------|--------------|-------------------|----------------------|----------------------|---------------------|
| 11           | 35                    | 800          | 456          | 401,28            | 54,72                | 11,13                | 0,0141              |
| 11           | 35                    | 580          | 330,6        | 306,43            | 24,17                | 8,91                 | 0,0150              |
| 11           | 35                    | 400          | 228          | 202,92            | 25,08                | 5,91                 | 0,0147              |

As a result of the presented works, we can make following conclusion.

Energy efficiency parameter $\varepsilon$ of the processes and power of the heat flow to the substrate $Q_{sp}^{sub}$ respectively decreases with increasing pressure in the pressure range from 2 to 11 Pa with a constant discharge power $P_d$. When in the range of inlet gas flow sccm = 15 - 35, energy efficiency parameter $\varepsilon$ of the processes decrease on average by 20% and while the inlet value of sccm = 45 the difference is already 40% which indicates a sharp decreasing of the power of heat flow to the substrate.

The power of the heat flux $Q_{sp}^{tag}$ is caused by sputtering of the target decreases by 30-40% with increasing pressure. And the power of the heat flow to the substrate $Q_{sp}^{sub}$ and also the energy efficiency parameter of the sputtering process nonlinearly depend on the inlets (gas flow rate), because in the range of inlets (gas flow rate) sccm = 30..40 was observed a maximum for a pressure of 11 Pa and in the range of inlets (gas flow rate) sccm = 20..30 was observed a maximum for a pressure of 2 Pa.

The energy efficiency parameter of the spraying process $\varepsilon$ does practically not depend on the discharge power.

References

[1] Yuriev A V, Bleicher G A, Stepanova O M and Yuriev Y N 2014 News of Universities. Physics 3 276–80
[2] Zhukov V V, Krivobokov V P, Patsevich V V and Yanin S N 2006 News of Tomsk Polytechnic University 1 56–9
[3] Yuriev A B 2017 Deposition of metallic coatings using a magnetron sputtering system with a liquid-phase target (Tomsk: National Research of Tomsk Polytechnical University)
[4] Ivanova N V 2018 Modeling of a thermal process on a substrate when sputtering a hot titanium target (St. Petersburg: St. Petersburg State Electrotechnical University)
[5] Mikheev M A and Mikheev I M 1977 The basics of heat transfer (Moscow, Energy) 1 344
[6] Minzhulina E A, Smirnov V V, Kozin A A and Shapovalov V I 2017 Fundamental problems of electronic Instrumentation 2 543–6
[7] Cormier P A, Thomann A L, Dolique V, Balhamri A, Dussart R, Semmar N, Lecas T, Brault P, Snyders R and Konstantinidis S 2013 Thin Solid Films 545 44–9