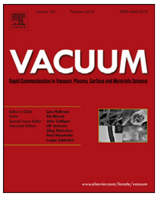
Vacuum 124 (2016) 11–17

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum



Energy and substance transfer in magnetron sputtering systems with liquid-phase target

G.A. Bleykher*, V.P. Krivobokov, A.V. Yurjeva, I. Sadykova

Institute of Physics and Technology, Tomsk Polytechnic University, Lenin Avenue, 2a, Tomsk 634028, Russia

ARTICLE INFO

Article history:
Received 12 September 2015
Received in revised form
11 November 2015
Accepted 14 November 2015
Available online 1 December 2015

Keywords:
Magnetron sputtering systems
Liquid-phase target
Erosion
Sputtering
Evaporation
High-rate coating deposition

ABSTRACT

The regularities of energy and matter transfer in the magnetron sputtering systems (MSS) with liquid-phase targets were analyzed. For this purpose a mathematical model of heat and erosion processes in a thermally insulated target of MSS has been developed and the problem of energy balance in a substrate and its heating during coating deposition was solved.

The model is based on the fact that the flow of atoms from the surface of the liquid-phase target under the action of plasma consists of two independent components: sputtered and vaporized particles. The reliability of this model is confirmed by a good agreement between the calculated and experimental data.

Using the model developed the regularities of the rate of the target surface erosion and metal coatings deposition were revealed. We investigated the effect of the ion current power density and material properties of the cathode. The calculations according to this model and experiments show the growth rate of metal coatings reaches from 100 to 1000 nm/s when intense evaporation occurs. It is one or two orders of magnitude higher than the rate of coating deposition when using solid target. The results can be useful for the development of technologies of high-rate coating deposition.

1. Introduction

Nowadays, magnetron sputtering systems (MSS) are widely used for the deposition of modifying coatings on the surface of materials as they provide a high quality and reveal a wide variety of functional properties.

The basis of MSS operation is generation of gas discharge plasma in a diode gap under electric and magnetic crossed fields. This plasma affects the surface of a special target. The main mechanism of the action is ion bombardment with energies of a few hundreds of eV extracted from plasma [1,2].

As a result, the surface of a target undergoes erosion. The flow of particles is removed from it, propagates mainly in the direction opposite of the target and deposit**s** on a modified surface.

Among fundamental problems related to modern MSS, the most significant problems are low rate of coating deposition and low flux density of the deposited particles. In particular, metal coating growth rate is from 1 to 10 nm/s for direct-current MSS [1–3] and it is much less for coatings of complex compositions [4–6]. The reason is that the main mechanism of atomic emission from the surface of the target is sputtering of intensity which linearly depends on power density of ion current, and is limited by this parameter.

One of the ways to solve this problem is “activating” an evaporation mechanism which ensures the nonlinear growth of the atomic emission rate with increasing the power density of plasma action on the surface of the target. Therefore, it is possible to reach a high intensity of removing substance from the irradiated surface. This effect occurs particularly under the action of high intensity charged particle pulsed beams [7,8].

During MSS operation, evaporation can be created using a thermal-isolated target from cooling elements of the cathode assembly. In this case, thermal energy which is released in the surface layers under plasma is kept in the target. Under certain circumstances it proves to be enough to melt the target substance and to create intense evaporation. This causes the problem to prevent the spreading of a liquid target. Therefore, it must be placed in a special crucible, which forms a cathode assembly along with the target. Fig. 1 shows the scheme of MSS operation with a thermal-isolated melted target.

The experimental and theoretical study show that using such MSS allows increasing the coating growth rate about 100 times

---

* Corresponding author.
E-mail address: bga@tpu.ru (G.A. Bleykher).

http://dx.doi.org/10.1016/j.vacuum.2015.11.009
0042-207X/© 2015 Elsevier Ltd. All rights reserved.

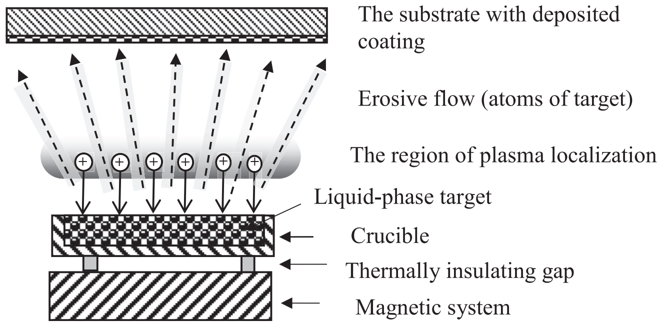


Fig. 1. The scheme of coating deposition in MSS with a liquid-phase target.

[9,10] superior to realization of the conventional sputtering of the cooled solid targets [1–3]. The efficiency of deposition from liquid phase also must be no less than 10 times higher compared the case of hot solid target sputtering [12]. This circumstance makes these MSS very attractive to implement in the modern vacuum-plasma technologies of material modification.

However, this approach has not found a big application in practice. This situation is obviously determined by a set of technological problems caused by their use, such as instability of operation, coating contamination by atoms of crucible substance, and high heating of the substrate. On the one hand, these factors cause functional properties degradation of the treated products. On the other hand, significant increase in temperature enables, for example, enhancement of diffusion mobility of atoms which implies improvement of coating adhesion to the substrate, composite material mixing, etc.

To reveal the MSS capabilities and to determine their optimal parameters when solving the specific technological tasks, it is necessary to have a clear vision of the regularities of the processes of energy and substance transfer in the “target–substrate” system of the magnetron. It would be desirable to have effective means to predict their intensity. Because of this, we offer a mathematical model, which allows determination of the parameters of atomic emission from the surface of the liquid-phase target. This also allows calculation of the coating growth rate and evolution of thermal processes in the substrate in relation to the functional parameters of MSS with a thermal isolated target. Its structure and obtained characteristics are described in the paper. The correctness of the model approximations is proved by a good agreement between the calculated and experimental results.

2. Theory and model approximation

2.1. A mathematical model of thermal processes in the target and atomic emission from its surface

When a solid target of MSS is heated to the temperature close to melting, evaporation occurs in addition to the surface sputtering. The mechanisms of collision sputtering and evaporation have different natures and do not affect each other considerably. Therefore, the flux of atoms from the surface of highly heated target consists of two independent components: sputtered and vaporized particles. In that case, the velocity V of the boundary separating the condensed and gas phases is presented as the sum:

$$V = V_s + V_{ev}, \tag{1}$$

where V_s and V_{ev} are interface velocities caused by sputtering and evaporation, respectively. Hereafter we will define V_s and V_{ev} as sputtering and evaporation velocities and V as erosion velocity of target surface.

Sputtering velocity is proportional to the density of ion current I_{ion} and sputtering yield S:

$$V_s = \frac{S \cdot I_{ion}}{e \cdot n_0}, \tag{2}$$

where e is the electron charge, n_0 is the nuclear density of the target substance.

According to [13], in the experiments with a copper target the value of I_{ion} is equal to $(0.925–0.975)I_d$, where I_d is the discharge current density. As for the cases when the targets are made of the other metals, the portion of ion current shall comprise approximately the same value [2].

The sputtering yield depends on ion energy. Therefore, to obtain the proper estimation of sputtering velocity it is necessary to know the energy values of ions which irradiate the target surface.

The study of the energy spectra of ions directed to the target showed that the average ion energy E_0 is about 0.6 U_d, where U_d is the discharge gap voltage [2]. Since U_d in MSS lies in the keV range, the sputtering yield can be calculated with using the known expression:

$$S \approx \frac{3}{4\pi^2}\alpha\frac{\gamma E_0}{U_S};\ E_0 >> U_S, \tag{3}$$

derived by P. Sigmund for the regime of primary knocking out [14], where $\gamma = 4M_1M_2/(M_1+M_2)^2$, M_1 and M_2 are the atomic mass of incident particles and target atomic mass respectively; α is the parameter which depends on the mass relation M_2/M_1; and U_S is the surface-binding energy of the target substance.

Therefore, sputtering velocity equals the following equation:

$$V_S = \frac{3\alpha M_1 M_2 \cdot W_{ion}}{\pi^2 (M_1+M_2)^2 n_0 U_S}, \tag{4}$$

where W_{ion} is the power density of ion current directed to the target. From the above, it might be assumed that its value is approximately equal to:

$$W_{ion} = I_{ion} \cdot E_0 \approx 0,6U_d \cdot 0,95I_d = 0,57P_d, \tag{5}$$

where P_d is the discharge power density.

Let us calculate the evaporation velocity in vacuum using Hertz-Knudsen formula [15]:

$$V_{ev}(T) = \frac{1}{n_0(2\pi mkT)^{1/2}}\left(p_{sat}(T) - P^*\right). \tag{6}$$

here m is the mass of the evaporating atom (molecular); k is the Boltzmann constant; $p_{sat}(T)$ is the pressure of the saturated vapor at temperature of the surface T, P^* is the hydrostatic pressure above the surface of evaporation.

The function $p_{sat}(T)$ has the exponent-described form [16].

The value P^* is summed up with the pressure of the evaporated substance located over the surface (P) and the pressure of a working gas in the chamber (P_{res}).

As a rule, the values of P_{res} under MSS operation are a few tenths of Pa that is several orders less than the pressure of saturated metal vapors at melting temperature. Therefore, we can assume that $P_{res} = 0$ when calculating the evaporation velocity.

Regarding the pressure of the evaporated substance to the surface (P), its value can happen to be quite high under high evaporation velocities, and we should take it into consideration. It will happen, if at the resulting concentration of the vapor atoms