

FEATURES OF HIGH-CURRENT PULSED REGIMES IN MAGNETRON SPUTTERING SYSTEMS

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The high-current pulsed magnetron sputtering system is presented and its operation regimes are studied. The comparative technological trials of the system are carried out at various types of the discharge: stationary magnetron, pulsed magnetron and pulsed arc. A procedure of calculation of dynamics and distribution of temperature in a near surface layer of the target material at heat application to a surface in conditions of low pressures of working gases is described.

PACS: 52.40.Hf

1. INTRODUCTION

The investigation of the pulsed magnetron sputtering system (MSS) in modes with large discharge currents is stimulated by an opportunity to decrease energy expenses on the process of ion sputtering at large densities of ion current to the target when transition of ion-nuclear interaction into a mode of "thermal peaks" occurs [1-4]. The realization of these opportunities of pulsed conditions of the MSS is especially attractive at use of conventional discharge systems and power units for a dc MSS. At the same time, the modes of operations of the MSS with large densities of ion current to the sputtered target are accompanied by processes of intensive heating of a target surface that can lead to transition into the mode of "thermal peaks", and to thermal explosion of microroughnesses of the surface or even to melting of a target material.

In the presented work the high-current pulsed MSS is submitted and the modes its operation are studied. The comparative technological trials of the system are carried out at various types of the discharge: stationary magnetron, pulsed magnetron and pulsed arc. In the presented work a procedure of calculation of dynamics and distribution of temperature in a near surface layer of the material also is given at heat application to a surface in conditions of low pressures of working gases.

2. MATERIALS AND METHODS

The experiments on study of pulsed conditions of the MSS were carried out on conventional planar magnetron with a target diameter of 150 mm (copper). Intensity of a magnetic field on a surface of a target was about $H=250$ Oe. The anode of the magnetron was grounded and the negative voltage from a conventional magnetron power unit was applied to the target: a discharge voltage up to 1000 V, discharge current up to 5 A in a range of pressures of $p=(1 \div 8) \cdot 10^{-3}$ Torr (working gas - argon).

At investigation of pulsed conditions of the MSS between a power unit and magnetron the store of energy (pulsed capacitor with a capacity of 10 ÷ 100 μF) and

thyristor circuit changer-transformer was included. The circuit changer-transformer provided delivery of negative impulses of a voltage $U=1 \div 3$ kV to the target with duration of 50 ÷ 200 μs and frequency of 50 Hz and adjustment of a discharge current in a range of 20 ÷ 5000 A.

3. RESULTS OF EXPERIMENTS AND DISCUSSION

The pulsed magnetron discharge, in contrast to stationary, stably develops at much lower pressures of working gas. The limiting pressure of the discharge ignition in stationary conditions was $2 \cdot 10^{-3}$ Torr, in pulsed - $3 \cdot 10^{-4}$ Torr. The current-voltage characteristics and the discharge parameters are typical for the magnetron discharge. In this mode of operation of the MSS, in spite of the facts that the current of the discharge exceeds average current of a cathode spot for a copper electrode (75 A) and the duration of existence of the discharge is sufficient for occurrence of a cathode spot, the transition into an arc mode does not occur. When the discharge current exceeds some critical value in a range of 80 ÷ 120 A, we can observe formation of cathode spots on the target surface. The apparent phenomena, probably, are related to a breakdown of an external magnetic field of the magnetron by own magnetic field of a drift (Hall) electron current. In the Fig.1, the schematic figure of analytical model of circular planar magnetron is given. Owing to axial symmetry the zx -plane with radius of the magnetron loop of 5 cm is considered only.

In Fig.2, the results of numerical modelling of superposition of own external magnetic field of the planar magnetron with value on the target surface of $B=200$ Oe and magnetic field created by a Hall current with a value of $I_d=80$ A is shown.

The field inside the section of a conductor was calculated from the theory about circulation of magnetic intensity, and outside of section of a conductor by means of vector potential (elliptic integrals of 1-st and 2-nd sort). One can see that at large currents the configuration of

magnetic field loses confining properties and the discharge transfers from the discharge with cross magnetic field into the discharge with longitudinal magnetic field.

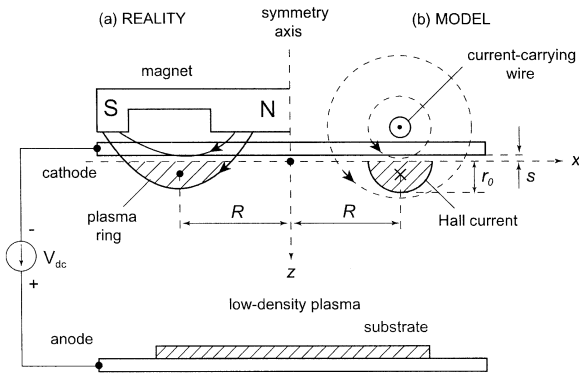


Fig. 1. Schematic of analytical model of circular planar magnetron

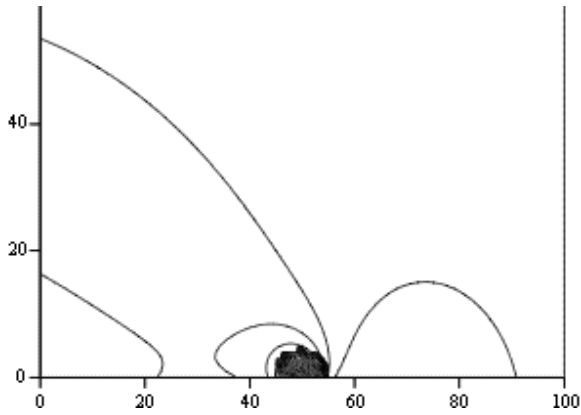


Fig. 2. Change of topography of magnetic surfaces of the MSS in the region of magnetic trap

The technological trials have shown that the deposition rate of coatings depends on the discharge type in the MSS and this dependence in pulsed conditions is stronger than in stationary ones. At average power of 3 kW and peak pulsed currents for each type of the discharge the deposition rate of a copper in the pulsed magnetron discharge was incremented in 1.2 ÷ 1.3 times, in pulsed arc - in 3 ÷ 3.5 times. The mechanical and adhesive characteristics of coatings were also improved.

Increase of velocity of mass transfer at pulsed high-current operation mode of the MSS probably is connected with transition of an ion sputtering into a mode of "thermal peaks" when the discharge current reaches values typical for an electric arc, but the transition into an electric arc and occurrence of cathode spots does not occur.

At pulsed conditions of operation of the MSS heating of a surface layer of a material of a sputtered target occurs. During period between impulses the processes of cooling occurs. For evaluation of dynamics of distribution of temperature in a near surface layer, we shall take the equation of a thermal conduction:

$$\frac{\partial T}{\partial t} = a^2 \frac{\partial^2 T}{\partial x^2},$$

where $a^2 = k/c\rho$ is the thermal diffusivity of the target material, T is the temperature in a selected point of the material, c is the specific heat capacity, ρ is the density of the target material, k is the thermal conductivity.

The boundary and initial conditions for the equation of a thermal conduction for alternating periods of heating and cooling of the surface have a various looks. Therefore for the analytical solution of the problem on distribution of temperature in a near surface layer of the target it is necessary to divide the problem on two parts. One part describes the process of heating of the surface during one impulse, and second part describes the process of cooling of the surface between impulses:

$$1) \quad \frac{\partial T_1}{\partial t} = a^2 \frac{\partial^2 T_1}{\partial x^2}, \quad k \frac{\partial T_1(L, t)}{\partial x} = -q(t),$$

$$k \frac{\partial T_1(0, t)}{\partial x} = 0, \quad T_1(x, 0) = T_0, \quad \text{where}$$

$q(t) = 4Q(t/\tau - t^2/\tau^2)$ is the parabolic shape pulse, τ is the pulse duration, L is the thickness of near surface layer.

$$2) \quad \frac{\partial T_2}{\partial t} = a^2 \frac{\partial^2 T_2}{\partial x^2}, \quad \frac{\partial T_2(L, t)}{\partial x} = hT(L, t),$$

$T_2(0, t) = 0$ with initial conditions corresponding $T_1(x, \tau)$.

Using cosine-transformation Fourier it is possible to obtain the following solution describing spatial-temporal distribution of temperature in near surface layer of target with thickness L during her heating:

$$T_1(x, t) = \frac{4Qa^2}{kL\tau} \left\{ -\frac{t^3}{3\tau} + \frac{t^2}{2} + 2 \sum_{n=1}^{\infty} (-1)^n \cos \frac{\pi nx}{L} \cdot \right. \\ \left. \exp\left(-\frac{a^2 \pi^2 n^2 t}{L^2}\right) \left(-\frac{2L^6}{\tau a^6 \pi^6 n^6} + \frac{L^4}{a^4 \pi^4 n^4} \right) + \right. \\ \left. \frac{L^2(2L^4 - 2a^2 \pi^2 n^2 L^2 t + a^4 \pi^4 n^4 t^2)}{\tau a^6 \pi^6 n^6} + \right. \\ \left. + \frac{L^2(-L^2 + a^2 \pi^2 n^2 t^2)}{a^4 \pi^4 n^4} \right\} + T_0.$$

At the time of $t = \tau$ we shall obtain expression for spatial distribution of temperature in the layer after heating:

$$T_1(x, \tau) = \frac{4Qa^2}{kL\tau} \left\{ \frac{\tau^2}{6} + 2 \sum_{n=1}^{\infty} (-1)^n A_n \cos \frac{\pi nx}{L} \right\} + T_0,$$

where

$$A_n = \exp\left(-\frac{a^2 \pi^2 n^2 \tau}{L^2}\right) \left(-\frac{2L^6}{\tau a^6 \pi^6 n^6} + \frac{L^4}{a^4 \pi^4 n^4} \right) + \\ + \frac{L^2(2L^4 - 2a^2 \pi^2 n^2 L^2 \tau + a^4 \pi^4 n^4 \tau^2)}{\tau a^6 \pi^6 n^6} + \\ + \frac{L^2(-L^2 + a^2 \pi^2 n^2 \tau^2)}{a^4 \pi^4 n^4}$$

Using a method of partitioning variable Fourier it is possible to obtain the following solution for the problem which describes cooling of the surface between impulses

$$T_2(x, t) = \frac{2}{L^2} \left\{ \sum_{m=1}^{\infty} \left[\frac{2 Q a^2 \tau L (1 - \cos \lambda_m)}{3k \lambda_m} + \frac{T_0 L (1 - \cos \lambda_m)}{\lambda_m} + \frac{8 Q a^2}{k \tau} \sum_{n=1}^{\infty} (-1)^n A_n \cdot \int_0^L \cos \frac{\pi n x}{L} \sin \lambda_m dx \right] \cdot \sin \lambda_m x \exp \left(-\frac{a^2 \lambda_m^2 t}{L^2} \right) \right\}.$$

The natural numbers λ_m are obtained by graphical calculation from the trigonometric equation $\lambda = htg \lambda L$.

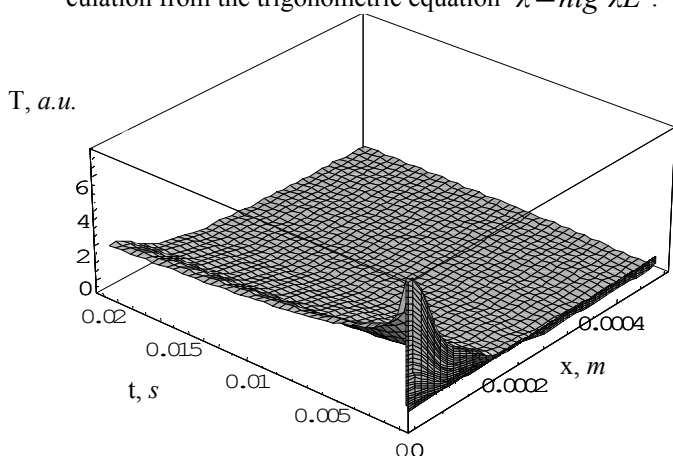


Fig.3. Spatial - temporal distribution of temperature in a copper target of magnetron sputter system

In Fig.3 the spatial-temporal distribution of temperature in the near surface layer of the target with thickness of $L = 0.5 \text{ mm}$ is shown at a pulsed heating (the pulse duration is $\tau = 100 \mu\text{s}$, the density of applied power is $Q = 6 \cdot 10^6 \text{ W/m}^2$) and subsequent cooling of the target during the time period of 0.02 s corresponding to repetition rate of impulses 50 Hz .

The average temperature of a surface and volume grows linearly with time, however the pulsed temperature of a surface can essentially exceed the temperature of volume. In the gaps between impulses partial cooling of the

surface due to heat exchange to environmental gas and propagation of a thermal wave deep into the target occurs. The calculations show that at the pulsed high-current magnetron discharge the temperature of the copper target surface grows in 2-3 times, but does not reach the value of melting temperature that proves by experimental data. At the same time, essential increase of the discharge current and deposition rates of coating in this mode testify to growth of velocity of mass transfer as a result of transition from an ion - atom sputtering of the target to a mode of "thermal peaks".

4. CONCLUSIONS

Thus, the transition from stationary to pulsed operation of a conventional magnetron sputtering system (MSS) has allowed to obtain universal technological system (stationary magnetron - pulsed high-current magnetron with enhanced deposition rate - arc evaporator) with increased density of pulsed reactionary plasma. It is theoretically shown that the transition to an arc mode occurs as a result of deformation of configuration of magnetic trap and loss of confining properties of the trap when the discharge current exceeds the critical value. The scheme of calculation of temperature distribution in the sputtered target at pulsed thermal action on a surface is proposed that significantly simplifies a choice of optimum parameters for various vacuum-plasma surface processing.

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ОСОБЕННОСТИ СИЛЬНОТОЧНЫХ ИМПУЛЬСНЫХ РЕЖИМОВ В МАГНЕТРОННЫХ РАСПЫЛИТЕЛЬНЫХ СИСТЕМАХ

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Представлена сильноточная импульсная магнетронная распылительная система и изучены режимы ее работы. Проведены сравнительные технологические испытания системы при различных типах разряда: стационарном магнетронном, импульсном магнетронном и импульсном дуговом. Приведена методика вычисления динамики и распределения температуры в приповерхностном слое материала мишени при подводе тепла к поверхности в условиях низких давлений рабочих газов.

ОСОБЛИВОСТІ ПОТУЖНОСТРУМОВИХ ІМПУЛЬСНИХ РЕЖИМІВ У МАГНЕТРОННИХ РОЗПИЛЮВАЛЬНИХ СИСТЕМАХ

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Описана сильнострумова імпульсна магнетронна розпилювальна система та вивчені режими її роботи. Проведені порівняльні технологічні випробування системи при різних типах розряду: стаціонарному магнетронному, імпульсному магнетронному та імпульсному дуговому. Приведена методика розрахунку динаміки і розподілу температури в приповерхневому шарі матеріалу мішені при підводі тепла до поверхні в умовах низьких тисків робочих газів.