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GENERAL EXPERIMENTAL TECHNIQUE

Physical Sputtering of a Copper Anode of a Planar Magnetron by a Beam of Accelerated Argon Ions with an Energy of 1–10 keV

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Abstract—During the approximation of kinetic energy transfer in collision cascades, a numerical estimate of the sputtering coefficient of the copper anode of a magnetron is considered. It has been shown that when a 1–10 keV ion beam is injected into a magnetron, the sputtering coefficient of the copper anode of the magnetron is three to six atoms per incident ion, which makes it possible to introduce and control impurities, in particular copper, under conditions of synthesis of superhard TiN–Cu coatings by reactive magnetron sputtering and directed action on the nanocrystalline structure of the coatings with high accuracy and in small fractional ratios (units of at %).

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INTRODUCTION

The processes of TiN synthesis in Cu vapors appear promising for the synthesis of composite nanostructured TiN–Cu coatings [1–5]. The dependence of the hardness of the coating on the copper content is nonmonotonic. The maximum value of hardness is achieved at relatively low copper concentrations of ~1–2 at% with the formation of a nanocomposite structure. The achievement of high hardness of TiN–Cu coatings is associated with the content of low atomic concentrations of copper in the synthesized TiN coatings, which allow high accuracy of filling with copper. Gas-discharge sputtering devices, in which Cu vapors are created by an accelerated ion beam, are of particular interest [6]. In the general case, the main quantitative characteristic of ion sputtering is the sputtering coefficient, as the average number of atoms that are knocked out of the target by one incident ion. By knowing the dependence of the sputtering coefficient of copper on the ion energy one can set the required atomic concentration of sputtered atoms and control the hardness of the TiN–Cu composite coating directionally. In addition, the processes of sputtering targets in a vacuum by an accelerated ion beam occupy a prominent place in a number of priority beam technologies and are at the same time one of the developing areas of application, in particular, of gas-discharge ion sources [7–11].

In this paper, we consider the physical sputtering of the central copper anode of a planar magnetron by an accelerated beam of argon ions in the design of a sputtering gas-discharge device [6] and estimate the sputtering coefficient of a copper anode in the approximation of kinetic energy transfer in collision cascades.

EXPERIMENTAL

The calculation of the sputtering coefficient of the central copper anode was carried out in relation to the characteristics of a gas-discharge spraying device based on the principle of injection of an ion beam into a planar magnetron [6]. The magnetron contains a titanium cathode, as well as annular and central anodes, installed along the perimeter and on the axis of the device, respectively. The central copper anode acts as a target. A discharge chamber of the plasma ion source is installed at the periphery of the magnetron, along the axis of the central anode [12–14].

In the discharge chamber of the ion source, reflective discharge occurs with a hollow cathode with a current of 0.05–0.1 A. Argon ions are extracted from the near-cathode discharge plasma through the emission channel by supplying voltage from a high-voltage rectifier with an output voltage of 1–10 keV. In this case, depending on the ratio of the discharge current and the accelerating voltage, plasma focusing allows the formation of a relatively weakly diverging ion beam (Fig. 1). Longitudinally accelerated ions initiate physical sputtering of the central copper anode, performing a copper vapor function.

RESULTS AND DISCUSSION

It is believed [15–17] that the directed flux of particles that are knocked out, in particular, from a cop-

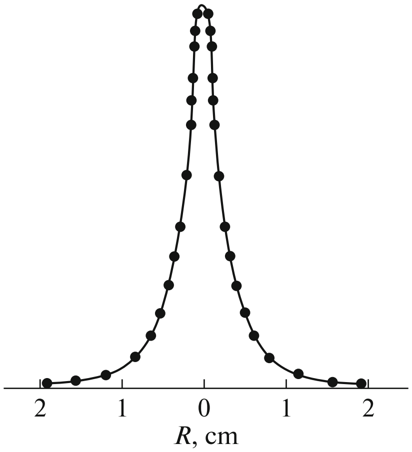

Fig. 1. The distribution of the ion current on the surface of the copper anode of the magnetron: the diameter of the emission channel is 4 mm, the beam current is 4 mA, and the accelerating voltage is 10 kV.

per target, consists mainly of copper-containing plasma (copper atoms, including excited and ionized ones, clusters and electrons).

The efficiency of sputtering a Cu target by Ar$^+$ ions is characterized by the spray ratio Y_{Cu}. The number of atoms $Y_{Cu}(0)$ knocked out in the regime of linear cascades, average energies and masses of ions by one ion that is incident normally on the target, is described in the approximation of kinetic energy transfer in collision cascades based on the solution of the linearized Boltzmann equation in its integral–differential form [15–19].

Based on the solution of the equations of the cascade theory [19], the calculation formula $Y_{Cu}(0)$ for kiloelectronvolts energies and average masses of sputtering ions can be reduced to the form

$$Y_{Cu}(0) = \frac{0.467\alpha e^2 \alpha_o s_n(\varepsilon)}{U_o} \times \frac{Z_{Ar}Z_{Cu}}{(Z_{Ar}^{1/2} + Z_{Cu}^{1/2})^{2/3}} \frac{M_{Ar}}{M_{Ar} + M_{Cu}}, \qquad (1)$$

where α is the dimensionless ratio function, M_{Cu}/M_{Ar} is the atomized atom mass to the atomizing ion mass; α_o is the Bohr radius; Z_{Ar}, Z_{Cu} are atomic numbers; e^2 is the square of the electron charge; $s_n(\varepsilon)$ is the reduced cross section of nuclear deceleration for the Thomas–Fermi interaction; and U_o is the energy of sublimation Cu.

The nature of the dependence of the α parameter on the M_{Cu}/M_{Ar} ratio, the mass of the Cu atom to the mass of the Ar$^+$ ion [16]:

M_{Cu}/M_{Ar}	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
α	0.164	0.17	0.175	0.186	0.197	0.205	0.225	0.237	0.243	0.256
M_{Cu}/M_{Ar}	2	3	4	5	6	7	8	9	10	
α	0.406	0.546	0.69	0.83	0.95	1.06	1.15	1.25	1.39	

When $M_{Cu}/M_{Ar} = 1.59$ $\alpha = 0.351$.

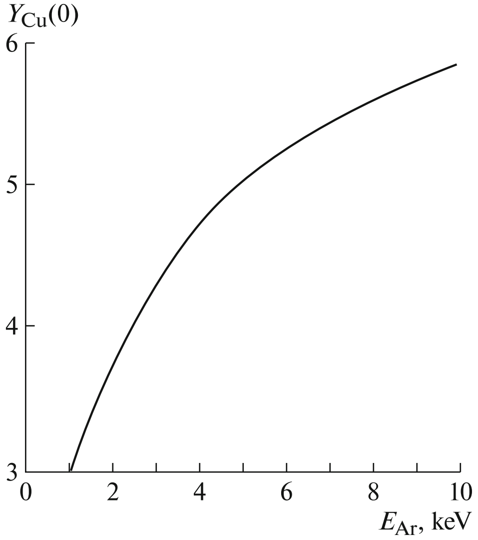

Fig. 2. The calculated dependence of the sputtering coefficient of copper on the energy of sputtering argon ions.

The following formula [18] is used to calculate ε, which is the reduced Lindhard energy for the energies of sputtering ions in the range of 1–10 keV:

$$\varepsilon = \frac{0.885 M_{Cu} E_{Ar} \alpha_o}{Z_{Ar} Z_{Cu} e^2 (M_{Ar} + M_{Cu})} \frac{1}{(Z_{Ar}^{1/2} + Z_{Cu}^{1/2})^{2/3}}, \qquad (2)$$

where E_{Ar}, eV, is the energy of Ar$^+$ sputtering ions.

We find ε by substituting $\alpha_o = 0.529$ Å, $M_{Cu} = 63.54$, $M_{Ar} = 39.94$, $Z_{Ar} = 18$, $Z_{Cu} = 29$, and $e^2 = 14.395$ eV Å in (2). The values of ε correspond to the values of the reduced cross sections for nuclear deceleration $s_n(\varepsilon)$ for the Thomas–Fermi interaction [18], presented below:

E_{Ar}, keV	1	2	3	4	5	6	7	8	9	10
ε	0.0085	0.017	0.0255	0.034	0.0425	0.051	0.0595	0.068	0.0765	0.085
$s_n(\varepsilon)$	0.193	0.246	0.265	0.286	0.319	0.322	0.334	0.347	0.356	0.361

By choosing $\alpha = 0.351$, $M_{Cu}/M_{Ar} = 1.59$, $\alpha_o = 0.529$ Å, $Z_{Ar} = 18$, $Z_{Cu} = 29$, $e^2 = 14.395$ eV Å, $U_o = 3.46$ eV [18], $M_{Cu} = 63.54$, and $M_{Ar} = 39.94$ in (1) we find the values of the sputtering coefficient $Y_{Cu}(0)$ numerically depending on the ion energy (Fig. 2) at a normal incidence of ions at $\theta = 0$ (θ is the angle of incidence of the ions). This numerical estimate is in good agreement with the experimental values of the coefficient of sputtering of Cu by Ar$^+$ ions in the energy range of 1–10 keV [16].

Under experimental conditions, ions fall on the copper anode of the magnetron obliquely due to the divergence of the ion beam under the action of its own space charge (Fig. 1). The angle of incidence of ions, θ, on the anode differs from normal incidence. For oblique incidence of ions, the deviation from the normal incidence by an angle $\theta > 0$ leads to a reduction in the penetration depth of some of the ions by $\cos\theta$ and, as a consequence, to the concentration of the collision cascade in the region of the surface of the copper anode. In the general case, the sputtering coefficient is expressed by the relationship [20]

$$Y_{\mathrm{Cu}}(\theta) \sim \frac{Y_{\mathrm{Cu}}(0)}{(\cos\theta)^k}. \tag{3}$$

When $M_{\mathrm{Ar}} < M_{\mathrm{Cu}}$ the exponent $k \sim 1$. From the nonmonotonic character of the dependence of the sputtering coefficient on the angle of incidence of sputtering ions, it follows that $Y_{\mathrm{Cu}}(\theta) > Y_{\mathrm{Cu}}(0)$. Formula (3) indicates that the correction of the numerical value of the sputtering coefficient depends on the choice of the average value of the angle of incidence of ions θ in the diverging beam for sputtering the magnetron anode (Fig. 1).

CONCLUSIONS

One of the approaches to synthesizing TiN–Cu composite coatings is the physical sputtering of the central copper anode of the magnetron with an accelerated beam of argon ions. When a 1–10 keV ion beam is injected into the magnetron, the sputtering coefficient of the copper anode of the magnetron is three–six atoms per incident ion. Physical sputtering by an ion beam makes it possible to introduce and control an impurity with high accuracy and in small proportions, in particular, copper, under the conditions of the synthesis of superhard TiN–Cu coatings by reactive magnetron sputtering and directed action on the nanocrystalline structure of the coatings. Thus [1–5] indicate that at a copper concentration of ~1.5 at %, the hardness of the TiN–Cu coating is 42–45 GPa and the crystallite size is 5–25 nm.

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