ON THE DEPENDENCE OF TARGET SPUTTERING ON THE ANGLE OF INCIDENCE OF THE BOMBARDING PARTICLES

PHYSICS

1969

SovietRxiv

Abstract

Full Text

UDC 537-334.8

PHYSICS

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ON THE DEPENDENCE OF TARGET SPUTTERING ON THE ANGLE OF INCIDENCE OF THE BOMBARDING PARTICLES

(Presented by Academician M. A. Leontovich, March 7, 1969)

In the sputtering of a solid under bombardment by particles with energies of several kilovolts or higher, collisions of the particles with atoms of the medium play a role only in an effective surface layer of order several $N^{-1/3}$, where N is the number of atoms per unit volume of the medium.

From the standpoint of the focuson theory (1–4), the effective depth h, expressed in units of $N^{-1/3}$, responsible for sputtering is determined by the focuson range. This length is determined mainly by collisions of the focuson with crystal defects and, consequently, depends only on the medium.

If the medium may be regarded as amorphous, then

$$h \sim (\Delta E/E_d)^{1/3} \tag{1}$$

(where ΔE is the mean energy lost by the bombarding particle over the path $N^{-1/3}$ in the region under consideration, E_d is the energy of detachment of an atom of the medium from the surface) depends only weakly on the energy of the bombarding particles and increases weakly with their atomic number.

If the range of the bombarding particles in the medium greatly exceeds h, then the energy transferred to atoms of the medium in the effective layer, and consequently also the sputtering coefficient, are proportional to $\sec\vartheta_0 = \xi_0^{-1}$, where ϑ_0 is the angle of incidence of the bombarding particles, $\cos\vartheta_0 = \xi_0 \approx \pi/2 - \vartheta_0$ is the grazing angle, if $\pi/2 - \vartheta_0 \ll 1$.

However, as ϑ_0 increases, a lag is observed in the growth of the sputtering coefficient relative to $\sec\vartheta_0$, and then, at $\vartheta_0 > \pi/3$, the sputtering coefficient reaches a maximum and begins to decrease. The secondary electron emission coefficient behaves analogously; however, no maximum was observed up to $\vartheta_0 = 85^\circ$ (5). Apparently, in the latter case the values of h are smaller.

Such behavior of the sputtering coefficients may be due either to the bombarding particle stopping within the depth h—this case is not considered here—or, as was assumed in a number of works [1,6,9], to scattering, as a result of which the particles leave the medium or go steeply into a depth considerably exceeding h.

On the basis of such a hypothesis, it is natural to expect that the maximum of the sputtering coefficient corresponds to scattering of the particles, on average, through an angle of approximately $4\xi_0'$ at the depth h, i.e., over a path $\sim hN^{-1/3}/\xi_0'$, where ξ_0' is related to ξ_0 by the relation $(V_0/E < \xi_0 \ll 1)$

$$\xi_0' \equiv \eta = \sqrt{\xi_0^2 - V_0/E}. \tag{2}$$

$\xi_0' = \eta$ is the grazing angle in the medium, which is smaller than ξ_0 owing to refraction; V_0 is the mean potential energy of the bombarding atom in the medium; E is the particle energy;

$$V_0 \simeq 40 Z_1 Z_2 e^2 b_0^2 N / [\sqrt{Z_1} + \sqrt{Z_2}]^{1/3}; \tag{3}$$

here Z_1, Z_2 are the atomic numbers of the bombarding particles and of the atoms of the medium; $b_0^2 = \hbar^2/me^2$ is the Bohr radius, and the remaining notation is conventional.

Thus, one may write

$$h \simeq \eta / \left(\pi\rho^2(4\eta) \cdot N^{2/3}\right), \tag{4}$$

where ρ is the impact parameter corresponding to a scattering angle of 4η.

If $4\eta \ll 1$ and it is assumed that the interaction of the particles with the atoms of the medium is described by the potential [12]

$$V(\rho) = \frac{e^2}{\rho}\chi\left(\frac{1.13[\sqrt{Z_1} + \sqrt{Z_2}]^{2/3}\rho}{b_0}\right),$$

then

$$\begin{aligned} 4E\eta &\simeq \frac{kZ_1Z_2e^2}{\rho}\chi\left(\frac{1.13[\sqrt{Z_1} + \sqrt{Z_2}]^{2/3}\rho}{b_0}\right) \\ &= 1.13kZ_1Z_2[\sqrt{Z_1} + \sqrt{Z_2}]^{2/3}\frac{e^2}{b_0}\frac{b_0}{1.13[\sqrt{Z_1} + \sqrt{Z_2}]^{2/3}\rho}\chi\left(\frac{1.13[\sqrt{Z_1} + \sqrt{Z_2}]^{2/3}\rho}{b_0}\right), \end{aligned} \tag{5}$$

where χ is the Thomas–Fermi function. The coefficient k in single scattering varies from 1 to 2 when the argument of χ changes from 0 to 10. However, here, taking into account the approximate character of the calculation, it is expedient to put $k = 2$ in all cases. This partly takes into account the increase in the role of multiple collisions as the argument of χ decreases, and corresponds to the logarithmic factor—the "Coulomb logarithm," equal to 4—which should be introduced into the denominator in (4) for the case of small arguments of χ.

If the last equation is now solved with respect to ρ^2, we obtain

$$\rho^2(4\eta) = \frac{b_0^2}{1.28[\sqrt{Z_1} + \sqrt{Z_2}]^{4/3}} \varphi^2(2\mathcal{E}\eta), \tag{6}$$

where

$$\mathcal{E} = E/\left(1.13 Z_1 Z_2 [\sqrt{Z_1} + \sqrt{Z_2}]^{2/3} \frac{e^2}{b_0}\right); \tag{7}$$

$$\mathcal{E}\eta = \frac{1}{2}\xi = \sqrt{(\mathcal{E}\xi_0)^2 - \frac{40 b_0^2 N \mathcal{E}}{1.13[\sqrt{Z_1} + \sqrt{Z_2}]^2}}; \tag{8}$$

$\pi b_0^2/1.28 = 7 \cdot 10^{-17}$ cm^2; $1.13 e^2/b_0 = 30.8$ eV; $40 b_0^3/1.13 = 5.43 \cdot 10^{-24}$ cm^3.

The function $\varphi(\xi)$ is approximated by the expression

$$\varphi^2(\xi) \simeq (\xi^2 + 1.88\xi + 0.01)^{-1}; \tag{9}$$

φ is the argument of the function $\chi(\varphi)/\varphi$, and approximation (9) corresponds to the approximation $\chi(\varphi)$

$$\tilde{\chi}(\varphi) = \sqrt{0.8736\varphi^2 + 1} - 0.94\varphi. \tag{10}$$

The error of approximation (10) nowhere exceeds 3%, as long as $\varphi < 6$, but $\tilde{\chi}(10) = 0$.

On the basis of works [6–11], the values of h were calculated. Since often $\eta \ll \xi_0$, the relative error in h can be very large—the scatter of h for Cu proved to be 22-fold (from $h = 0.43$ to $h = 9.4$). The results are as follows: from [6–11] Cu $h = 4.6 \pm 3$, from [10] Ag $h = 2.7 \pm 0.3$; from [8] Ni $h = 3.5$; from [11] Fe $h = 1.25 \pm 0.29$; from [8,11] Mo $h = 2.34 \pm 1.3$ (here the root-mean-square error over all experiments is given).

Although the bombardment was carried out with different ions and at different ion energies, no regularity was found in the obtained values of h. In all experiments, a change in ξ_0 by $\pm10\%$ corresponds to a change in $h \simeq \pm1$–1.5. ξ_0 lay within $5^\circ \leq \xi_0 \leq 20^\circ$.

The absolute value of h obtained here is related to the fact that it has been assumed, somewhat arbitrarily, that the maximum corresponds to scattering of the bombarding particles through an angle equal on average to 4η along the path $hN^{-1/3}\eta^{-1}$. The value of h is approximately proportional to this factor (in the present case 4). However, this factor can hardly be substantially larger.

Table 1

	Particle energy (in keV)	$\zeta_{0\text{theor}}$ (in deg.)	$\zeta_{0\text{expt}}$ (in deg.)	λ_{expt} (in units of $N^{-1/3}$)	Source		Particle energy (in keV)	$\zeta_{0\text{theor}}$ (in deg.)	$\zeta_{0\text{expt}}$ (in deg.)	λ_{expt} (in units of $N^{-1/3}$)	Source
Cu—N	23	7	5	0.87	(7)	Mo—Ar	27	9	10	4.0	(8)
Cu—N	14	10	12	9.2	(7)	Mo—Ar	12	13	12	2.0	(11)
Cu—Ne	23	8	8	5.0	(7)	Mo—Xe	18	16	20	1.1	(11)
Cu—Ne	14	12	12	5.4	(7)	Ag—Ne	30	7	7	2.9	(10)
Cu—Ar	23	10	13	9.4	(7)	Ag—Ar	30	9	9	3.0	(10)
Cu—Ar	27	10	12	7.5	(6)	Ag—Kr	25	12	12	2.3	(10)
Cu—Ar	27	10	10	4.2	(8)	Ni—Ar	27	10	10	3.5	(8)
Cu—Ar	8	18	14	1.1	(11)	Fe—Ar	6	16	15	0.85	(11)
Cu—Ar	4	25	24	3.2	(11)	Fe—Ar	4	19	20	1.65	(11)

	Particle energy (in keV)	$\zeta_{0\text{theor}}$ (in deg.)	$\zeta_{0\text{expt}}$ (in deg.)	λ_{expt} (in units of $N^{-1/3}$)	Source	Particle energy (in keV)	$\zeta_{0\text{theor}}$ (in deg.)	$\zeta_{0\text{expt}}$ (in deg.)	λ_{expt} (in units of $N^{-1/3}$)	Source
Cu – Cs	8	27	17	0.43	(11)					

Apparently, h in the focusing theory may depend on the treatment of the target, i.e., on the size of the crystals in the polycrystal, on the number of defects, but it is unlikely to depend substantially on the target material. If $h \ll 4$, then, evidently, focusons cannot play a role in sputtering—they simply do not have time to form along the path of the disturbance to the surface.

When $0.01 < \delta^2\xi_0 < 0.7$ (all cases of the experimental works cited here satisfy this condition), approximately $\varphi^2(\xi) \approx 0.45/\xi$. Then

$$\zeta_0 \simeq \sqrt{\frac{\hbar^2 N^{2/3}}{mE} \frac{Z_1 Z_2}{\left|\sqrt{Z_1}+\sqrt{Z_2}\right|^{2/3}} \left(0.63h - \frac{40 b_0 N^{1/3}}{\left|\sqrt{Z_1}+\sqrt{Z_2}\right|^{2/3}}\right)}. \qquad (11)$$

The theoretical values of ζ_0 given in Table 1 were calculated from this formula with averaged values of h for the given target material. I express my gratitude to Yu. V. Martynenko, Yu. A. Ryzhev, E. S. Mashkova, and V. A. Molchanov for discussions.

Received
25 II 1969

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Note: Figure translations are in progress. See original paper for figures.