ANGLE OF INCIDENCE DEPENDENCE OF THE SPUTTERING YIELD AT ION BOMBARDMENT OF SOLIDS

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Introduction. Dependence of sputtering yield on the angle of ion incidence represents one of the important characteristics of sputtering. When the angle of ion incidence is variated, sputtering yield firstly increases from its value at normal incidence $Y(0)$ to some maximum value, and then decreases to the value $Y(90^0)$ at grazing angles of incidence [1] – see experimental data in Figure 1. Computer simulation by the program SRIM [2] gives finite values of $Y(90^0)$, but in reference [3] the author obtained zero values of $Y(90^0)$ in simulation of silicon and germanium sputtering by ions of noble gases. In the present work, the problem of angle of incidence dependence of sputtering yield is considered theoretically and by the method of computer simulation [4, 5].

Theoretical analysis is based on the solution of the system of two equations of transfer – for scattered ions (1) and cascade atoms (2):

$$cos\theta \frac{\partial F_1}{\partial x} = Collision\ Integral\ _1 \tag{1}$$

$$cos\theta \frac{\partial F_2}{\partial x} = Collision\ Integral\ _2 + Source\ Function \tag{2}$$

Here F_1 and F_2 represent distribution functions of ions and atoms respectively, x is the normalized target depth, $cos\theta$ denotes the directional cosine, and the source function in equation (2) is calculated after solution of equation (1).

We applied Mellin transformation over energy variable, and then solved the system of equations by the method of discrete streams, dividing the interval of variation of directional cosine in the collision integral into N equal parts, and considered the unknown values of distribution function in $N+1$ discrete points [4]. To calculate the unknown values, we expanded solution in a series of decreasing exponential functions and solved the problem of eigenvalues and eigenvectors of a quadratic matrix. The constants of expansion were obtained from the boundary conditions, and inverse Mellin transformation gave the final result. We performed numerical solution of the problem using increasing number of discrete streams, with maximum value being equal to $N = 500$. The method was justified by a series of test problems with known analytical solutions and by computer simulation program PAOLA.

Computer simulation is performed by the program PAOLA [5] based on the binary collision approximation and screened Coulomb potential. Before each elastic collision, the code generates three random numbers R_1, R_2, R_3 in the range between 0 and 1. These numbers define the particle path length between two collisions, $\lambda = \lambda_0 \ log(1/R_1)$, the polar scattering angle ω in the center-of-mass system,

$$cos\ \omega = \frac{2(1+\varepsilon)\ R_2 - 1}{1 + 2R_2\varepsilon} \qquad (3),$$

and the azimuthal scattering angle $\psi = 2\pi R_3$, where λ_0 represents the mean free path length and ε is the reduced energy. The scattering angles and energies of colliding particles are calculated from the conservation laws. Divergence between theoretical results and the results of simulation by the program PAOLA does not exceed 2% and it is visually indistinguishable.

Results. Figures 2 and 3 present the angle of incidence dependence of sputtering yield $Y(\theta_0)$ as a function of ion mass and ion energy. All sputtering yields are normalized to their values at normal incidence. We can see that the ratio of sputtering yields at grazing and normal incidence, $Y(90^0)/Y(0)$, decreases with decreasing ion mass and decreases also with increasing ratio of the ion energy E_0 to the cut-off energy E_{min}. It is demonstrated that sputtering yield at the angle 90^0 (limiting grazing incidence) always takes finite values.

References

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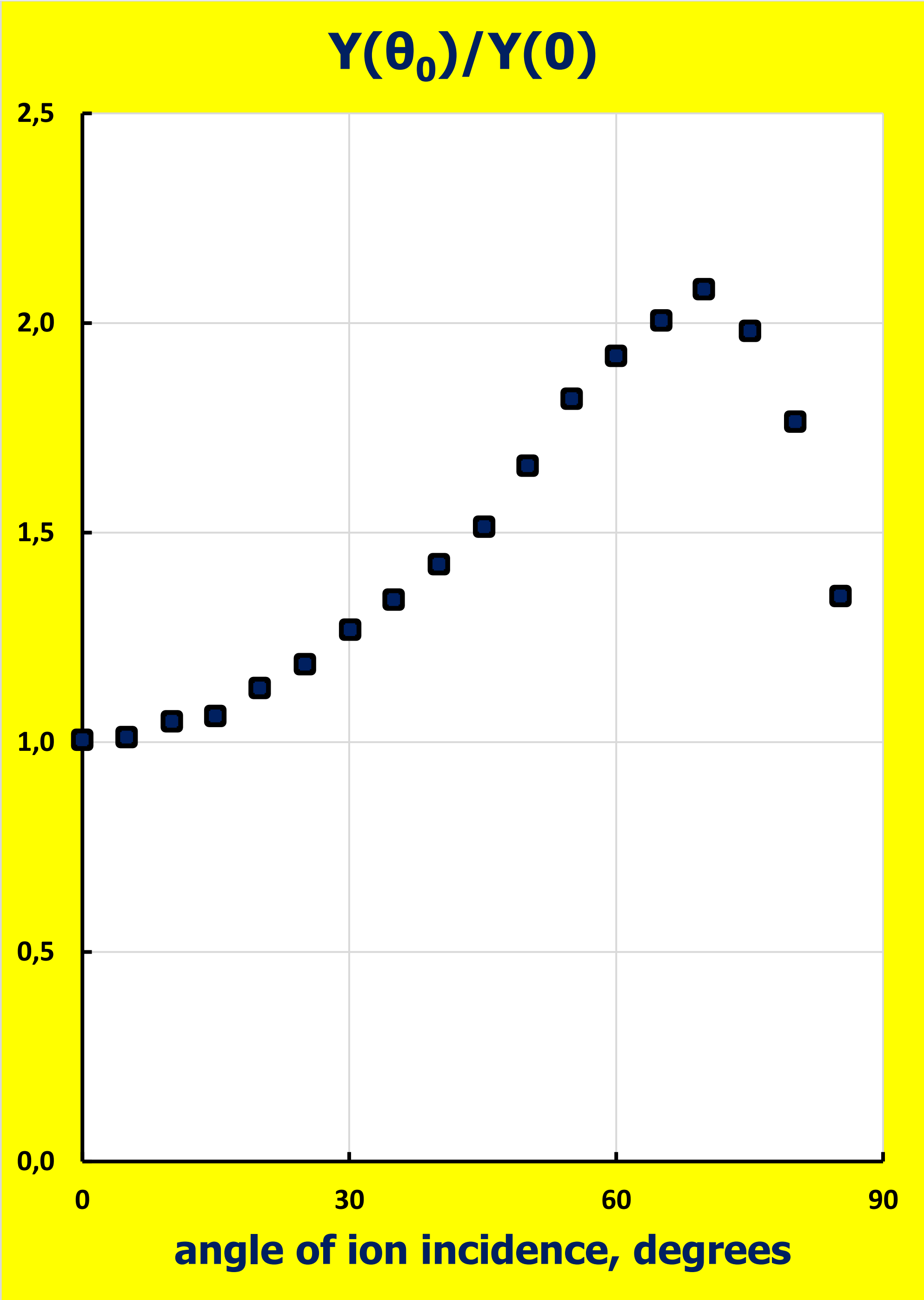

Figure 1

Dependence of sputtering yield on the angle of ion incidence.

Experimental data [1].

1 keV argon ions bombarding titanium target.

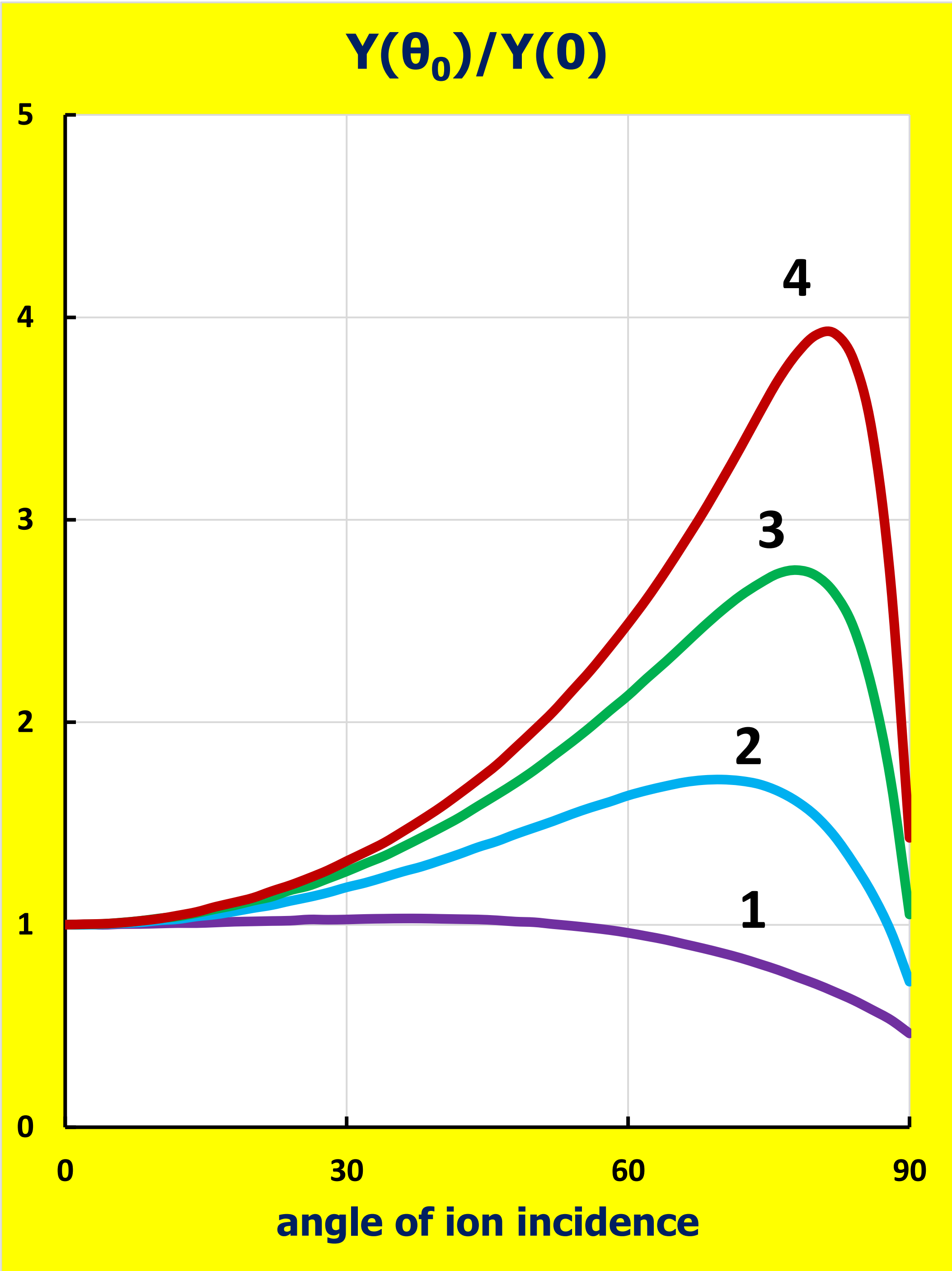

Figure 2

Dependence of sputtering yield on the angle of ion incidence for different ion to atom mass ratios $M_1/M_2=1$ (line 1), 5 (2), 10 (3), 15 (4) at ion energy $E_0/E_{min} = 1000$

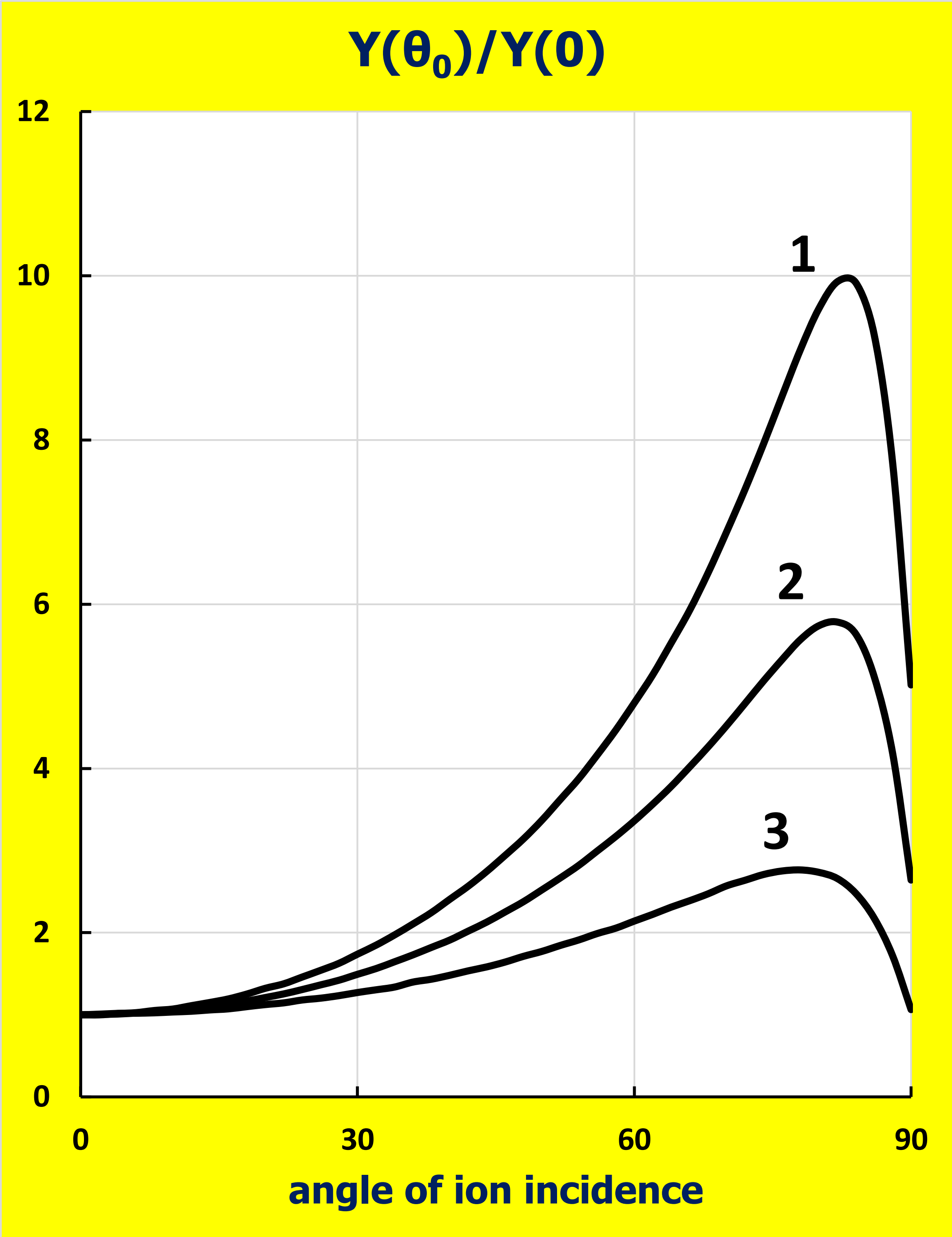

Figure 3

Dependence of sputtering yield on the angle of ion incidence for different ion energies

E_0/E_{min} = 100 (line 1), 200 (2), 1000 (3).

at mass ratio $M_1/M_2=10$