YUDIN'S APPROXIMATION OF NUCLEAR STOPPING POWER IN THE SPUTTERING YIELD CALCULATIONS

By J. Sielanko

Institute of Physics, M. Curie-Skłodowska University, Lublin*

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An analytical form of the nuclear stopping model suggested by Yudin was applied to Sigmund's sputtering yield expression. The simple equation for sputtering yields thus obtained gives good agreement with the calculated and experimental data over a broad range of ion target-energy combinations.

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1. Introduction

Sputtering i.e. the erosion of the solid surface by ion beams is of practical interest in thin film production and surface technology, erosion problems in plasma-wall-interactions, and more recently, in surface analysis (SIMS). In all cases knowledge of sputtering yield is of great importance.

The value of the sputtering yield S is a complicated energy dependence function and as a matter of fact, the available theories cannot explain it in a wide energy range. Moreover, within the same energy region several workers have derived quite different results due to the assumption of different atomic interaction models. For example, Keywell [1] predicted $S \sim E^{1/2}$ based on the hard sphere potential at the low energy range (0.1–1 keV). Sigmund [2] proposed the theoretical model where high energy collisions are characterized by the Thomas-Fermi type of interactions, while the Born-Mayer interatomic potential is applied in the low energy region. From his calculations at low energies $S \sim E$. Goldman and Simon [3] used the Rutherford type of collisions at high energy and predicted $S \sim \frac{\ln E}{E}$. Furthermore, the medium energy region was described by the combined theory of Rol, Fluit and Kistemaker [4] based on the weakly screened model of the Born-Mayer potential. Recently, Schwarz and Helms [5] proposed an elementary statistical model of sputtering based on simple geometrical considerations and calculated accurately the variations of the sputtering yields as a function of ion energy, mass, and incident angle. Unfortunately, their model was valid only in that energy region in which the standard approximation

* Address: Instytut Fizyki UMCS, Plac M. Curie-Skłodowskiej 1, 20-031 Lublin, Poland.

of nuclear stopping power $-S_n^0$ (independent of projectile energy) — can explain the range — energy dependence of implanted ions [6].

The most sophisticated treatment based upon the collision-cascade model in a random and infinite target has been given by Sigmund [2]. Using linear Boltzmann transport equation he determined the deposited energy distribution function in the target and showed, that the back sputtering yield is proportional to the value of this function at the surface. Sigmund assumed that all the atomic interactions take place through binary collisions, and high energy interaction (between ions and target atoms) are characterized by a Thomas--Fermi type cross section and low energy collisions can be described by the Born-Mayer interatomic potential. In the present paper it will be shown that when the simple analytical form of the nuclear stopping model suggested by Yudin [7] is introduced into Sigmund's sputtering yield expression, excellent conformity with the calculated and experimental data in a wide range of ions-target-energy combinations was obtained.

2. Sputtering yield expression. Experimental comparisons

According to Sigmund [2] at energies smaller than 1 keV the expression for sputtering yield at perpendicular incidence is given by

$$S = 0.076\frac{\alpha T_m}{U_0}, \tag{1}$$

where T_m is the maximum transferable energy in a head-on collision

$$T_m = \gamma E, \quad \gamma = \frac{4M_1M_2}{(M_1+M_2)^2}.$$

U_0 is the surface binding energy which is usually taken as the heat of vaporization. For pure elastic collisions, α is an energy independent function [2] of the ratio between target mass M_2 and projectile mass M_1 (Fig. 1). When the inelastic processes are included [8] the weak energy dependence of α is introduced. The variations with mass ratio in two curves of α (elastic and inelastic) are nearly identical for $M_2/M_1 \leqslant 1$ but they differ at higher mass ratios [9].

For the keV range of energy, the sputtering yield S for perpendicular incidence [2] is given by

$$S = 4.2\times 10^{14}\frac{\alpha S_n(E)}{U_0}, \tag{2}$$

where $S_n(E)$ is the nuclear stopping power

$$S_n(E) = 1.82\times 10^{-6} a Z_1 Z_2 \left[\frac{M_1}{M_1+M_2}\right] S_n(\varepsilon). \tag{3}$$

ε is the LSS [8] dimensionless reduced energy

$$\varepsilon = FE, \quad F = \frac{6.9\times 10^6 a M_2}{Z_1 Z_2 (M_1+M_2)}$$

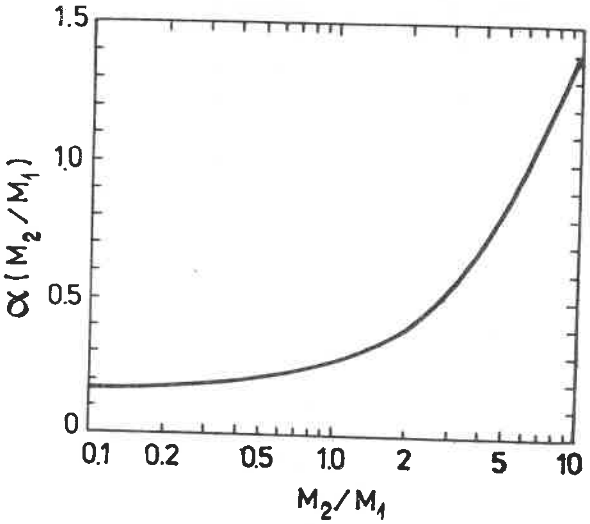

Fig. 1. Factor α as a function of mass ratio [2]

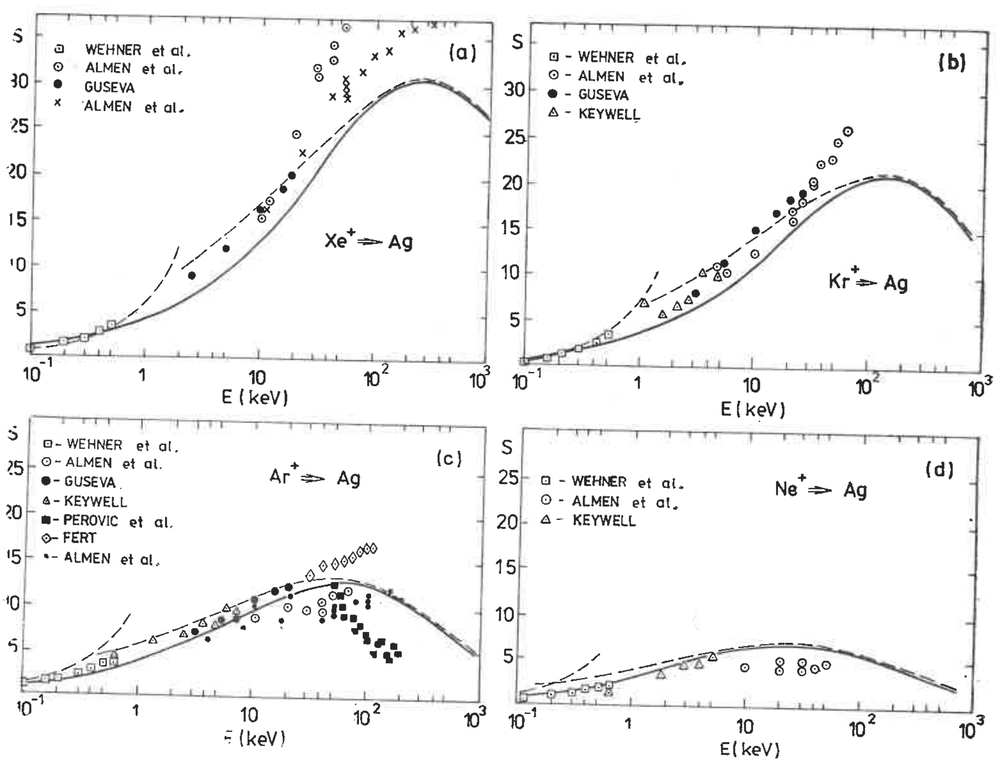

Fig. 2. Sputtering yields of Ag versus ion energy for Xe, Kr, Ar and Ne ions calculated by Sigmund (dashed lines) and calculated from Eq. (2) with nuclear stopping power as expressed by Eq. (4) (solid lines). Experimental data compilation from Sigmund [2]

and $a = 0.8853\, a_0 (Z_1^{2/3}+Z_2^{2/3})^{-1/2}$ is the Thomas-Fermi screening length, $Z_1 Z_2$ are atomic numbers of ion 1 and target atom 2, $S_n(\varepsilon)$ is the reduced nuclear stopping cross section for the T–F interaction tabulated by Lindhard [9]. In the above equations U_0 and a are in units of eV and cm respectively.

It is well known, that the nuclear stopping power is substantially overestimated by the LSS-theory [10]. According to [11] the Lenz-Jensen (L–J) potential is more convenient at low energies.

Recently Yudin [7] proposed a simple analytical form of the nuclear stopping power in the form

$$S_n(E) = \frac{h}{N}\,\frac{E^{1/2}}{E_i+E}, \tag{4}$$

where $h = \dfrac{cL}{F^{3/2}}$, $E_i = \dfrac{d}{F}$, $L = N\pi a^2 \gamma$ is a reduced range multiplier, N is the density of target atoms, c, d are constants which depend on the type of interatomic potential. The c value equal to 0.45 and $d = 0.3$ [7] provide to intermediate values of $S_n(E)$ as compared with the T–F and L–J interactions. The same value of c and d were also used in this work.

In Fig. 2 the heavy solid lines illustrate the application of Eq. (4) to the sputtering yield formula (Eq. (2)). For comparison, Sigmund's compilation of experimental data of a silver target sputtered by noble gases ions have been used. Figure 2 also shows the theoretical curves of Sigmund (dashed lines).

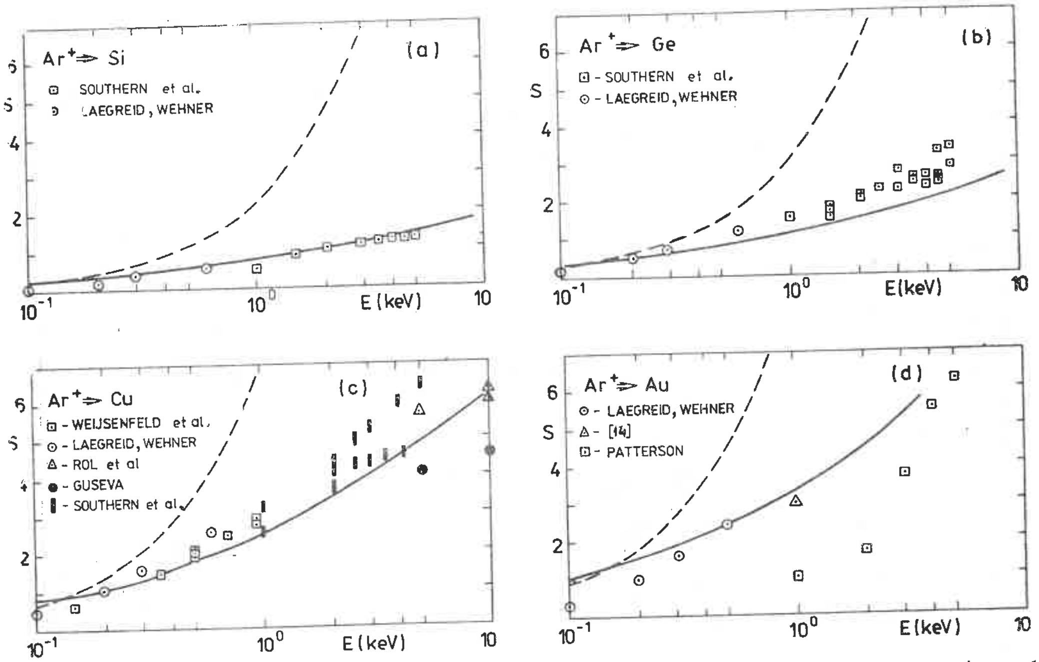

Fig. 3. Low energy sputtering yields for Ar^+ ions incident on Si, Ge, Cu and Au targets. Experimental results from Ref. [12–18]. Dashed curves: theoretical results from Eq. (1). Solid curves — calculated from Eq. (2) with nuclear stopping power expressed by Eq. (4)

Comparisons were also made for Si, Ge, Cu and Au sputtered by Ar^+ ions in the low energy range and illustrated pictorially in Fig. 3. In each case good agreement between the experiment and theoretical results calculated assuming the nuclear stopping power to be of the form (4) were obtained. It has to be mentioned that in some cases Sigmund's theory, based on the assumption that there is linear energy transport in the collision cascade, does not give a satisfactory description of the experimental results (see Ref. [9]). Nonlinear effects can modify the results and enhance the sputtering yield. The enhancement is substantial only below maximum in the nuclear stopping cross section. For light targets this effect can be neglected, but it gains in importance as Z_1, and Z_2 increase.

3. *Conclusion*

1. The use of Yudin's [7] simple approximation formula for the nuclear stopping power in sputtering yield S provides good agreement between calculated and experimental data in a wide range of ion-target-energy combinations.

2. In the lower energy range, the experimental data shows better agreement with the calculated values according to Eqs. (2) and (4) than those calculated using Eq. (1).

3. In the high energy range, the results of the present work fit well the theoretical curves calculated by Sigmund. This good fit is due to the coincidence in the behaviour of the nuclear stopping power function, given by Eq. (4), with that calculated according to the T–F interaction.

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