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ON THE ENERGY EFFICIENCY OF SPUTTERING

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Abstract. The optimum energy and the type of sputtering inert gas (Ne, Ar, Kr or Xe) used to achieve maximum productivity of the sputtering process of elemental targets, are assessed using the sputtering yield formula of Yamamura et al. [3]. The erosion efficiency η was found to have maximum at ion energy E of $7E_{th}$ (E_{th} is the threshold energy for sputtering). η_{max} exhibits oscillations with the atomic number Z_2 of the target and has values in the interval 0.4—4 %. This efficiency is relatively high ($\eta > 0.8\,\eta_{max}$) for E between 3 E_{th} and 20 E_{th} which for most ion-target combinations corresponds to energies within the 50—1000 eV interval. The η_{max} values for a given target do not differ significantly for different inert gases. For $Z_2 < 50$ targets Ar provides sufficiently higher efficiency (within 20 % compared with other inert gases) while for heavier targets Kr and Xe can have 40—70 % higher efficiency than Ar.

Резюме. Сделана оценка оптимальной энергии и типа распыляющего инертного газа (Ne, Ar, Kr или Xe), используемых для достижения максимальной производительности процесса распыления одноэлементных мишеней. Это сделано на основе формулы Ямамуры и др. [3] для коэффициента распыления. Установлено, что эрозионная энергийная эффективность η имеет максимум при энергии иона $E \cong 7E_{th}$ (E_{th} — пороговая энергия распыления). η_{max} осциллирует с атомным номером Z_2 мишени и имеет значения в интервале 0.4—4 %. Эта эффективность относительно высокая ($\eta > 0.8\,\eta_{max}$) для E в интервале $3E_{th}$—$20E_{th}$, который для большинства комбинаций соответствует энергиям в интервале 50—1000 eV. Значения η_{max} для данной мишени не отличаются значительно для разных инертных газов. Для мишеней с $Z_2 < 50$ аргон обеспечивает относительно более высокую эффективность (в рамках 20-ти процентов) по сравнению с другими инертными газами, а для более тяжелых мишеней криптон и ксенон могут иметь на 40—70 % более высокую эффективность, чем аргон.

1. Introduction

The parameter energy efficiency of sputtering ξ was introduced by Hosokawa et al. [1] as an important characteristic of the sputtering process. It was defined as the ratio of the flux of atoms J_n sputtered from the surface of the target to the power density P of the sputtering ion flux J_i. If we use $Y(E)$ to denote the energy dependence of the sputtering yield, we can write

$$J_n = J_i Y(E) \tag{1}$$

and

$$P = EJ_i \tag{2}$$

thus obtaining for ξ

$$\xi = Y(E)/E. \tag{3}$$

From eqn (3) making use of a reliable low energy sputtering yield formula $Y(E, M_1, M_2)$ (M_1 and M_2 are the masses of the ion and the target, respectively) one may estimate the maximum values of the energy efficiency of the sputtering process and analyze the question to what extent the proper choice of the mass and the energy for a given target can increase the productivity of the sputter deposition process. Previous considerations of the problem are briefly reviewed in Section 2. The power efficiency of the sputtering is analyzed in this work using the formula for $Y(E)$ of Yamamura et al. [3] with the correction of the threshold energy, presented in eqn (4) below. This formula was chosen by comparing [2] with low-energy sputtering yield formulas for elemental targets at normal incidence [3—9], paying particular attention to heavy ion ($M_1 > 20$ amu) and low-energy ($E < 2$ keV) sputtering. It was concluded that the elaborate formulas of Yamamura et al. [3] and Matsunamy et al. [7] best agree with experimental data. In both cases, however, the threshold energy for sputtering E_{th} seems to be overestimated for mass ratio $M_2/M_1 < 0.3$. The E_{th} expression proposed later by Yamamura and Mizuno [14] for the $Y(E)$ dependence of Matsunamy et al. [7] eliminates this discrepancy. Similar results are obtained [2] for the formula of Yamamura et al. [3] if a modified threshold formula is used for $M_2/M_1 < 0.3$

$$E_{th} = 10U_0(M_2/M_1)^{-1/3} \tag{4}$$

where U_0 is the sublimation energy of the target.

For the purposes of the estimation here, the formula of Matsunamy et al. [7, 14] as well as a more recent refinement of the same approach [10] would give practically identical results.

2. Previous data on the parameters characterizing the energy efficiency of the sputtering process

In order to evaluate the power efficiency of the sputtering process ξ, Hosokawa et al. [1] use experimental data on Y for several ion-target combinations. They conclude that ξ has a maximum in the 200—500 eV energy range.

Using Sigmund's low-energy and high-energy formulas and experimental data on $Y(E)$, Carter et al. [11] predict a plateau in the $\xi(E)$ dependence at low-energies (between 100 and 2000 eV), followed by monotonous decrease at higher energies. As a more suitable criterion for evaluating the energy efficiency of the sputtering process, they propose the dimensionless parameter η — the erosion energy efficiency (coefficient of energy efficiency)

$$\eta = U_0\,\xi \tag{5}$$

which is interpreted as the portion of the initial energy of the ion beam expended for sputtering (it is assumed that every sputtered atom requires energy equal to the binding energy U_0).

Using the formula of Bohdansky et al. [6] I. Petrov has shown [12] that

ξ has a maximum at $E=6\,E_{\mathrm{th}}$ with $\xi \geq 0.8\,\xi_{\max}$ in the interval $E=(3-10)E_{\mathrm{th}}$, which corresponds to energies in the 150—500 eV range.

Concerning the dependence of $Y(E)$, ξ and η on the ion mass for a given target, we may note that at high energies (10—100 keV) these parameters rise with increasing ion mass. This conclusion may be drawn from both experimental data [13] and Sigmund's high-energy formula. At low-energies, however, the curves for the different inert gases cross and the dependence on the ion mass is more complicated.

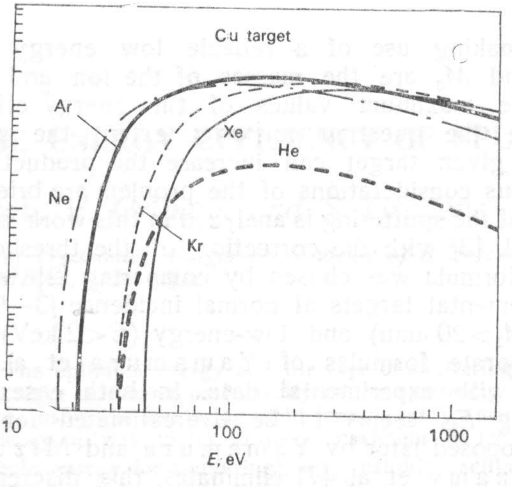

Fig. 1. Energy dependence of the coefficient of energy efficiency of the sputtering process $\eta = U_0 \xi$ for the fine noble gases (He, Ne, Ar, Kr, Xe) for sputtering a copper target

On the basis of Sigmund's low-energy formula, Carter et al. [11] conclude that η has a maximum value of about 2% at $M_2/M_1=1$ and varies from about 0.4% at $M_2/M_1=0.1$ to about 1.6% at $M_2/M_1=10$. On the other hand, based on his low-energy formula and neglecting the E_{th} vs M_2/M_1 dependence, Zalm [8] concludes that at low energies $Y(E)$ is not greatly dependent on the ion type.

3. Assessment of the energy efficiency of the sputtering process in the low-energy region

Here we shall attempt to extract some information on the ξ and η vs energy dependence and the type of the ion by using the formula of Yamamura et al. [3] and correcting it for E_{th} as in [2] for small M_2/M_1 ratios.

Figure 1 compares the dependences of $\eta(E)$ (in percents) on the type of inert gas (He, Ne, Ar, Kr, Xe) in the case of sputtering a copper target. The picture is similar for all the five gases. It can be seen that the energy efficiency of helium is significantly lower than for the heavier inert gases. For this reason helium will be excluded from further discussions. The values of η for the different gases differ significantly (by orders of magnitude) at energies immediately above the threshold $E \leq (2-3)E_{\mathrm{th}}$. The shape of all $E_{\mathrm{th}}/U_0 = f(M_2/M_1)$ dependences compared in ref. [2], indicates that the threshold energy is the lowest if the sputtering is performed with ions whose mass is 3 to 5 times lower than the mass of the target atoms ($M_2/M_1 \approx 3$—5). Therefore, in the energy region immediately above the threshold energy, the use of such ions in the sputtering process may have an essential advantage. At higher energies ($E \geq 3E_{\mathrm{th}}$), the curves of the coefficients of energy efficiency $\eta(E)$ for the different inert gases are considerably closer together and the values of η are of the same order of magnitude. In all cases $\eta(E)$ passes through a maximum which occurs at an energy about $E = 7E_{\mathrm{th}}$. In the energy region above the maximum, η decreases more slowly with increasing energy and the interval in which $\eta(E) \geq 0.8\ \eta_{\max}$ is approximately $\Delta E = (3$—$20)\ E_{\mathrm{th}}$.

Comparing these results with previous assessment of the energy efficiency of the sputtering process (ξ or η) [8, 11, 12] we may note the following. Similar to the work of Petrov [12], we may conclude that the optimum energy for obtaining maximum energy efficiency for every ion-target combination is closely related to the threshold energy E_{th}. However, in contrast to Bohdansky's formula, which is used in [12], Yamamura's formula predicts a significantly broader high-energy interval (up to $E = 20\ E_{\mathrm{th}}$ for $\eta \geq 0.8\ \eta_{\max}$) in which $\eta(E)$ has a relatively high value. Taking into account the fact that for the ions considered here (Ne, Ar, Kr and Xe) the threshold energies for the sputtering of various targets are typically ([14] and references therein) in the 15—60 eV interval (carbon with a threshold energy about 100 eV is an exception) we may conclude that the optimum energies for sputtering ($E = 7\ E_{\mathrm{th}}$) lie in the 100—400 eV interval. This interval contains the optimum energies for about 90% of the considered 136 ion-target combinations, whereas the 100—300 eV interval contains about 75% of these combinations. Taking into account the broadness of the maxima of η, one may conclude that the sputtering process is energy efficient in the energy region from about 50 to 1000 eV.

By comparing these results with the assessment presented in Refs [11] and [12], we may note that the energy interval is broadened towards the lower energies. Since an ideal sputtering source should provide an ion flux of optimum energy and high density, it follows from the above discussion that the magnetron sputtering system has parameters which are very close to the ideal. The accelerating voltages in magne-

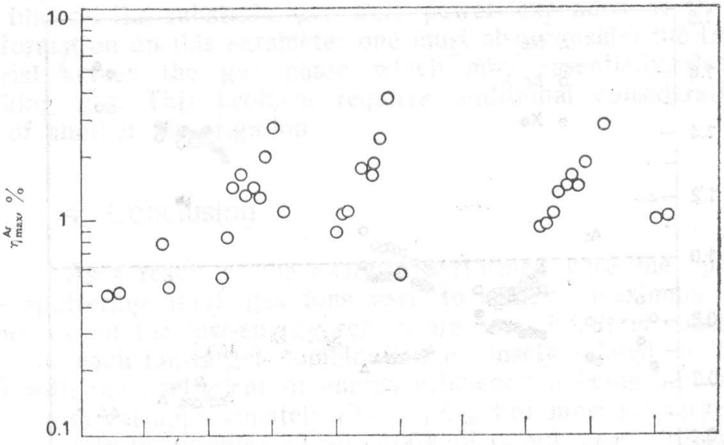

Fig. 2. Maximum values of the coefficient of energy efficiency of the sputtering process for sputtering by argon ions $\eta^{\mathrm{Ar}}_{\max}$ (in %) as a function of the target's atomic number Z_2

trons are in the 300—800 V interval, i. e. they provide an ion energy above the optimum value. However, efforts to the additionally broaden operating voltages towards lower energies — down to 100—200 V — would be worthwhile. This would increase the energy efficiency of the sputtering process for many ion-target combinations. An example of such a solution is the triode system proposed by Cuomo and Rossnagel [15], which permits to sustain the discharge at such low votages.

On the basis of the analysis performed here we may also draw another conclusion about the practical application of the sputtering process in the case of multi-component targets. If the separate components have significantly different binding energies, then the use of ion energies, immediatly above threshold $E=(2—3)E_{th}$ at which the partial sputtering yields differ significantly, would lead to differences in the composition of the target and of the layers obtained. Thus, in such cases it should be recommended to use ion energies significantly above the threshold.

Consider now the dependence of the energy efficiency of the sputtering process on the ion mass. Figure 2 presents the values of η_{max} in the case of sputtering of different materials with argon ions (note that for the different targets the energy at which η has its maximum ($\eta_{max}=\eta(7\,E_{th})$) is different depending on the target's atomic number Z_2. It is seen that the values of η_{max} are in the 0.4—4 % interval, being between 0.5 and 2 % for most of the targets. These values are very close to those obtained by Carter et al. [11].

Clearly seen in Fig. 2 is a periodic oscillation of η_{max} with the target's atomic number Z_2. This result differs from the values obtained in Ref. [11] on the basis of Sigmund's low-energy formula which predicts a gradual change of η_{max} with the mass ratio M_2/M_1 (for a fixed gas this is equivalent to changing M_2) and a maximum in the case of equal masses ($Z_2=18$ in the case of Fig. 2). Similar oscillations in the Z_2-dependence have also been observed for the sputtering yield Y. However, whereas in that case the oscillations are associated with the periodic dependence of the sublimation energy U_0, which is included in the formula for Y on Z_2 [16],

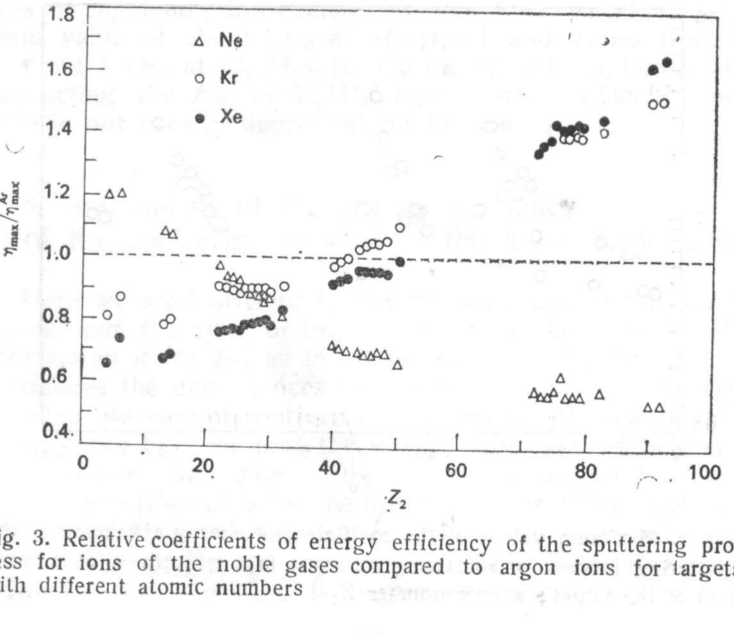

Fig. 3. Relative coefficients of energy efficiency of the sputtering process for ions of the noble gases compared to argon ions for targets with different atomic numbers

in the case of the oscillations shown in Fig. 2 such a simple explanation cannot be used since the coefficient of energy efficiency η introduced by Carter et al. [11] is practically independent of the sublimation energy U_0.

Since the dependences of η_{max} on Z_2 for the other inert gases considered here — Ne, Kr and Xe — exhibit a similar periodic behaviour, Fig. 3 shows the ratios of η_{max} for each of the other three noble gases to η^{Ar}_{max} for the respective target in order to illustrate the dependence of the energy efficiency on the ion mass. This Figure shows more clearly that ions whose mass is close to the mass of the respective target, i. e. for $M_2/M_1 \geq 1$ (Ne for small Z_2 and Kr and Xe for large Z_2) actually provide higher η_{max} values which agrees with the conclusion of Carter et al. [11]. According to Fig. 3, neon has an advantage for targets from groups 2 and 3 of the Periodic table, argon — for targets from group 4, krypton — for group 5 and xenon — for the heavier elements. It should be noted, however, that in agreement with Zalm's [8] conclusion for targets with $Z_2 \leq 50$, the values of η_{max} for the different noble gases are very close. For such targets, argon provides η_{max} which is only 20% lower than the values of η_{max} for neon and the lighter targets and η_{max} for krypton and the heavier targets. A more noticeable difference (40—70%) would be obtained by substituting xenon for argon in the case of targets with atomic number $Z_2 \geq 70$. It is seen that for such Z_2 the η_{max} values for krypton are very close to those for xenon.

At high energies (of the order of 50 keV), some systematic data on the sputtering yield [13] and Sigmund's high-energy formula indicate that for all targets the sputtering yield approximately doubles when going from Ne to Ar, Kr and Xe. In contrast, in the low-energy range, where the sputtering process is energetically the most efficient, it is not possible through selection of the mass of the sputtering inert gas to significantly increase the productivity of the sputtering systems (e. g. for ion etching or thin film deposition in high vacuum conditions). However, if we are interested in the process of thin film deposition by sputtering in a gaseous medium (e. g. magnetron sputter deposition) the above parameters ξ and η, which describe the energy efficiency, characterize only the vapour phase generation process by ion sputtering of the target. In such cases [1] more important is the parameter which characterizes the growth rate of the thin film on the substrate per unit power expended at the target. To obtain complete information on this parameter one must also consider the transport of the sputtered material across the gas phase which may essentially depend on the type of the working gas. This problem requires additional consideration which will be the subject of another investigation.

4. Conclusion

As a result of the analysis performed here the optimum energies and types of the sputtering inert gas ions used to achieve maximum productivity of the sputtering process in the low-energy region are assessed. It is concluded that the optimum energy for each ion-target combination is closely related to the threshold energy ($E_{opt} \approx 7\, E_{th}$) with the coefficient of energy efficiency η being higher than 80% of η_{max} in the energy interval approximately $(3-20)\, E_{th}$. For most ion-target combinations this interval corresponds to energies of 50—1000 eV — an energy interval which is broadened towards lower energies with respect to previous assessments. The η_{max} values for a given target do not differ significantly between the inert gases. For targets of $Z_2 < 50$ Ar provides sufficiently high efficiency (with 20% compared with other inert gases) while for heavier targets Kr and Xe can have 40—70% higher efficiency than Ar.

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