

EFFECTS OF LOW-ENERGY ION BOMBARDMENT
OF SURFACES AS FUNDAMENTAL PROCESSES IN PLASMA-SURFACE INTERACTION

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1. INTRODUCTION

The interaction of a plasma with a surrounding surface involves a variety of simultaneous processes which determine plasma properties and can also modify the surface. For instance, in controlled fusion devices crucial phenomena such as impurity influx, recycling, energy confinement, wall erosion etc. depend to a large extent on surface interactions. It is generally assumed that these interactions can be described by the linear superposition of the various different effects which occur between the plasma particles and the surface. That is, synergistic processes do not play a too important role. Consequently, particular single interaction processes are studied in order to obtain an improved understanding of the complex plasma surface interaction. In fusion research this is documented in a series of international conferences on plasma surface interaction, see ref. 1.

In this context some effects of the bombardment of surfaces with ions of energies below a few kilo-electron-volts will be considered in the following. The topics are scattering of ions, sputtering of bulk material and adsorption layers, surface changes and emission of excited particles. The basic physical concepts which lead to a simplified but rather general understanding of these effects will be outlined.

2. ION SCATTERING

In the low energy regime the interaction between an incident ion and surface atoms and also between energetic recoils in the collision cascade is governed by elastic binary collisions. That is, kinetic energy is transferred to the center of mass of the target atoms. Inelastic effects, such as energy transfer to kinetic or potential energy of the electrons are less important though not negligible. For elastic binary collisions the energy E_1 of the scattered particle relative to the primary energy E_0 is a function of the laboratory scattering angle ϑ_1 and the mass ratio M_2/M_1 of target and projectile atomic mass, respectively,

$$E_1/E_0 = (1+M_2/M_1)^{-2} \left\{ \cos^2 \vartheta_1 + [(M_2/M_1)^2 - \sin^2 \vartheta_1]^{1/2} \right\}^2. \quad (1)$$

Similarly, the relative energy transferred to the recoil atoms is

$$E_2/E_0 = \gamma \cdot \cos^2 \theta_2, \quad (2)$$

where γ is the maximum fraction of energy which can be transferred in a single collision

$$\gamma = \frac{4M_1M_2}{(M_1+M_2)^2} \quad (3)$$

That means good energy transfer only for comparable masses. It has been proven that formulae 1 and 2 are applicable for surface scattering of low energy rare gas ions /2/. Figure 1 shows as an example an energy spectrum of He^+ scattered from Ta_2O_5 .

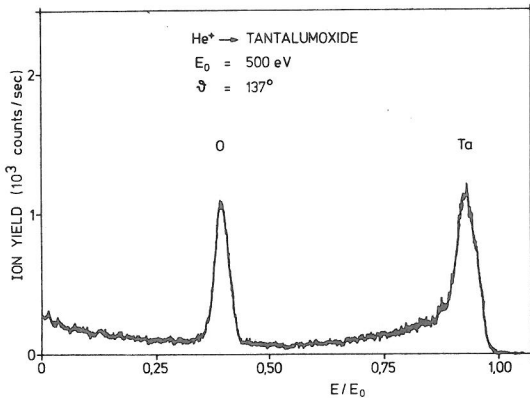


Fig. 1

The validity of this binary model has been demonstrated for single and multiple ion scattering down to about 20 eV primary energy /3/. The probability for a scattering event is governed by the interaction potential which is often described by a screened Coulomb potential. For a power dependence of the screening function the scattering cross-section is /4/

$$d\sigma = C E_0^{-m} E_2^{-1-m} dE_2 \quad (4)$$

where C is a constant for a given projectile-target pair and m is a number between 0 (low energy limit) and 1 (Rutherford scattering).

$d\delta$ decreases with increasing primary energy and transferred energy, i.e. increasing scattering angle.

The simple relations sketched above can be used as a basis for understanding a variety of ion surface interactions. They also give the basis for numerical Monte Carlo simulations of these processes.

3. REFLECTION

An important question in our context is the number and energy distribution of particles which are reflected from the surface. The particle reflection coefficient R_N , i.e. the number of kinetically reflected particles per incident particle, has been measured for light ions at normal incidence on various materials /5/. Figure 2 shows that R_N scales within a factor of 2 if the data are plotted versus Lindhard's reduced energy ϵ /4/.

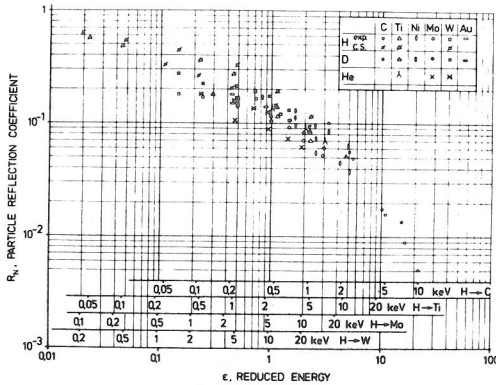


Fig. 2

The agreement with calculations using the binary collision cascade program MARLOWE /6/ is good. Similar results have been obtained for the energy reflection coefficient R_E /6,7/. If the particles impinge at grazing angles the reflection is generally increased. The energy distribution depends very much on the primary ion energy. For low energies (for H $E_0 \leq 100$ eV /6/, for He $E_0 \leq 1$ keV) the maximum is close to E_0 , i.e. most particles are backscattered from the surface after essentially one violent collision and retain the energy corresponding to equ. 1. For higher energies most particles penetrate deeper into the solid and lose energy on their way in and out. Consequently, the maximum in the energy distribution shifts to lower energies. It should be noted that the reflection can be quite different for ions and neutra-

lized particles. Particularly, noble gas ions are reflected without neutralization only from the surface /2,3/. Inelastic energy losses are also important for the reflection coefficient as can be seen from the comparison of experimental and calculated values /8/. The angular distributions depend on the angle and energy of the incident particles. For surface scattering (low energies and grazing incidence) there is a maximum in the angular distribution about the specular direction /9/, whereas for higher energies (H and He above 5 keV) and normal incidence cosine distribution was found /8/.

The complementary effect to reflection is trapping. For increasing fluence of primary particles other than kinetic effects have to be considered, such as solubility, damage distribution, diffusion and hence temperature. For many materials a saturation concentration of implanted particles is reached at room temperature and further bombardment results in an equivalent amount of reemitted particles /10/.

4. SPUTTERING

An energetic projectile transfers energy and momentum to the target atoms in the collision cascade. If surface atoms obtain enough energy they can be released from the surface. This collisional model of sputtering has been elaborated in the sputtering theory of Sigmund for amorphous solids /11/. It is natural that the amount of possible energy transfer ϕ and the atomic surface binding energy E_B are important parameters for sputtering. This will be illustrated for some important examples.

5. SPUTTERING YIELD

In low energy sputtering the energy dependence of the sputtering yield is very similar for many projectile ion - target combinations. This has been used by Bohdansky et al. /12,13/ to develop an empirical universal form for the ~~normalized~~ sputtering yields S_N as a function of the reduced energy E' , which allows to predict sputtering yields with fair accuracy:

$$S_N(E') = 6.4 \times 10^{-3} \times M_2 \times \phi^{5/3} E'^{1/4} \left(1 - \frac{1}{E'}\right)^{7/2} \quad (5)$$

The reduced energy is $E' = E/E_{th}$. Fitting parameters are the threshold energy E_{th} and the yield factor Y . For $M_2/M_1 > 2.5$ the threshold energy can be approximated by

$$E_{th} = \frac{E_B}{\phi(1-\phi)} \quad (6)$$

The yield factor follows quite universally a relation like

$$Y = M_2 \times 0.75 \phi^{5/3} \quad (7)$$

The normalized sputtering yields for a great number of metals and metal carbides are plotted in Figure 3. The good general agreement with the empirical formula (5) in the low energy region is demonstrated.

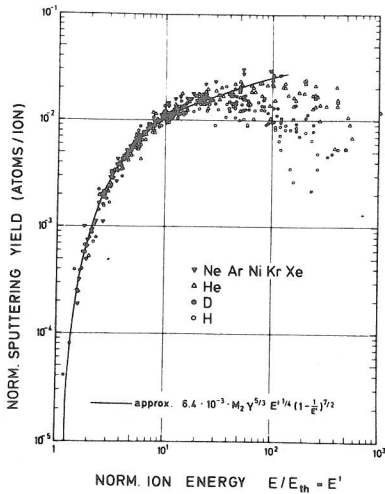


Fig. 3

6. DESORPTION OF ADSORBATES (GAS SPUTTERING)

The sputtering or desorption of adsorbed layers by ion impact is of interest for fusion experiments in the present stage, because it can contribute decisively to plasma contamination /14,15/. The desorption cross-section σ_D has been determined for O, CO, H, and S on various metals /16,17/. σ_D is used instead of the sputtering yields S in order to have a coverage independent measure. They are related by the monolayer atomic density N_{ML} :

$$S = \sigma_D \times N_{ML} \quad (8)$$

For the simple atomic adsorbates the magnitude of σ_D and its dependence on parameters such as primary ion energy, ionic mass, angle of incidence etc. again can be explained on the basis of binary collision approximations. This is shown by comparing the experimental data with calculations using either the numerical code MORLAY, a modification of MARLOWE /14/ or the analytic estimates of Winters & Sigmund /19/. Figure 4 shows the energy dependence of σ_D for O on Ni bombarded with Ar^+ in the energy range between 100 eV and 1800 eV. Without fitting experiment and calculations agree within a factor of three or better. Some deviations of this agreement are encountered with CO desorbed from Ni /20/.

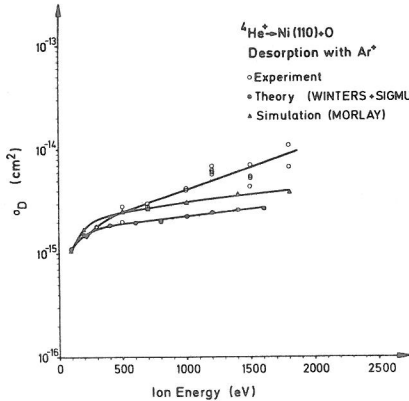


Fig. 4

7. SURFACE BINDING ENERGY

The question of surface binding energy and its possible angular dependence has often been considered in connection with sputtering, see e.g. refs. 11 and 21. Directional effects in surface binding of adsorbates and their influence on electron stimulated desorption could recently be clearly demonstrated /22, 23/. For sputtering calculations usually planar or isotropic surface barriers are assumed. In theory /11/ or numerical calculations /21/ generally a variation of the sputtering yield with binding energy like $S \sim E_B^{-1}$ is obtained. An attempt to check this relation experimentally was made /24/ by determining the desorption cross-section for oxygen (and CO) adsorbed on various metals with different oxygen surface binding energies. The results are shown in Figures 5 and 6. Figure 5 shows the experimental results for S_D as a function of the inverse heat of adsorption and Figure 6 shows the corresponding MORLAY calculations. The common trend of both data clearly supports the E_B^{-1} relation. There are also some systematic deviations due to the different substrates. The S_D values for higher masses are systematically above the comparable values for lower atomic mass. This indicates an increased contribution of the backscattered primary ion flux for targets with higher atomic mass (lower γ , larger $d\sigma$).

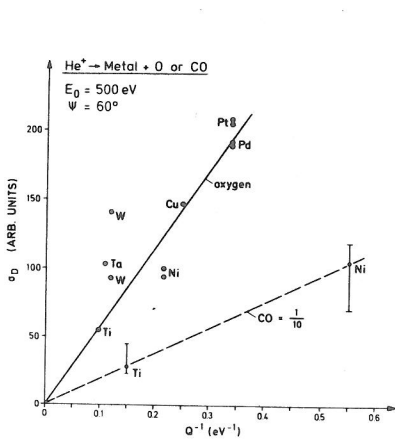


Fig. 5

$\text{He} \rightarrow \text{METAL} + \text{O}$ (MORLAY)

$E_0 = 500 \text{ eV}$

$\Psi = 60^\circ$

isotropic surface binding

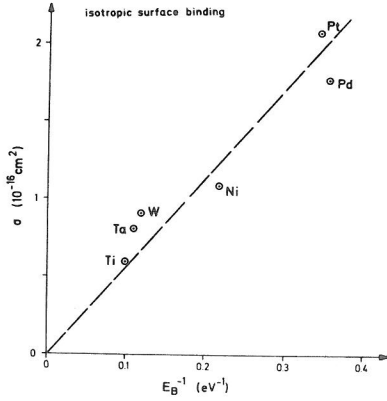


Fig. 6

8. SURFACE MODIFICATIONS

Besides the effect of releasing particles, e.g. into the plasma, ion bombardment also causes surface modifications. These changes can be both, structural and compositional and they in turn represent altered wall conditions for the plasma. An example for compositional changes is shown in Figure 7. The surface composition of WC is altered by He^+ and Ar^+ bom-

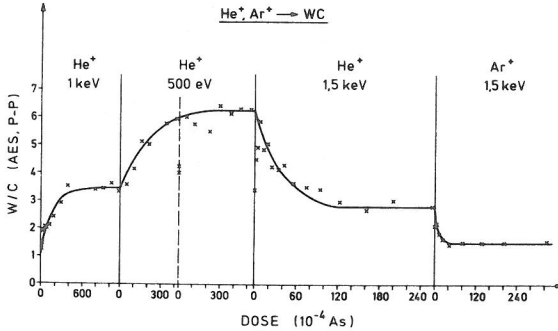


Fig. 7

bombardment. These changes depend on the mass and energy of the bombarding ions and are completely reversible. The surface becomes carbon depleted by the ion bombardment and this depletion is more pronounced for lower energies and light ions. Very similar results have been obtained for TaC and Ta₂O₅ /25/. This behaviour again can be understood in terms of collisional energy transfer. As can be seen from equ. 3 both projectiles can transfer more energy in a single collision to a C atom than to a W atom. The relation of both transfer factors is 1.5 for Ar and 9 for He. Therefore it can be assumed that with light ion bombardment mainly the carbon "sublattice" is set into motion and thus C is preferentially sputtered from the surface until an equilibrium concentration is reached. This equilibrium concentration depends also on the relative surface binding energies. The strong energy dependence of the depletion for low energies is caused by threshold effects. It can be deduced from fig. 3 that the sputtering yield decreases steeply with energy below a maximum value which is of the order of ten times the threshold energy. E_{th} for He on WC is determined by the removal of W and is 86 eV /26/. This is consistent with the results in Fig. 7 where we find a much stronger energy dependence between 1 keV and 500 eV than between 1500 eV and 1 keV.

Further ion induced surface compositional changes are caused by implantation of the bombarding ions (see sect.3) and recoil implantations of surface contaminants /27/. Structural changes have also been observed in many systems /28/. For instance, cone formation on metal surfaces depends very much on the chemical nature of the bombarding particles /29/. Presently it is being disputed whether these cones lead to a decrease /30/ or increase /31/ of the sputtering yields.

9. INELASTIC EFFECTS

Inelastic effects, i.e. processes in which electronic transitions are important, can only be briefly mentioned here. They are, however, very important in determining the charge states of reflected particles as well as sputtered particles, secondary electron emission etc. All these effects depend very much on the surface conditions. Charge states for light ions backscattered from metal surfaces have been measured by Eckstein and Verbeek in the energy range from 1.5 keV to 15 keV /32/. The increase of secondary ion and excited NiI emission with surface coverage (Ni with CO) is shown as an example in Figure 8 /27/. It shows a linear dependence of the ionized or excited particle yield with surface coverage. Thus a model in which the excitation occurs locally in a bond-breaking mechanism is supported by these results (rather than a surface plasma or a band structure model). The importance of charge states for plasma physics lies for instance in the impurity influx control, which depends on the probability that particles leaving the surface penetrate into the plasma without being diverted by magnetic fields /33/.

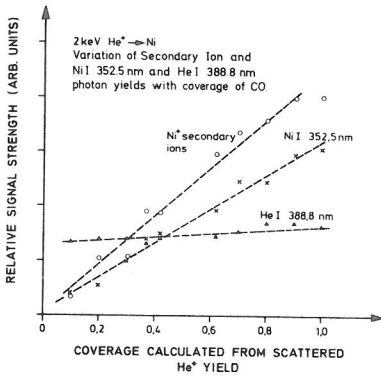


Fig. 8

10. CONCLUSIONS

For the interaction of ions with surfaces a (limited) number of effects has been considered, such as backscattering, sputtering, surface modifications, emission of excited particles. It turns out that a great deal of these phenomena can be understood in terms of two-particle collisions. Thus some general rules can be found and calculations can be made for quantitative predictions. However, many processes have to be studied in more detail and a large amount of data is still required /34, 35/. These data are of fundamental importance for plasma surface interaction, i.e. for understanding and controlling the discharge, the impurity release and the wall erosion.

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