LOW-ENERGY HYDROGEN SPUTTERING OF Au, Ni AND STAINLESS STEEL*

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Normal incidence sputtering yields have been measured for 200 - 2000 V hydrogen ions on Au, Ni and 304 stainless steel films using a Rutherford backscattering technique. The measured yields agree well with recent results obtained at higher ion doses using the weight-loss method as well as with model calculations based on the binary collision approximation.

1. INTRODUCTION

The sputtering of first-wall materials by low-energy light ions escaping the plasma may contribute significantly to impurity introduction and wall erosion in proposed fusion devices [1]. Recently, extensive measurements [2-5] of light-ion sputtering yields using the weight-loss method have led to an improved understanding of low-energy sputtering processes [6]. These measurements require the removal of large numbers of atoms and have generally been performed at doses of $>10^{18}/\text{cm}^2$ for hydrogen ions. In the present work, a more sensitive Rutherford backscattering technique has been used to determine normal incidence sputtering yields for 200 to 2000 V H^+ on Au, Ni and 304 stainless steel films at doses of $10^{18} - 10^{19}/\text{cm}^2$. The present results therefore approximate more closely the hydrogen fluences in typical tokamak discharges ($10^{16} - 10^{17}/\text{cm}^2$). The measured sputtering yields are correlated with the higher dose weight-loss results as well as with predicted yields based on binary collision models [6,7].

2. EXPERIMENTAL

The experimental arrangement is shown schematically in Fig. 1. The sputtering beam was extracted at 35 kV from an ion implantation accelerator and decelerated to its final energy using an electrostatic lens [8]. Before entering the lens system, the beam was mass-analyzed and electrostatically deflected to eliminate neutral components. Pressures of 10^{-9} Torr were maintained in the beam transport system. The base pressure in the target chamber was $<10^{-9}$ Torr and rose to 2×10^{-7} Torr during sputtering.

The deceleration system consisted of a biased collimator for defining the uniform central position of the sputtering beam, an aperture for reflecting secondary electrons in the beam which escape the collimator, and an electrostatic lens

referenced to the extraction voltage through a floating power supply. The final beam energy was determined by biasing the target with respect to the extraction voltage. Beam currents were integrated directly off the target (maintained positive with respect to the lens body for secondary electron suppression) and were periodically checked using a Faraday cup. Neutral components in the beam were estimated to be less than 1% of the charged beam from secondary electron emission yields measured inside the Faraday cup at 0 and 35 kV final beam energies. The lens was strongly focussing with current densities at the focal spot up to 10 times greater than nominal beam densities. The target could be translated along the beam axis to focus 10 μA of H^+ in a 1mm spot ($<1\text{mA}/\text{cm}^2$) for final beam energies between 200 and 2000 V.

The targets were prepared by sputter depositing 500Å films of Au, Ni and 304 stainless steel on graphite and polished Si wafers. Previous experiments [3,9] have established similar sputtering rates for bulk and sputter-deposited stainless steel. Film thicknesses were determined gravimetrically and from the energy loss of backscattered 2.5 MV He^+ ions. The independent thickness measurements agreed within 10%. The film thicknesses were chosen to be several times the range of 2000V H^+ in the film material. Target films were exposed to air prior to sputtering but the influence of oxide layers could be neglected for Au for H^+ doses above $10^{19}/\text{cm}^2$ and for Ni and stainless steel above $10^{18}/\text{cm}^2$.

The loss of sputtered material was monitored in situ from changes in the Rutherford backscattering yield of a 2.5 MV He^+ beam which could also be directed onto the sputter spot (Fig. 1). The mass-specificity of the backscattering technique allows the separation of scattering from the target film and the lower mass substrate. The change in the average thickness of the film can be determined from the energy width of the backscattering spectrum while the sputtering yield is determined from changes in the integrated spectrum. Additional details are given elsewhere [9]. Some typical backscattering spectra for 1.0 kV H^+ sputtering of Au

* Research sponsored by the Office of Fusion Energy, U.S. Department of Energy under contract W-7405-eng-26 with the Union Carbide Corporation.

Fig. 1. Schematic of the deceleration system showing the sputtering and analysis beams.

are shown in Fig. 2. These measurements were performed during sputtering at a He⁺ scattering angle of 70°. The resulting sputtering yields agree well with yields deduced from 160° backscattering measurements following completion of sputtering.

Fig. 2. Rutherford backscattering spectra for Au sputtered at various H⁺ doses.

The analyzing beam was collimated to uniformly irradiate the entire sputtered crater. The incident beam current was monitored using a rotating vane in the beam and the backscattered He was detected with a surface barrier detector. The He beam cross section at the target position was determined by measuring the current from a

wire passed through the beam. Sputtering yields measured using nominal 1.0 and 1.5 μm analyzing beams agreed within 15%. The He irradiated volume was determined from the thickness of the target film and the area of the He beam. Overall, uncertainties in the H⁺ dose (10%), target thickness (10%), He beam area (20%) and backscattering statistics (15%) contribute to an estimated 30% uncertainty in the absolute sputtering yields. Relative yields are more accurately determined.

3. RESULTS

The energy-dependent sputtering yields for Au, Ni and 304 stainless steel are summarized in Table I. These results are generally for H⁺ doses of $0.6 - 1 \times 10^{19}/\text{cm}^2$ and include measurements using target films deposited on polished Si and rough-textured graphite. No significant differences in sputtering yields for the two substrate materials were observed. A surface structure consisting of large numbers of $\sim 10\text{nm}$ blisters developed at all energies and doses for the Au targets but no evidence of exfoliation was found. Some small blisters were observed for the stainless steel targets. No blistering was observed for Ni.

Table I. Normal incidence H⁺ sputtering yields for Au, Ni and stainless steel.

Target	Energy (eV)	Sputtering Yield (atoms/ion) _b		
		Present	Weight-Loss	Theory
Au	400	0.9×10^{-3}	0.8×10^{-3}	(1.4×10^{-3})
	750	4.1×10^{-3}	3.5×10^{-3}	(5.2×10^{-3})
	1000	7.0×10^{-3}	5.8×10^{-3}	(7.2×10^{-3})
	1500	1.1×10^{-2}	0.9×10^{-2}	(0.9×10^{-2})
	2000	1.3×10^{-2}	1.1×10^{-2}	(1.1×10^{-2})
Ni	200	3.0×10^{-3}	4.0×10^{-3}	4.0×10^{-3}
	400	7.7×10^{-3}	9.2×10^{-3}	1.0×10^{-2}
	750	1.2×10^{-2}	1.3×10^{-2}	1.4×10^{-2}
	1000	1.1×10^{-2}	1.4×10^{-2}	1.6×10^{-2}
	1500	1.0×10^{-2}	1.4×10^{-2}	1.6×10^{-2}
304 SS	400	0.7×10^{-2}	0.6×10^{-2}	0.8×10^{-2}
	750	0.7×10^{-2}	0.8×10^{-2}	1.0×10^{-2}
	1000	0.9×10^{-2}	1.0×10^{-2}	1.2×10^{-2}

^aAu results [2], Ni and SS [3].

^bNi theory [7], Fe theory [6] used for SS, Au theory extrapolated from D sputtering calculation [7] using empirical formalism [2].

Some typical experimental curves for total sputtered Au as a function of H⁺ dose are shown in Fig. 3. The results demonstrate a linear dependence for material erosion vs dose down to fluences as low as $2 \times 10^{18}/\text{cm}^2$. The slight curvature in the extrapolated curves below $2 \times 10^{18}/\text{cm}^2$ suggests that initial sputtering rates may be higher than "steady-state" rates

Fig. 3. Total sputtered material vs ion dose for 500 and 1000 V H^+ on Au.

for Au. The presence of an oxide layer on the Ni and stainless steel targets precluded bulk sputtering measurements below $\sim 10^{19} \text{ H}^+/\text{cm}^2$ although reduced yields have been previously reported for oxide layers under similar conditions [9].

4. DISCUSSION

The sputtering yields for the present experiment can be compared with previous higher dose measurements [2,3] obtained using the weight-loss method and with recent theoretical calculations [6,7] in Table I. The present results are generally consistent with the higher dose weight-loss data as well as with the predictions of the binary collision calculations. Additional comparisons can be made with other measurements cited in [2,3] and agreements better than a factor of two are generally found for these materials. Overall, the results indicate similar sputtering behavior for thin films and bulk material and suggest that high-dose H^+ sputtering data may extrapolate reasonably to the lower doses characteristic of fusion reactor discharges. The good correlation between the experimental and theoretical results indicates an improved understanding of the physical sputtering process for low-energy light ions [6].

The authors wish to thank B. R. Appleton, J. Bohdanský, M. T. Robinson, O. E. Schow, H. Vernickel and C. W. White for helpful discussions and B. F. Early for preparing the target films.

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