A.5. Ion-Surface Interactions

A.5.1. Energy and Charge Dependence of the Sputtering Induced by Highly Charged Xe Ions—*T. Sekioka,* M. Terasawa,* T. Mitamura,* M.P. Stöckli, U. Lehnert, and D. Fry*

The interaction between low energy highly charged ion (HCI) and solid has been an active research area in recent years. We have been studying the above subject by measuring the secondary ions from conductive materials bombarded by heavy HCI at the projectile velocity smaller than 1 a.u. One of the many characteristic features of HCI-solid interaction is the very fast relaxation of the ion in the solid [1-4]. Therefore it can be said that charge neutralization of HCI impinging on the metal target proceeds very rapidly and that the electronic potential energy of HCI is released very near the surface. We measured the yield of the sputtered ions from metals and a semiconductor (Al, Ni, Cu, Ag, Si) bombarded by Xe^{q+} (q = 15 - 44) at 1.0 MeV, and found a remarkable increase of the secondary ion yield as the charge of the projectile ions increased. This is attributed to the electronic excitation in the solid near the surface by the potential of the incident HCI [5].

Momentum transfer to target atoms can be accomplished through elastic collisions or electronic processes. At low energies, nuclear stopping is the major mechanism of the energy loss of the singly charged ion penetrating in the solid. Sigmund's theory [6,7] predicts the sputtering yield S, i.e., the number of sputtered target atoms per incoming particle. Bay *et al*. [8] found a pronounced nonlinear behavior of the sputtering yield in the energy dependence of gold selfsputtering. Collision spikes were presumed to be the reason for this enhancement. A spike is a limited volume in the target where the major part of the atoms is in motion, and it may be created at the end of the slowing-down process in a dense collision cascade, where linear transport theory does not apply.

Schenkel *et al*. [9] measured the emission of secondary ions and neutrals from uranium oxide for impact of highly charged heavy ions. Total ablation rates and secondary ion yields increased rapidly in their measurement. They have shown the presence of the interaction regime where electronic excitation by charge neutralization and elastic collision spike combine synergistically.

We have measured the yield of the sputtered ions from the surface of solid targets of conductive materials (Al, Ni, Cu) and a semiconductor (Si) bombarded by Xe^{q+} (q = 15 - 44) at 300 keV, which is the vicinity of the maximum of Sigmund's sputtering theory. The secondary ion yields showed a significant increase with increasing projectile charge state q, demonstrating the electronic sputtering in the interaction of slow highly charged ions with conductive materials at this energy.

We also report on our measurement of the bombarding energy dependence of the secondary sputtering ion yield from the surface of conductive materials (Al, C) bombarded by Xe^{q+} (q = 30, 36, 44) between 76 keV (v = 0.15 a.u.) and 6.0 MeV (v = 1.3 a.u.). The results suggest the presence of synergistic effects of electronic excitation by the potential energy of highly charged heavy ions and elastic collision spike at higher charge (q = 36, 44) state.

Pulsed beams of Xe^{q+} (q = 15 - 44) with initial energies between 76 keV (v = 0.15 a.u.) and 6.0 MeV (v = 1.3 a.u.) were emitted by the Kansas State University cryogenic electron beam ion source (CRYEBIS) [10] in micro-bunching mode [11], and analyzed with a double-focusing 90° dipole magnet. We used target materials (Al, Ni, Cu, Si) for the measurement of the charge dependence and (C, Al) for the measurement of the energy dependence. The incident highly charged Xe ion beam was cast upon the target at 45°. The mass spectra of the secondary ions were measured using a time-of-flight (TOF) spectrometer 45 cm in length. A positive voltage of 300 V was applied to the target to extract the secondary ions into the TOF. The FWHM of the time structure of the pulsed beam was typically 0.1 μs. The pressure of the target region was lower than $5\mu 10^{-9}$ torr. The surface of the target was cleaned by using a 3 kV Ar^{+} ion beam shortly before the secondary ion measurement. The cleaning procedure was crucial.

As it is difficult to obtain start signals by secondary electrons from solid targets, our experiment requires electronic signals indicating the arrival of the incoming ions to measure the flight time of secondary particles. Therefore, a pulsed HCI beam is indispensable for our experiment. The CRYEBIS produced a pulsed, highly charged xenon ion beam in the micro-bunching expulsion mode, in which the ion bunch is divided into several or many micro-bunches. This can be accomplished with fast expulsions of only a fraction of the ions of a single batch. A repetition of rapid partial lowering of the dam voltage combining with slow increasing of main trap voltage allows for the ions of a single batch in many small micro-bunches with variable intervals, to maintain the low energy spread and the increased duty cycle of slow expulsions.

Secondary ion yields were obtained from the secondary ion mass spectra after subtracting the background and de-convolution, if necessary. The secondary ion yield was normalized by the integrated beam current, and divided by the estimated detection efficiency of the TOF that we obtained by the ion trajectory calculation. In the estimation, we assumed a 100% efficiency of the ion detection of the MCP in the TOF.

We have done new measurements of the charge dependence of the secondary ion yields from conductive materials (Al, Ni, Cu) and a semiconductor (Si) bombarded by highly charged Xe ions at 300 keV, and the results are shown in Fig. 1. Secondary ion yields increase significantly, especially above q = 30. This suggests the importance of the electronic excitation caused by the potential energy of highly charged ions.

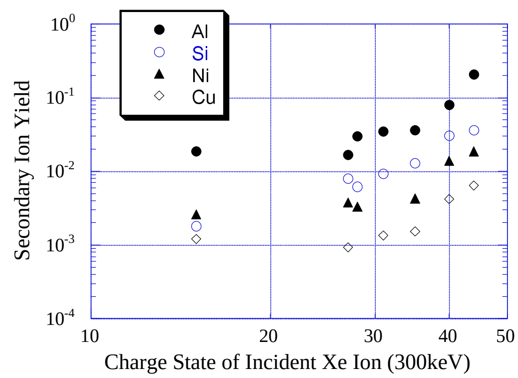

Figure 1. The charge dependence of the secondary ion yields from conductive materials (Al, Ni, Cu) and a semiconductor (Si) bombarded by highly charged Xe ions at 300 keV.

Figure 2 shows the bombarding energy dependence of the secondary ion yield from the surface of C bombarded by Xe^{q+} (q = 30, 36, 44). Figure 3 shows the same as Fig. 2 from the surface of Al bombarded by Xe^{q+} (q = 30, 36). The solid lines in Figs. 2 and 3 represent the prediction of Sigmund's sputtering theory [6], which gives the number of sputtered target atoms per incoming projectile at normal incidence. We calculated these curves by using the formula given by Yamamura and Tawara [13] and multiplying normalization factors. For both C and Al bombarded by Xe^{30+} projectiles, ion yields vary weakly with bombarding energy, and the dependence of the secondary ion yields on the projectile velocity can be reproduced rather well with the theoretical curves.

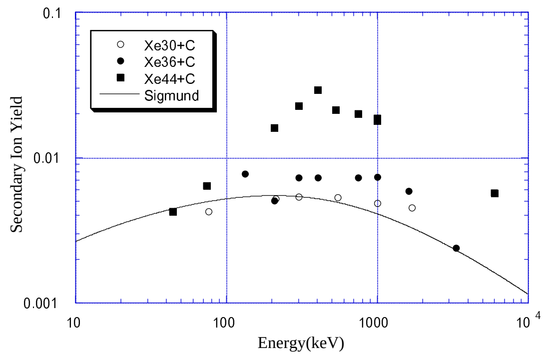

Figure 2. Bombarding energy dependence of the secondary ion yield from the surface of C bombarded by Xe^{q+} (q = 30, 36, 44). The solid line represents the theoretical calculation.

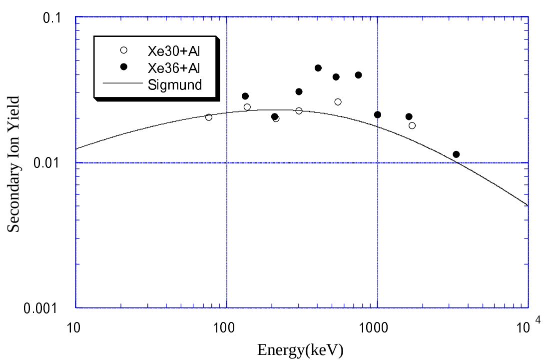

Figure 3. The same as Fig. 2 from the surface of Al bombarded by Xe^{q+} (q = 30, 36). The solid line represents the theoretical calculation.

For a C target, the yield dependence for Xe^{36+} displays some enhancement and the data for Xe^{44+} show a pronounced enhancement. For an Al target, the yield dependence for Xe^{36+} displays a pronounced enhancement. These enhancements are seen especially remarkable at around the energy where total sputtering yield predicted by the theory is maximum.

We have already measured the charge dependence of the secondary ion yields from conductive materials (Al, Ni, Cu, Ag) and a semiconductor (Si) bombarded by highly charged Xe^{q+} (q = 15 - 44) ions at 1.0 MeV using the same experimental setup, where the secondary ion yields showed a significant increase with increasing projectile charge state q, demonstrating the electronic sputtering in the interaction of slow, highly charged ions with conductive materials [5].

At higher charge state of the projectile, the additional electronic excitation energy and elastic collision spike are combined synergistically. Our experimental results demonstrate that the synergy of electronic excitation and elastic collision spikes depends crucially on the potential energy of the projectile in the sputtering of conductive materials by highly charged heavy ions at this energy.

We have measured the yield of the sputtered ions from metals and a semiconductor (Al, Ni, Cu, Si) bombarded by Xe^{q+} (q = 15 - 44) at 300 keV, which is near the maximum of the sputtering yield predicted by the theory. The secondary ion yields show a significant increase with increasing projectile charge state q demonstrating the importance of the electronic excitation effect at this energy.

We have measured the yield of the sputtered ions from the surface of solid targets of conductive materials (C, Al) bombarded by Xe^{q+} (q = 30, 36, 44) between 76 keV (v = 0.15 a.u.) and 6.0 MeV (v = 1.3 a.u.). The energy dependence of the secondary ion is fundamentally reproduced by Sigmund's theory, but at higher charge states of the projectile, enhancements are found near the maximum of the nuclear stopping power. These enhancements are attributed to the synergy of the electronic excitation and elastic collision spike.

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