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Charge State Dependence of Proton Sputtering from Solid Surfaces with Slow Highly Charged Ions

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Abstract

Proton sputtering from an uncleaned surface of a CuO mesh has been experimentally studied for very slow highly charged ions of 500 eV Ne^{q+} ($q = 4$–8), Ar^{q+} ($q = 4$–13), Kr^{q+} ($q = 5$–17) and Xe^{q+} ($q = 7$–24). It is found that (i) for $q <= 10$, the sputtering yield of protons showed a power-law dependence ($\sim q^{\gamma}$) with an exponent of $\gamma = 5 \pm 1$ for all ions measured, and (ii) for $q < 10$, the yield saturated and deviated from the power law. Such a characteristic feature has been reproduced well by a model based on the classical over-barrier model.

1. Introduction

When a charged particle impacts upon a surface, secondary ions and neutral atoms are emitted from the surface as a result of energy deposition from the charged particle. For several tens of keV/u or higher, the dominant energy deposition mechanism is the “electronic” (electronic excitation and ionization) process [1]. As the projectile energy decreases, the electronic process gets less important as compared with a “kinetic” (binary nuclear collision sequence) process [1]. At even lower energies, the kinetic process becomes also less effective. Particularly, in the case of slow highly charged ions (HCI), a “potential” process (electron transfer and relaxation), which is induced by their strong electric field and their high potential energy, becomes the dominant process of the energy deposition to targets. The HCI induces multiple electron transfer from the target to the ion when it approaches the surface [2]. We have measured the sputtering yield of protons from hydrogen-containing C_{60} targets which is deposited on a Cu-mesh using very slow Ar^{q+} (500 eV, $q = 4$ –16) ions [3]. The proton yield showed a power-law dependence like $q^{4.6}$.

Such strong q dependence of the proton sputtering yield has been found to be reproduced by a simulation based on the classical over-barrier (COB) model [4]. In the case of HCIs having higher kinetic energies (e.g. 18 keV Ar^{q+}($q = 1$–11)) the proton yields were reported to be proportional to q^3 [5].

In the present experimental work, we extend such proton sputtering studies to 500 eV Ne^{q+}($q = 4$–8), Ar^{q+} ($q = 4$–13), Kr^{q+} ($q = 5$–17) and Xe^{q+} ($q = 7$–24) ions colliding with an uncleaned CuO mesh target.

2. Experiment

A detailed description of the experimental setup has been given elsewhere [3]. Low energy HCIs produced at a mini-EBIS [6] were transported to a target chamber via two Einzel lenses, a Wien-filter and a beam chopper. The beam intensity was controlled so that the average number of ions in each chopped ion train was much smaller than unity to count the total number of HCIs correctly. A micro-channel plate (MCP) is located in front of the target of a CuO mesh having a 60% optical transmission, and a channeltron is located behind the target. The MCP has a center hole (6 mmϕ), and its active diameter is 75 mm. We made no cleaning treatment to the mesh. The mesh is considered to be covered by a few monolayers of hydrocarbon. The chopped HCIs pass an aperture and the center hole of the MCP and hit the target surface. The experiments were performed using 500 eV Ne^{q+}($q = 4$–8), Ar^{q+} ($q = 4$–13), Kr^{q+} ($q = 5$–17) and Xe^{q+} ($q = 7$–24). When the chopped HCI hits the front side of the target mesh, secondary electron(s) and secondary ion(s) are ejected. The secondary electrons pass through the mesh openings and are detected by the channeltron behind the target mesh. The secondary ions are detected by the MCP. The time of flight (TOF) of the secondary ions was measured using the secondary electron as a start signal and the secondary ion as a stop signal. The mass to charge ratio of secondary ions were determined using the TOF. The pressure of the target chamber was 1×10^{-7} Torr during the measurement.

3. Results and discussion

Figure 1 shows the proton sputtering yields from the uncleaned CuO surface for 500 eV Ne^{q+}($q = 4$–8), Ar^{q+} ($q = 4$–13), Kr^{q+} ($q = 5$–17) and Xe^{q+} ($q = 7$–24). The yields from the C_{60} for Ar^{q+} (500 eV, $q = 4$–16) [3] are also plotted. The proton yields are reproduced well by a power law, q^{γ}. The exponents γ for q are 4.0, 4.6, 4.8, 5.5 and 6.2 for Ne^{q+}($q = 4$–8), Ar^{q+} (C_{60}, $q = 4$–16), Ar^{q+}($q = 4$–13), Kr^{q+}($q = 5$–11) and Xe^{q+}($q = 7$–12), respectively. It is seen that the exponents γ for Ar^{q+} are roughly the same between the CuO and the C_{60} targets. Figure 1 shows further that the proton yields for Kr^{q+} and Xe^{q+} for $q > 10$ indicate saturation from the power law dependence. A simulation using the COB model [4] predicted such strong q dependence. In this model, the proton is emitted by the coulomb repulsion between a H^+ and a C^+ as the result of two-electron removal from the covalent C-H bond by the HCI. The proton is emitted from the surface before the HCIs impact upon the surface (above surface interaction). This model also predicts the satu-

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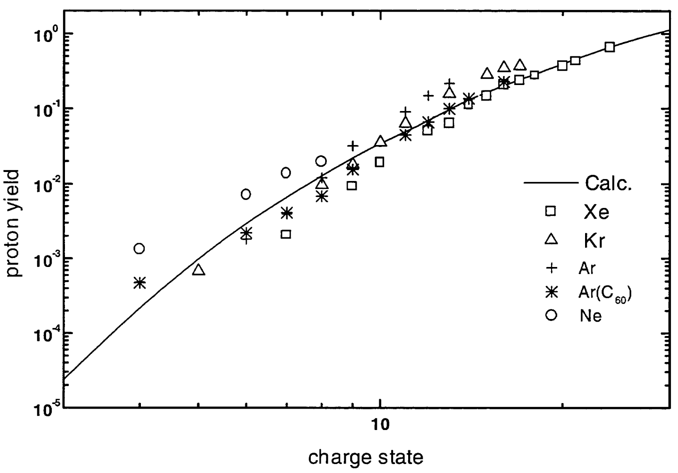

Fig. 1. Charge state dependence of proton sputtering yield for 500 eV Ne^{q+}($q=4$–8), Ar^{q+} ($q=4$–13), Kr^{q+} ($q=5$–17), Xe^{q+} ($q=7$–24) impact on CuO and Ar^{q+} ($q=4$–16) impacts on C_{60}. The solid line shows the calculation by the classical over-barrier (COB) model taking into account two-electron removal from a hydrogen-containing chemical bond [4].

ration of the q dependence for higher charge states ($q > 10$). This saturation is explained as due to the delayed approach to the ionization equilibrium and to the above-surface interaction time, which is intrinsically limited by the image acceleration of the HCI [7,8]. The result of the simulation is given by the solid curve in fig. 1, which shows a good agreement with the experimental results. It is seen from fig. 1 that the sputtering yield for Ne^{q+} is consistently higher than that for Ar^{q+} for $q < 8$. This observation may be related with the facts that (i) the potential energy of Ne^{q+} is consistently higher than that of $Ar^{q'+}$ at $q=q'$, which may enhance a below surface sputtering, and (ii) the velocity of Ne^{q+} is higher than that of Ar^{q+}, which may increase the kinetic sputtering yield.

4. Conclusions

In conclusion, proton sputtering from an uncleaned CuO surface has been experimentally studied using very slow HCIs of 500 eV Ne^{q+}($q=4$–8), Ar^{q+} ($q=4$–13), Kr^{q+} ($q=5$–17) and Xe^{q+} ($q=7$–24). The yield of proton sputtering showed a power-law dependence ($\sim q^{\gamma}$) for all ions measured with an exponent of $\gamma = 5\pm1$ for $q <= 10$, the yield curve indicates saturation for $q > 10$. Such a characteristic feature is consistent with the COB model taking into account two-electron removal from a hydrogen-containing chemical bond.

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References

1. "Sputtering by particle bombardment III", (Edited by R. Behrisch and K. Wittmaak), (Springer, Berlin, 1991).
   "Sputtering by particle bombardment I and II", (Edited by R. Behrisch), (Springer, Berlin, 1981, 1983).
2. Burgdörfer, J., Lerner, P., Meyer, F., Phys. Rev. A**44**, 5674 (1991).
3. Kakutani, N. *et al.*, Nucl. Instrum. Methods B **96**, 541 (1995).
4. Burgdörfer, J. and Yamazaki, Y., Phys. Rev. A **54**, 4140 (1996).
5. Della-Negra, S., Depauw, J., Joret, H., Le Beyec,Y. and Schweikert, E. A., Phys. Rev. Lett. **60**, 948 (1988).
   Bitensky, I., Parilis E., Della-Negra, S. and Le Beyec, Y., Nucl. Instr. Methods B **72**, 380 (1992).
6. Okuno, K., Jpn. J. Appl. Phys. **28**, 1124 (1989).
7. Winter, H., Europhys. Lett. **18**, 207 (1992).
8. Burgdörfer, J. and Meyer, F., Phys. Rev. A**47**, R20 (1993).

