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Velocities of Sputtered Atoms*

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The average velocity of atoms sputtered from metal surfaces by normally incident Hg$^+$—ions in a low pressure discharge was found to be unexpectedly high, corresponding to kinetic energies of the order of 10 to 30 ev.

By sputtering atoms from a (110) surface of a fcc crystal, rather dense atomic beams ejected normal to the target surface can be obtained. The fact that the kinetic energies of the atoms are more than 100 times higher than thermal evaporation energies makes such a beam interesting.

PROCEDURE AND SETUP

Paul and Wessel[1] have published an interesting and simple method for measuring the velocity of vacuum evaporated atoms. Their method can be readily adapted to determining the average velocity of atoms sputtered from a metal surface in a low pressure gas discharge.

Figure 1 is a schematic of the experimental arrangement. A low pressure Hg plasma is maintained between an anode and a Hg pool cathode in a demountable tube similar to the one described in detail in connection with our sputtering studies.[2,3] The function of grid 1 is to increase the plasma density in the anode or target space.[4] The target is bombarded with Hg$^+$—ions under normal incidence when a negative potential is applied with respect to the surrounding plasma. Sputtered atoms, being neutral, have no difficulty in passing through grid 2, which is made slightly negative with respect to the plasma and serves the purpose of preventing electrons from entering into the upper space thus keeping the region above grid 2 free of plasma. A quartz helix balance with a little quartz pan are suspended in the upper part of the tube. Sputtered atoms deposited at the underside of the pan exert a force $\dot{M}\bar{v}_z$ (mass per second arriving × average velocity component normal to the pan surface). This force displaces the pan upward by a certain distance when the target is connected with the negative bombarding voltage. The continuous deposition of sputtered material, on the other hand, increases the weight of the pan with time and one can determine the time interval, t, required for the pan to return to its original position. At this moment the momentum force has been compensated by the weight increase. From $\dot{M}\bar{v}_z=\dot{M}tg$ ($g=981$ cm/sec^2) it follows that $\bar{v}_z$ can be determined by a simple time measurement without knowledge of $\dot{M}$ or the constants of the balance.

The reliability of this method depends on the following conditions:

(a) All or at least a large percentage of the sputtered atoms reaching the pan should adhere to its surface. If this would not be the case the velocities would be measured too high. From study of the distribution of sputtered deposits, in particular the shadow formation behind tube structures, we have found that sputtered atoms must have come essentially from the target and no other parts of the tubes. Thus we think that this condition has been met to a large degree in our tube.

(b) No Hg atoms deposited from the Hg gas should become imbedded in the sputtered deposit, otherwise the velocities measured would be too low. This condition is met by keeping the pan at an elevated temperature during deposition by means of a heating coil which surrounds the pan inside the tube (Fig. 1). In an Au layer deposited under similar conditions, spectroscopic analysis showed that Hg was present in an amount not exceeding 0.3%.

(c) The mean free path of sputtered atoms should be large compared to the tube dimensions, otherwise velocities measured would be velocities after collisions and not ejection velocities. This is accomplished by operating the tube at low gas pressure (5°C bath temperature

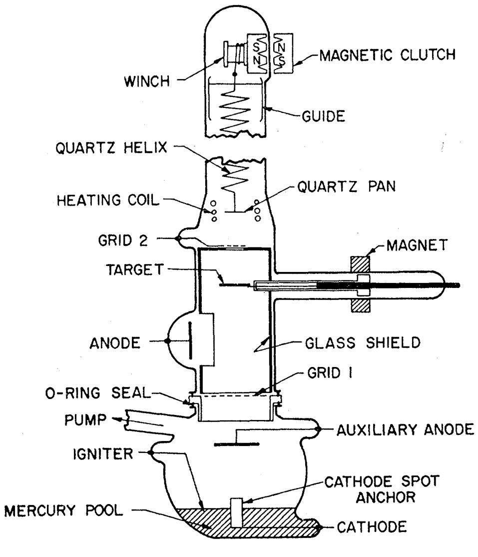

Fig. 1. Tube used for velocity measurements.

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[3] G. Wehner, Phys. Rev. **112**, 1120 (1958).

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corresponding to an Hg gas pressure of 0.2 micron) where the gas-kinetic mean free path is of the order of 20 cm.

(d) The sputtered beam should consist essentially of target atoms or, in other words, the number of reflected neutralized Hg$^+$—ions or Hg atoms sputtered from the target should be small. Such Hg atoms would exert a force but, because of their re-evaporation from the pan, do not contribute to its weight increase. The question of reflected neutralized Hg$^+$—ions has recently been investigated in connection with a study of the forces arising on ion-bombarded electrodes.[5] It was found that the accommodation coefficients for Hg$^+$—ions on clean Au, Cu, Ag, Ni, and Pt surfaces in the range of the bombarding energies studied here is very close to unity, and the number of reflected neutralized Hg$^+$—ions is very small indeed. The question of sputtered Hg atoms becomes important only at low target temperature ($<300°$C) when the "dwelling time"[6] of Hg atoms becomes long enough to cause Hg coverage. Sputtering yields were found to be independent of the target temperature at temperatures above 300°C. This demonstrates that Hg sputtering cannot play a major role in the temperature range (400°–500°C), which the target reached in our experiments.

(e) The number of atoms sputtered from grid 2 onto the pan should be negligibly small. This is accomplished by selecting a grid material such as Mo which has a high sputtering threshold energy. The absence of a zero shift of the pan, with the discharge in operation but the target not being sputtered, proves that this condition has been met.

(f) The pan is under continuous bombardment by Hg$^+$—ions injected into the upper space through grid 2. Forces arising from this bombardment and from the electrical field between the now positively charged pan and grid 2 are independent, however, of the sputtering conditions. A constant superimposed force does not interfere with the velocity measurements.

(g) The number of multiply-charged Hg$^+$—ions in the plasma should be kept negligibly small by operating the tube at a sufficiently low voltage drop.[7] On a large flat target one then has fairly well-controlled conditions in that only Hg$^+$—ions bombarded the surface under normal incidence with an ion energy which is approximately equal to the potential difference applied between target and anode. Probe measurements showed that anode potential and plasma potential in the target vicinity differ by not more than 5 volts.

The tube was operated under the following conditions: main discharge current 2.5 amp; voltage between main anode and cathode 25 volts; ion current density at target $\sim$3 ma/cm^2; Hg gas pressure 0.2 micron; grid 1: graphite, 36 holes per cm^2, diameter of holes 0.12 cm; grid 2: Mo-mesh, 400 holes per cm^2, $\sim$60 volts negative with respect to anode; distance from target to pan $\sim$5 cm. The quartz helix balance had a sensitivity of approximately 10 μg/mm. The zero position of the pan (0.5-cm diameter) could be adjusted from the outside with a winch and magnets. The target disc could be rotated or withdrawn from the plasma by means of an outside magnet. The displacement of the balance pan caused by impinging sputtered atoms was of the order of several millimeters and was observed with a cathetometer.

RESULTS

The displacement due to sputtered atoms disappears, of course, when the target is withdrawn or is rotated into a position such that the pan sees the target sideways and receives only very few sputtered atoms. The displacement of the pan increases when the pan is brought closer to the target, but t or $\bar{v}_z$, it was found, remain independent of the zero position of the pan. The displacement is proportional to the ion current density at the target, but the ion current has no influence on $\bar{v}_z$.

Figure 2 shows the average velocity of Ni and of W atoms sputtered by 600 to 900 ev Hg$^+$—ions. The average velocity of 6.5×10^5 cm/sec for Ni corresponds to an energy of 12.7 ev. In the case of W we measured the average velocity of atoms ejected normal to the target surface and also (with an inclined target) the velocities of atoms ejected under 30 degrees to the surface normal. The latter, requiring less directional change of momentum, were found to have higher velocities (5.5×10^5 cm/sec corresponding to 28 ev) than atoms ejected normal to the target surface (3.5×10^5 cm/sec corresponding to 12 ev).

For those materials which have high sputtering yields as well as high atomic weights, the deflection of the pan becomes high enough to permit carrying the measurements to lower bombarding energies. Figure 3 shows the results for a polycrystalline Pt surface and for a single crystal Au surface in the 200 to 900 ev energy range. The Pt atoms ejected normal to the target surface have average velocities of 4×10^5 cm/sec which correspond to 16-ev energy. The average velocities do not seem to change significantly with ion energy. Atoms ejected in the [110] direction normal to the target

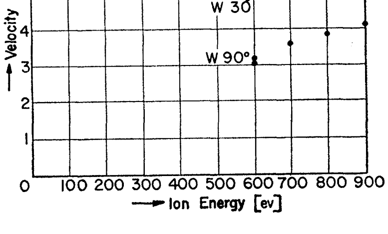

FIG. 2. Average velocities of Ni and W atoms sputtered by normally incident Hg$^+$—ions. Atoms ejected more obliquely to the target surface (W30°) have higher velocities than those ejected normal to the target surface (W90°).

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[7] A. v. Engel and M. Steenbeck, *Elektrische Gasestladungen* (Verlag Julius Springer, Berlin, 1932), Vol. 1, p. 37.

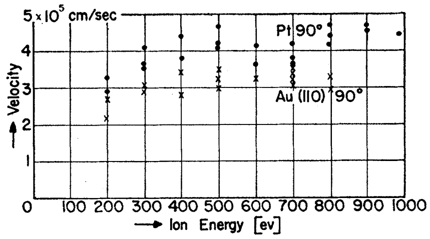

FIG. 3. Average velocities of Pt and Au atoms sputtered by normally incident Hg$^+$—ions. Au atoms were sputtered from a (110) single crystal surface.

surface from a (110) single crystal Au surface have average velocities of 3×10^5 cm/sec corresponding to 9-ev energy. The (110) surface of an fcc crystal is of interest because here at higher bombarding energies the atoms are sputtered preferentially normal to the target surface. Figure 4, for instance, shows the distribution of deposits sputtered from a (110) Ni surface in a (111) plane normal to the target surface with the bombarding energy varied between 100 and 2000 ev. The technique previously described for obtaining such ejection patterns[8] was modified in this case so that sputtered material was collected not on flat plates but rather on glass ribbons laid flush against the inside wall of the cylindrical tube, with the crystal (110) surface facing the ribbon and mounted in the center of the tube. At low ion energy, it can be seen that the sputtered material is ejected mostly in the [110] or closest packed directions which require the least directional change of momentum and which are inclined to the surface normal (see Fig. 4, left strip, 100 ev). With increasing energy (see Fig. 4, strips to right) more and more atoms are ejected normal to the target surface and at 2000 ev (Fig. 4, strip at extreme right) nearly all the sputtered material is to be found at the center spot corresponding to the [110] direction normal to the target surface. This fact makes it possible to create rather dense atomic beams. For instance, Au sputtered by normally incident Hg$^+$—ions of 2000-ev energy (yield ~8 atoms/ion) from a (110) crystal surface at 10 ma/cm^2 (a value which can be attained easily) would yield an Au atom beam with $\sim5\times10^{17}$ atoms/sec cm^2 or ~500 monolayers/sec. The fact that the average kinetic energy of the Au atoms is of the order of 10 ev or more than 100 times higher than thermal evaporation energies makes this beam rather unique.

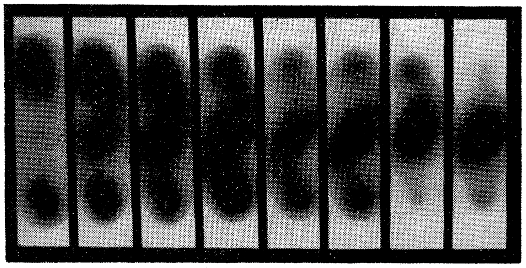

FIG. 4. Deposits obtained at the tube wall when a (110) Ni surface is sputtered by Hg$^+$—ions. Strips from left to right correspond to bombarding energies of 100, 150, 200, 300, 400, 600, 1000, and 2000 ev.

The method described here unfortunately does not allow the determination of the velocity distribution. The accuracy of these measurements is probably not better than ±20% and is limited by sporadic fluctuations of the pan positions caused by changes in plasma density when the cathode spot changes position at its anchor.

The fact that the average kinetic energy of sputtered atoms is so much higher than thermal evaporation energies can be considered to be additional supporting evidence in disproving the thermal evaporation theory of sputtering.

It should be pointed out that we have other independent evidence for these high ejection velocities of sputtered atoms. This work dealing with the measurement of forces arising on ion-bombarded electrodes will be published separately.[5]

It is of interest that Sporn[9] found with a completely different method Mg atoms to be sputtered in an oxygen glow discharge with average kinetic energies of 7 ev.

ACKNOWLEDGMENTS

Largely responsible for the success in these measurements was the skill and patience of Mr. Bernd Richelmann and of our glass experts, Mr. Emil Benz and Mr. Arthur Haut.

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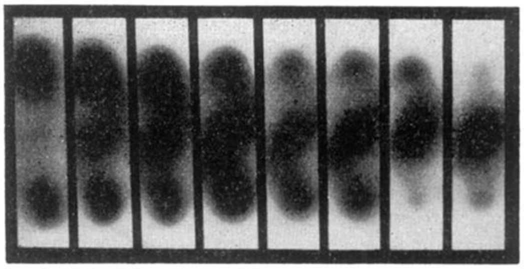

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