CALORIMETRIC MEASUREMENT OF THE AVERAGE ENERGY OF SPUTTERED METAL-ATOMS

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The ejection of neutral atoms from a metal surface under ionic bombardment (sputtering) is an increasingly important subject, both practically and theoretically. Although the sputtering *yield* owing to bombardment by ions with relatively low energy (< 1000 eV) has been measured extensively [1-3], only a few measurements of the *energy* of the sputtered particles exist. For a better understanding of the sputtering mechanism a knowledge of the ejection energies is quite useful. However, usually the number of released atoms is too small to allow an electrical measurement of their energy, and in most experimental devices the dimensions are too small to derive the velocity, and thus the energy, from time of flight measurements. To determine the average velocity of the sputtered particles Wehner developed two momentum-transfer methods [4,5]. We have recently developed a method for determining the average kinetic energy by directly converting this energy into heat.

The bombarding ions were created by a magnetically constricted beam of electrons in a gas of low pressure (10^{-4} torr). A few millimeters to the side of the beam the sputtering electrode was situated, its potential being negative with respect to the space potential in the electron beam. This electrode became surrounded by an ion sheath, like a large negative Langmuir probe. The ions were accelerated in the sheath and brought about a practically monoenergetic normally incident ionic bombardment on the sputtering electrode. The ionic current density amounted to 2 mA/cm^2, while the ion energy was readily variable between 10 and 1000 eV. This part of the apparatus was essentially the same as used in our sputtering yield studies and has been described in more detail elsewhere [3,6].

Part of the sputtered atoms were deposited on a thin metal foil in front of the sputtering electrode on the other side of the electron beam. When these metal atoms stuck to this collector their kinetic energy was converted into heat; besides that, heat of sublimation was liberated during the deposition of a solid metal layer. As a result the collector (aluminium, diameter 1 cm, thickness 5 μ) rose in temperature. The fixing of the collector was achieved by means of thermocouple wires thus enabling us to measure its temperature.

The amount of heat surrendered to the environment by conduction and radiation increases with the temperature of the collector. Gas pressure and thickness of the wires were such that the energy transport from the collector to the environment was largely determined by radiation. With a constant stream of sputtered particles a stationary situation could be reached within 30 seconds.

When this stationary state is reached the average energy per sputtered atom $\bar{E}$ can be derived from the energy balance equation:

$$\bar{E}\, i\, \gamma f = W ,$$

in which i is the total ionic current to the sputtering electrode in amperes, γ the sputtering yield in atoms per ion, f the fraction of sputtered atoms that sticks to the collector, and W the heat loss of the collector in watts. Thus $\bar{E}$ is found in eV per atom. Unfortunately, one is not able to find the energy spread in this way.

The relation between W and the measured thermoelectromotive force was determined by bombarding the collector with electrons or with krypton ions of known energy (50 - 100 eV). These two ways of heating the collector gave the same results, so we may conclude that there was no significant influence of reflection of neutralised gas ions from the collector. The calculated sensitivity of the collector system agrees with the just described experimentally determined temperature rise under ionic or electronic bombardment, provided that the "emissive power" of the collector foil is 8 percent, which is a very reasonable value.

We started the measurements with gold atoms sputtered under krypton ion bombardment. The fraction of sputtered gold atoms that sticks to the collector was determined by weighing the collector and the sputtering electrode before and after a one-hour experiment. The fraction f proved to be 0.03, largely determined by the solid angle at which the collector is seen from the sputtering electrode.

Since we used a spherical sputtering electrode, there was little influence of the angular distribution of sputtered material which could vary with the ion energy.

The sputtering yield γ as a function of the ion energy was determined relatively from the optical transmission of the metal layer deposited on a movable glass strip opposite the sputtering electrode, thus situated in the same position as the collector 6). The absolute yield was then found by determining the total weight loss of the sputtering electrode after about twelve experiments. The yield data obtained closely agree with the lately published data by Laegreid and Wegner 6), determined by weighing after each experiment.

Results of preliminary measurements indicate that the average energy of gold atoms sputtered under krypton ion bombardment increases linearly from 10 eV per atom at 400 eV to 20 eV per atom at 1000 eV krypton ion energy, after corrections for the heat of sublimation.

The temperature rise of the collector caused by the impinging gold atoms was of the order of several tens of degrees centigrade. There was a constant "zero shift" of about 30 degrees resulting from the heating of the collector by the radiation of the excited atoms in the electron beam and a small amount of ionic and electronic bombardment originating from the beam. We checked that another heating influence on the collector, the radiation from the sputtering electrode, does not contribute to the amount of energy received by the collector from sputtered atoms by more than 10 percent. The magnetic field prevents the secondary electrons of the sputtering electrode from reaching the collector.

There is still the possibility of a systematical error caused by neutralised reflected ions from the sputtering electrode and by inelastically reflected gold atoms on the collector. However, the testing of the collector with electron and krypton ion bombardment showed that the sticking coefficient for krypton ions on gold is close to unity, and the sticking coefficient for gold atoms on gold will also be close to unity 6). The inaccuracy of the measurements is estimated to be around 30 percent, which is caused by the large number of quantities which must be measured to find the average energy.

The fairly high average energies of sputtered atoms found in this way are of the same magnitude as Wehner's average velocity data of gold atoms sputtered under mercury ion bombardment 4).

With the present concept that sputtering is a result of successive two-body collisions in the surface layers of a metal lattice, it is not surprising to find average energies of the order of the displacement energy of metal lattice atoms, or somewhat below the maximum energy that can be transported in a focussing collision chain.

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ZUR INTERPRETATION DER ISOMERIEVERSCHIEBUNG IN Fe^{57}

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In der letzten Zeit sind eine Reihe von Arbeiten über den Mössbauer-Effekt in Fe^{57} erschienen. Neben der Quadrupolaufspaltung und dem Zeemann-Effekt wurde auch eine Isomerieverschiebung beobachtet 1-3). Diese Isomerieverschiebung wird beobachtet, wenn sich die Kerne der Quelle und des Absorbers in verschiedenen chemischen Verbindungen befinden. Sie ist zur Isotopieverschiebung analog, die bekanntlich auf dem Einfluss der endlichen Kernausdehnung auf die elektrostatische Bindungsenergie der Elektronen beruht, die sich bei Radiusänderung, z.B. durch Hinzufügen von Neutronen, ändert. Die Isomerieverschiebung beruht auf der Änderung der effektiven Ladungsverteilung im an-