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Abstract

Full Text

Physics

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Anisotropy of the Cathode-Sputtering Coefficient and Focused Collisions in Single Crystals

(Presented by Academician L. A. Artsimovich on 19 VI 1962)

In recent years great progress has been achieved in understanding the mechanism of destruction of metallic surfaces by fast ions. The discovery of the effect of impact focusing in single crystals (1) and Vineyard’ s work on the dynamics of radiation damage of matter (2), carried out with the use of electronic computers, have made qualitatively understandable such experimentally observed regularities of cathode sputtering as the preferential emission of sputtered material in the directions of certain axes of a single-crystal target (3) and the absence of a qualitative difference between the sputtering of metals by fast ions (when the ion energy is many orders of magnitude higher than the binding energy of atoms in the crystal lattice) and by slow ions (4). However, the reason for the anisotropy of the sputtering coefficient of single crystals (5–7) is still unclear. In contrast to the anisotropy of many other properties of crystals (for example, elastic properties, described by second-order curves; optical and dielectric properties, associated with the selection of optical axes; thermal and electrical conductivities, see (8,9)), the anisotropy of the sputtering coefficient of single crystals, even ones as symmetric as face-centered cubic crystals (copper, nickel), is extremely large. Thus, according to the data of (6), when the angle of incidence of argon ions on the (100) face of a copper single crystal is changed by 10°, the sputtering coefficient changes by approximately a factor of three. Moreover, the anisotropy clearly depends on the crystallographic directions with the lowest indices, and not on whether sputtering occurs along or perpendicular to some anisotropy axis.

There are two attempts to explain the anisotropy of the sputtering coefficient. In (5) the anisotropy is explained by a change in the “transparency” of the crystal when it is rotated relative to the direction of the ion beam. Minima of the sputtering coefficient occur for those directions in which the crystal is “transparent,” i.e., the mean free path of the primary ion is greatest, and maxima occur for those directions in which the path length is smallest. Although this explanation qualitatively correctly conveys the angular dependence of the sputtering coefficient, it is apparently insufficient, since it does not lead to the observed ratios of sputtering coefficients for different directions of incidence of the ion beam on the target.

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Fig. 1

Figure 1: Fig. 1

Fig. 2

Figure 2: Fig. 2

In the work (10) of one of the authors of the present article, the sharp decrease in the sputtering coefficient at certain angles of incidence of ions on the target is associated with focused collisions that carry into the depth of the crystal some part of the energy released during the slowing down of the ion in the crystal lattice. It is known (7,11) that a significant part of the sputtered material leaves the target in the direction of its principal axes. This indicates that the sputtering process begins not in the surface layer of the crystal but in its interior, and that the detachment of a surface atom is preceded by focused transfer of momentum along a densely packed direction over distances of up to hundreds of angstroms (direct evidence of this is available in (4), where the results of sputtering of thin crystal—

···lic films). It is obvious that only an insignificant part of the energy of the primary ion goes into sputtering. If, under certain conditions, the greater part of the energy is carried deep into the crystal—as occurs when the direction of the ion beam coincides with the direction of some axis of the target, along which focusing is possible—then the sputtering coefficient decreases. The present work is devoted to an experimental verification of this assumption.

It is known that the existence or absence of focusing along a given crystallographic axis is determined by the ratio, dependent on energy, of the effective atomic diameter to the interatomic distance (quantitative relations are given in (2, 10), and have also been obtained by M. Balarin). In some crystals the distances between atoms along different axes differ greatly, so that focusing is possible along some axes and impossible along others. By studying the anisotropy of the sputtering coefficient of such crystals, one can draw certain conclusions about the influence of focused collisions on the sputtering coefficient.

Fig. 1

Zinc, which has a hexagonal close-packed lattice (see Fig. 1), was chosen as the object of study. For hexagonal crystals the focusing directions in the basal plane will be ⟨100⟩; in other directions, in particular ⟨210⟩, indirect focusing is possible (caused by neighboring rows of atoms), but the transfer of energy in these directions is rapidly retarded (data of M. Balarin). Accordingly, it was to be expected that when the direction of propagation of the ion beam coincides with the ⟨100⟩ axes, substantial dips would be observed, while when it coincides with the ⟨210⟩ axis the dip should either be absent altogether or be smaller.

Fig. 2

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Fig. 3

Figure 3: Fig. 3

Fig. 3

The experiment was carried out under the conditions of (12). The angular dependence of the sputtering coefficient is shown in Fig. 2. As in the case of cubic crystals, with increasing angle of incidence of the ions on the target the sputtering coefficient increases; dips in the curve are observed at angles −12° and +48° (the ⟨100⟩ axes); in addition, a small dip is observed at an angle

18° (axis ⟨210⟩). A certain asymmetry of the curve is due to the fact that the normal to the cut plane of the crystal does not coincide with the ⟨210⟩ direction, but makes an angle of 18° with it.

The anisotropy of the sputtering coefficient was also studied when the crystal was rotated about the ⟨210⟩ axis (see Fig. 3). In this case, dips are observed at angles of 0° (the $\langle 00\bar{1}\rangle$ axis) and 28° (the ⟨101⟩ axis). Along the ⟨001⟩ axis indirect focusing is possible (M. Balarin' s data); in addition, a preferential yield of sputtered material is observed in the ⟨101⟩ directions, which indicates focusing along these axes. From a comparison of the curves in Figs. 2 and 3 it follows that, on average, the coefficient is larger the greater the distance between the corresponding atomic layers, i.e., the smaller the packing density of the axes (for the curves in Figs. 2 and 3 the packing densities in the directions of the principal minima differ by a factor of 1.86 [8]).

The results presented, as well as the close correspondence between the angular dependence of the sputtering coefficient and the angular distribution of the sputtered material [7,11,13], apparently indicate that the anisotropy of the sputtering coefficient is connected with focused collisions in the single crystal. However, some details of this connection are still not entirely clear. They will probably be clarified only after the appropriate calculations have been carried out on electronic computers by Vineyard' s method.

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