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Abstract

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PHYSICS

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EFFECT OF THE CRYSTALLINE STRUCTURE OF THE TARGET ON THE ENERGY SPECTRA OF SCATTERED IONS

(Presented by Academician L. A. Artsimovich, 3 XI 1964)

It is known that the ordered arrangement of atoms in a target has a substantial influence on many processes occurring when solid surfaces are irradiated with ion beams ($^{1-3,\ 11-13}$). It is of interest to study the influence of the crystalline structure of the target on the energy spectra of scattered ions. The measurement procedure was analogous to (^{4}); only the geometry of the analyzing device was somewhat improved. The targets were irradiated with singly charged argon ions of energy 30 keV. The targets were copper crystal plates of various orientations –see Figs. 1, 2, *a* and *b*. Rotation of the targets and of the analyzer was carried out about the $\langle 110 \rangle$ axis, lying in the plane of the target.

Figure 1 presents the energy spectra of ions scattered by the (100) face of the crystal. It is seen that the spectrum consists of a series of peaks corresponding (cf. (^{5,6})) to argon ions scattered without charge change, and also to those that have undergone stripping. As the scattering angle increases, the peaks shift toward lower energies and broaden (cf. (^{4})). At the same time, the intensity of the singly charged argon peaks first increases and then decreases, in a manner similar to what occurs in the scattering of ions neutralized on the target surface (^{9}). A qualitatively analogous dependence is also observed for ions that have undergone stripping upon scattering (cf. (^{6})). The dependence of the intensity of the A^+ peaks on the scattering angle, for different angles of incidence of the ions on the target, is also shown in Fig. 1.

Figure 2 presents the energy spectra of ions when the cut plane of the target made an angle of 18° with the crystallographic plane (100). The general character of the change in the spectra with increasing scattering angle is the same as in the preceding case. However, the argon peaks are somewhat narrower, and at scattering angles the parts of the peaks associated with single scattering (maxima) and multiple scattering through small angles (to the right of the maxima)

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Fig. 1

Figure 1: Fig. 1

are more clearly separated.

The most substantial difference between these spectra and those in Fig. 1 is the presence of copper peaks of different charge states. Copper peaks are absent at small scattering angles and appear at large ones (20; 28°). This fact is qualitatively understandable. Indeed, let the analyzer be set at a small angle φ to the primary beam. Then ions scattered through the angle φ, and fast target atoms whose recoil angle is equal to φ, enter it. It is easy to see that small recoil angles correspond to large deflection angles of those ions whose scattering has led to the appearance of recoil atoms. But the relative number of such ions is small, since ion scattering, owing to the Coulomb character of the interaction, occurs predominantly through small angles. Therefore, at small scattering angles both the ratio of the number of fast target atoms to the number of ions entering the analyzer is small. Calculation ([8]) shows that it is of the order of 10% at a scattering angle of 30° and less than 1% at a scattering angle of 10°.

Let us clarify the reason for the difference between the spectra in Figs. 1 and 2. For this purpose we note that, in the case of a single act of scattering, both the scattered ions and the atoms

recoil atoms are monoenergetic (to within inelastic energy losses), and their energy is uniquely determined by the scattering angle. The width of the peaks observed in experiments on the scattering of ions by a solid is associated with the effect of multiple scattering ([7]): it is known that, when ions are scattered by a solid, there is always a certain fraction of multiple collisions. It is easy to see that the fewer atoms of the target the scattered ion (or recoil atom) encounters on its path from the point where scattering occurred to the analyzer, the smaller the broadening of the peak. In crystals, because of the ordered arrangement of atoms, this number depends on the crystallographic direction. For particles propagating along the principal (low-index) axes of the target, such as ⟨110⟩, ⟨100⟩, ⟨112⟩, etc., partial screening of some target atoms by others takes place, so that in these directions the crystal is more transparent (see, for example, Fig. 5 in ([6])). It is well known that the different transparency of a crystal in different directions (for primary ions) leads, in particular, to a sharp anisotropy of the sputtering coefficients and electron emission of crystals ([2,3,10]). When the scattered ions and recoil atoms propagate along one of the principal axes of the crystal, they undergo fewer collisions with target atoms than when they propagate in crystallographic directions of low transparency. In addition, a small fraction of the fast particles propagates along the so-called open channels in the crystal lattice (see ([11–13])). In this case, particles are retained in the channels as a result of a series of po–

Fig. 1. The cut plane of the target coincides with the (100) face. The glancing

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Fig. 2

Figure 2: Fig. 2

angle ϑ and scattering angle φ are:
I–$\vartheta = 5°,\ \varphi = 10°$;
II–$\vartheta = 5°,\ \varphi = 15°$;
III–$\vartheta = 5°,\ \varphi = 20°$;
IV–$\vartheta = 5°,\ \varphi = 28°$;
V–$\vartheta = 10°,\ \varphi = 15°$;
VI–$\vartheta = 10°,\ \varphi = 20°$;
VII–$\vartheta = 10°,\ \varphi = 28°$;
$VIII$–$\vartheta = 15°,\ \varphi = 20°$;
IX–$\vartheta = 15°,\ \varphi = 28°$.
On the right–the A^+ line at 30 keV for $\varphi = 0°$ in the absence of a target. X–dependence of the intensity of the A^+ peak on the scattering angle at different glancing angles: 1–$\vartheta = 5°$, 2–$\vartheta = 10°$, 3–$\vartheta = 13°$; a–scheme of the arrangement of the ion beam, analyzer, and crystallographic axes of the target.

successive deflections through small angles, i.e., with a very small energy loss at each deflection (13). (Since, however, it follows from experiments on the scattering of medium-energy ions by the surfaces of solids (17) that the principal part of the scattered beam consists of ions scattered in the near-surface layer, there is no reason to expect that the latter effect will be significant.) Thus, the energy spectra of particles propagating in the directions of the principal axes of the crystal should differ somewhat from the spectra of particles propagating in directions in which the crystal is less transparent–in these spectra the peaks should be narrower, and the monoenergetic component should be represented more distinctly (14).

Fig. 2. The section plane of the target makes an angle of 18° with the (100) face.
I –$\vartheta = 5°,\ \varphi = 10°$; **II** –$\vartheta = 5°,\ \varphi = 15°$; **III** –$\vartheta = 5°,\ \varphi = 20°$; **IV** –$\vartheta = 5°,\ \varphi = 28°$; **V** –$\vartheta = 20°,\ \varphi = 28°$; **VI** –$\vartheta = 10°,\ \varphi = 28°$; **VII** –$\vartheta = 15°,\ \varphi = 28°$; **VIII** –dependence of the intensity of the A^+ scattering peak on the sliding angle at different sliding angles: **1** –$\vartheta = 5°$, **2** –$\vartheta = 10°$, **3** –$\vartheta = 15°$.
–diagram of the arrangement of the ion beam, the analyzer, and the crystallographic axes of the target.

Turning to Figs. 1 and 2 (the diagrams of the relative arrangement of the ion beam, the analyzer, and the crystallographic axes of the target), we see that in the first case (irradiation of the (100) face), at all scattering and sliding angles studied, not one of the principal crystallographic axes of the target coincides with the direction of the analyzer axis (cf. also the corresponding curves of the angular dependence of the sputtering and emission coefficients–Fig. 2 from (15)). The only exception is the $\langle 110 \rangle$ axis lying in the plane of the target. But in the direction of this axis (i.e., parallel to the surface of the target) the scattered particles and the primary displaced atoms of the target cannot propagate because of the microrelief (see also (9)).

In the second case (Fig. 2), at a scattering angle of 28° and a sliding angle of 10°, the $\langle 110 \rangle$ axis of the target coincides with the axis of the analyzer. It is seen that in this case the copper peaks appear distinctly in the energy spectrum, and the apex of the A^+ peak is narrower than at the same scattering and sliding angles in Fig. 1. It should be noted, however, that such a spectrum is observed not

only in the case when the $\langle 110 \rangle$ axis exactly coincides with the analyzer axis, but over a certain interval of grazing and scattering angles.

The energy spectra presented above show that the crystalline structure of the target has a substantial influence on the regularities of ion scattering. The qualitative arguments presented in this article can apparently explain some of these regularities. However, for a complete description of the process of ion scattering by crystals, calculations analogous to ([16]) must be carried out.

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