ANGULAR REGULARITIES OF THE ENERGY SPECTRA OF SECONDARY IONS SCATTERED BY A SINGLE CRYSTAL

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Fig. 1

Figure 1: Fig. 1

Abstract

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ANGULAR REGULARITIES OF THE ENERGY SPECTRA OF SECONDARY IONS SCATTERED BY A SINGLE CRYSTAL

It was shown in (1, 2) that, under ion bombardment of single crystals, along with anisotropy of the angular distribution, a structure is observed in the energy distribution of secondary ions, the nature of which is explained by double collisions of the bombarding ion with atoms of the single crystal. Such a structure was also found experimentally in (3, 4). The results of these experimental works agree well with the calculated data of E. S. Parilis and N. Yu. Turaev, who in (5) showed that the energy spectrum of ions reflected from a single crystal possesses a structure caused by double collisions.

However, the energy spectra show the presence of scattered ions with energies greater than those of ions that have undergone double collisions. The presence of such ions with maximum energies E_m, apparently, can be explained by collisions of higher multiplicity.

The present work is devoted to the study of the angular and energy dependence of these maximum energies of secondary ions scattered by the surface of a Mo single crystal as a result of single, double, and higher-order collisions.

Fig. 1. Oscillogram of the energy distribution of secondary ions obtained upon bombardment of the (110) face of a molybdenum target heated to 1800°K by Rb^+ ions with energy $E_0 = 600$ eV ($\Phi = \theta = 50^\circ$).

The study was carried out on the apparatus described in (6), where an electrostatic capacitor of the Yuz-Rozhanskii type served as the energy analyzer of secondary ions. However, in connection with work with a single crystal, and also in order to increase the resolving power of the apparatus, certain modifications and improvements were made (1).

Results of measurements. Figure 1 shows an oscillogram of the energy

Figure 2

Figure 2: Figure 2

Figure 3

Figure 3: Figure 3

distribution of secondary ions obtained upon bombardment of the (110) face of a Mo single crystal heated to 1800°K by Rb^+ ions with energy $E_0 = 600$ eV. Here the angle of incidence of the primary ions is $\Phi = 50°$, while the secondary ions propagating in a direction making an emission angle $\theta = 50°$ with the normal to the surface were subjected to energy analysis. The orientation of the target was such that the incident and scattered beams lay in a plane passing through the [010] axis of the Mo crystal.

It is clear from the oscillogram that here, just as in the case of bombardment of the (100), (110), and (111) faces of a tungsten target by ions ([1,2]), in addition to the peak of singly scattered ions, the spectrum also exhibits peaks with energies greater than those of singly scattered ions. Calculations analogous to ([5]) show that the peaks with the highest energies correspond to ions doubly scattered by atoms in the directions [010] and [021], while the peak close to the peaks of slow and evaporated ions corresponds closely to the energy of ions that underwent single collisions with the atom [000]. Here, too, the atom on the (110) Mo face at which the first collision occurs is conventionally chosen as the origin of the coordinates; the other indices ([010], [021]) denote the atom with which the repeated collision occurred after the first collision with the atom [000].

Fig. 2. Dependences of η_{n_1}, η_{n_2}, and η_m on the energy of the primary ions E_0 in the case of K^+ on (110) Mo ($\Phi = 0°,\ \theta = 50°$).

With increasing energy of the primary ions E_0, additional peaks are observed between the [000] and [010] peaks, analogous to what was observed in ([1,2]) (see Fig. 3). The origin of these peaks is apparently due to ions doubly scattered by atoms located in different directions from the atom with which the first collision occurred ([5]).

It is also evident from the oscillogram that the outermost peak [010] in the spectrum, on the side of higher energies, falls off not steeply, and its width clearly exceeds the natural width because of the presence of ions with energies exceeding the energy obtained in double collisions. It was shown that, with increasing E_0, the peaks corresponding to singly and doubly scattered ions shift toward higher energies, and their position depends linearly on E_0 in the region $E_0 > 500$ eV.

Fig. 3. Series of oscillograms of the distribution of secondary ions by energy, obtained at different Φ ($\theta = 50°$) in the case of K^+ on Mo, $E_0 = 1000$ eV.
1—$\Phi = 0°$; 2—10°; 3—20°; 4—30°; 5—40°; 6—50°; 7—60°; 8—70°; 9—80°.

Fig. 4

Figure 4: Fig. 4

Figure 2 gives the dependences of η_{n_1}, η_{n_2}, and η_m on E_0, where η_{n_1}, η_{n_2}, and η_m are the ratios of the energies of secondary ions that have undergone one, two, and more collisions, respectively, to the energy of the primary ions E_0. For comparison, the dependences of η_{T_1} and η_{T_2} on E_0 are also given there, where η_{T_1}, η_{T_2} are the calculated values of the energy ratios of K$^+$ ions that have undergone single and double collisions with a Mo atom to E_0. It is clear that the dependence of η_{n_1} on E_0 is analogous to the dependence η in the case of a polycrystal (^{7,8}). But the dependence of η_{n_2} and η_m on E_0 differs somewhat from the dependence of η_{n_1}: first, at small values of E_0, as E_0 decreases they grow faster than η_{n_1}; second, the deviations of the values

deviations of η_{n_2} and η_m from the rectilinear law begin at $E_0 \lesssim 500$ eV, and not at $E_0 \lesssim 300$ eV as for η_{n_1}. These differences can be explained by the influence of the binding energy of the target atoms in multiple collisions of the bombarding ion with the target atoms.

Figure 3 shows oscillograms of the energy distribution of secondary ions obtained at different angles of incidence of primary K^+ ions with energies $E_0 = 1000$ eV on the (110) face of a molybdenum target heated to 1800° K. Oscillogram 1 in Fig. 3 was obtained for normal incidence of the angle Φ at 10°. The emission angle θ in all cases is 50°. As is seen from the oscillogram, the peaks corresponding to single and double collisions, with increasing angle of incidence of the primary ions Φ, shift toward the region of higher energies. At the same time, an increase in Φ leads to an increase in the intensities of the peaks corresponding to doubly scattered ions, as compared with the intensity of the peak of a single collision. In some cases ($\Phi = \theta > 80°$) (the oscillogram is not shown here), against the background of the peaks corresponding to doubly scattered ions, the peak of singly scattered ions is absent. Such an effect apparently indicates a sharp increase in the number of ions undergoing repeated collisions when the angle of incidence and emission approaches grazing angles. This confirms the conclusions made by E. S. Parilis et al. in (^{9}) in considering a model of ions reflected from a chain of surface atoms of a single crystal, as the direction of incidence of the beam approaches a grazing angle.

Fig. 4. Dependences of η_{n_1}, η_{n_2}, and η_m on the scattering angle β in the case of K^+ on (110) Mo. $E_0 = 1000$ eV.

Depending on the angle of incidence Φ, appreciable changes also occur in the intensities of the peaks of slow and evaporated ions. With increasing Φ, the intensities of both peaks decrease strongly and, at $\Phi \gtrsim 80°$, disappear, apparently indicating the absence, in this case, of appreciable implantation of primary ions into the bulk of the target, as well as onto its surface. The absence of peaks of slow and evaporated ions apparently also indicates the possibility of cleaning the target surface by ion bombardment.

Figure 4 gives the dependences of η_{n_1}, η_{n_2}, and η_m on the scattering angle β, upon bombardment of the (110) face of a molybdenum target heated to 1800° K by K^+ ions with energy $E_0 = 1000$ eV. In the figure, the dashed curves correspond to the calculated values η_{T_1} and η_{T_2}. It is seen that the curves $\eta_{n_1}(\beta)$ and $\eta_{n_2}(\beta)$ coincide with $\eta_{T_1}(\beta)$ and $\eta_{T_2}(\beta)$, although some deviations toward smaller values of η are observed in the region $\beta < 40°$. The curve $\eta_m(\beta)$ lies higher than $\eta_{n_2}(\beta)$ and approaches $\eta_{T_2}(\beta)$ as β decreases.

Thus, consideration of the angular and energy dependence of the spectra of secondary ions scattered by the surface of a single crystal shows that the secondary emission contains not only ions that have undergone double collisions with target atoms, but also ions that have undergone collisions of higher multiplicity. Ions that have undergone single and double collisions appear in the spectrum in the form of a peak. The character of the energy distribution of the group of ions with maximum energy E_m and the change in their number with increasing angle of incidence and energy of the primary ions do not contradict the assumption that they originate as a result of more-than-double collisions. Indeed, if it is assumed that after each collision the ion is deflected by the same small angle β',

then the formula determining the energy retained by the ion as a result of multiple collisions through an angle β can be written in the form

$$E_m = \frac{E_0(\mu - 1)^{2n}}{[\cos\beta + \sqrt{\mu^2 - \sin\beta}]^{2n}},$$

where n is the number of repeated collisions. It is evident from the formula that, as the number of collisions n increases, the value of E_m tends to E_0. However, with an increase in the number of collisions, the intensity of multiply scattered particles with identical or close scattering angles decreases sharply.

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