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Abstract

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ANISOTROPY OF THE ANGULAR DISTRIBUTION AND STRUCTURE OF THE ENERGY DISTRIBUTION OF IONS SCATTERED BY THE SURFACE OF A SINGLE CRYSTAL

The results of studies ([1–4]) of the angular dependence of the energy spectra of secondary ions scattered by the surface of polycrystalline targets are well explained by a simple model of paired single and multiple elastic collisions of ions with atoms of a solid, taking into account the screened Coulomb repulsive potential; moreover, the appearance of secondary ions with energy and angular characteristics not described by the regularity of a single elastic collision is explained by the mechanism of multiple elastic collisions ([2–4]). The authors of works ([5–7]) also came to this conclusion.

In recent works ([8–10]), anisotropy of ion scattering by the surface of a single crystal was found as a function of its various crystallographic directions. It was predicted that one should expect not only anisotropy of angular scattering, but also structure in the energy distribution of ions scattered by a single crystal ([6]). The structure of the energy spectrum of scattered ions that have undergone single and double collisions with atoms of the surface layers of a definite face of a single crystal of cubic symmetry was calculated in ([11]). It was shown that the probability of double scattering of ions is by no means small, so that, with sufficient resolving power of the analyzer, it can be detected experimentally in the form of peaks in the low- and high-energy regions of the spectrum.

In work ([12]), the energy spectrum of secondary ions Ar^+, scattered by the surface of the [100] face of a Cu single crystal, was investigated. A peak was found in the region of the descending part of the peak of singly scattered Ar^+ ions toward higher energies of the spectrum, which was explained by multiple scattering of Ar^+ ions on Cu atoms. It was shown that the structure of the energy spectrum of scattered Ar^+ ions that have undergone single and double collisions with atoms of the [100] face of Cu, calculated analogously to ([11]), agrees with the experimental curves ([13]). Therefore it is of interest to investigate the angular dependence of the coefficient of secondary ion emission and of the energy

Fig. 1

Figure 1: Fig. 1

distribution of secondary alkali ions scattered by W and Mo single crystals.

The study was carried out on the apparatus described in ([2]); however, to increase the resolving power of the apparatus, minor modifications were made. The widths of the entrance and exit slits of the electrostatic analyzer of the Yuz–Rozhansky type ([14]) were reduced from 0.8 to 0.4 mm. The ion-electron multiplier with an amplification factor of $\sim 10^6$ at the analyzer output was replaced by a multiplier with an amplification factor of $\sim 10^8$. A preliminarily processed face of a W single crystal in the form of a rod served as the target. The target was cleaned by heating under electron bombardment from the reverse side.

Measurement Results

Figure 1 shows an oscillogram of the differential energy distribution of secondary ions obtained during bombardment of a heated–

···heated to 2000° K, the [100] face of W by Rb^+ ions with energy $E_0 = 1200$ eV. The primary ions struck the target at an angle $\Phi = 50°$; secondary ions propagating in a direction making an emission angle $\theta = 50°$ with the surface normal were subjected to energy analysis. The oscillogram of the energy distribution of the secondary ions has a somewhat different form than the oscillograms of the energy distribution of secondary ions obtained in bombardment of a polycrystalline target ([2]). In the spectrum, in addition to the peak of ions singly scattered from individual target atoms, two more peaks are observed in the high-energy region of the spectrum. Oscillograms of analogous character were obtained in bombardment of the [100] face of W by K^+ and Cs ions.

Calculations analogous to those carried out in ([10]) show that the outermost peak of the high-energy part of the spectrum corresponds to ions doubly scattered on the [100] atom, while the peak close to the peak of singly scattered ions corresponds to ions doubly scattered on the [110] atom. The index [000] on the oscillogram corresponds to a single collision, since, for the origin of coordinates, the atom on the [100] face at which the first collision occurs has been chosen conventionally; the remaining indices designate the atom with which the second collision occurred after the first collision with the [000] atom. The energy retained by the ion in single and double collisions at angle β is determined, respectively, by the relations

Fig. 1. Oscillogram of the energy distribution of secondary ions obtained in bombardment of the [100] face of W heated to 1800° K by Rb^+ ions with energy $E_0 = 1200$ eV ($\Phi = 50°,\ \theta = 50°$)

Fig. 2. Oscillograms of the energy distribution of secondary ions obtained in

Fig. 2

Figure 2: Fig. 2

Fig. 3 and Fig. 4 graphs

Figure 3: Fig. 3 and Fig. 4 graphs

bombardment of the [100] face of a W target heated to 1800° by Rb^+ ions with energy $E_0 = 1200$ eV for scattering angles 90° (1), 80° (2), 70° (3), and 60° (4).

$$E_{1(\beta)} = E_0 \frac{(\mu-1)^2}{\left[\cos\beta \pm \sqrt{\mu^2 - \sin^2\beta}\right]^2}; \tag{1}$$

$$E_{2(\beta)} = E_0 \frac{(\mu-1)^4}{\left[\cos\beta_1 \pm \sqrt{\mu^2 - \sin^2\beta_1}\right]^2 \left[\cos\beta_2 \pm \sqrt{\mu^2 - \sin^2\beta_2}\right]^2}, \tag{2}$$

where E_0 is the initial energy of the ions; $\mu = m_1/m_2$; m_1 is the mass of an atom of the single crystal; m_2 is the mass of the ion; β is the ion scattering angle, which was determined in accordance with the experimental condition: $\beta = [\pi - (\Phi + \theta)]$.

In the case of a double collision it was assumed that the first collision leads to scattering in the direction of one of the lattice atoms, determined by the polar scattering angle β_1 and the azimuthal angle φ, and the second—to an angle β_2, determined by the relation

$$\cos\beta_2 = \cos\beta\cos\beta_1 + \sin\beta\sin\beta_1\cos\varphi.$$

Figure 2 presents oscillograms of the energy distribution of secondary ions obtained upon bombardment of the [100] face of W by Rb^+ ions with energy $E_0 = 1200$ eV. The peaks corresponding to double collisions,

Fig. 3. Dependence of the values $\eta_e[000]$ and $\eta_e[100]$ on β upon bombardment of the [100] face of a W target by Rb^+ ions with energy $E_0 = 1200$ eV. The dashed curves are the angular dependences $\eta_t[000]$ and $\eta_t[100]$, calculated from the formulas for elastic single and double collisions of particles.

Fig. 4. Angular dependence of the coefficient of scattered ions upon bombardment of the [100] face of a W target heated to 1500°K by Rb^+ ions with energy $E_0 = 1$ keV (1), 2 keV (2), 3 keV (3).

with decreasing scattering angle, like the peak of singly scattered ions, shift into the region of higher energies. With decreasing β, the peaks of doubly scattered ions predominate and become fairly intense, which indicates an increase in the number of ions colliding with atoms [100] and [110] after the first collision with the atom [000].

Figure 3 plots the dependences $\eta_t(\beta)$, obtained from relations (1) and (2) for the case of single and double collisions, where η_t is the ratio of the energy of secondary ions to the energy of the primary ions. The points are the experimental values η_e[000] and η_e[100], found from oscillograms by measuring the energies corresponding to the positions of the peaks of elastically scattered Rb^+ ions at [000], [100]. η_t[000] and η_e[000], as well as η_t[100] and η_e[100], agree fairly well, which testifies to the validity of the calculation on the basis of the assumption of the possibility that secondary ions which have undergone double scattering on atoms [100], [010], [110], [210], etc., after the first collision with atom [000], can enter the electrostatic analyzer.

Figure 4 gives a series of curves $K_p(\Phi)$, obtained upon bombardment of the surface of the [100] face of a W single crystal heated to 1500°K by Rb^+ ions with energies of 1, 2, and 3 keV. As in the case of a polycrystal ([15,16]), with increasing Φ the scattering coefficient K_p increases.

For the single crystal, K_p is larger at all values of Φ than in the case of the polycrystal, and increases more rapidly as the angle of incidence increases. At $\Phi = 45°$ a minimum is observed, which indicates coincidence of the direction of the primary-ion beam with the crystallographic direction [110], i.e., in this case the beam of primary ions falls normally on the [110]W face. With increasing E_0, the value of K_p decreases, while the depth of the minimum increases somewhat, which apparently indicates the predominant role of ions scattered from the [110]W face, since an increase in the energy of the primary ions leads to an increase in the penetration depth of the primary ions into the solid.

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