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ANGULAR AND ENERGY DISTRIBUTION OF SECONDARY IONS DURING BOMBARDMENT OF A TARGET BY IONS AT GLANCING ANGLES

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Abstract

Full Text

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PHYSICS

Academician of the Academy of Sciences of the Uzbek SSR U. A. ARIFOV, A. A. ALIEV

ANGULAR AND ENERGY DISTRIBUTION OF SECONDARY IONS DURING BOMBARDMENT OF A TARGET BY IONS AT GLANCING ANGLES

In ([1]-[3]) it was established that the distribution over emission angles of secondary ions during bombardment of polycrystalline targets by ions of alkali elements in the energy range 0.5–3 keV obeys the cosine law in the interval of incidence angles Φ of the primary ions from 0° to 50°. It was also found ([3]) that at $\Phi > 50^\circ$ the angular distribution of secondary ions deviates from the cosinusoidal distribution, and a predominance is observed of ion scattering forward relative to the direction of motion of the incident ions. A study of the angular dependence of the energy spectra of secondary ions showed that the intensity-dominant peak of singly scattered ions corresponds to the angle of specular reflection ([4]-[6]).

As was shown by E. S. Parilis et al. ([7]) using a model of scattering from a chain of surface atoms, when the direction of incidence approaches glancing, the emission direction should approach the specular direction, and this effect is stronger the lower the ion energy. For our case (E_0 = 1-3 keV), specular reflection should, according to the estimate ([7]), be observed beginning at incidence angles of the order of 70°. Recently O. B. Firsov ([8]), approximately solving the Boltzmann equation, obtained an expression according to which the maximum of particle scattering at angles of incidence and reflection close to glancing corresponds to the angle of specular reflection. However, in Firsov' s work a formula is given for the scattering intensity integrated over the azimuthal angle φ, which makes it difficult to compare the experimental data with the theory.

Below we present the results of our investigations, the purpose of which was an experimental verification of the theoretical calculations ([7], [8]).

The investigation of the angular distribution of secondary ions was carried out by the dynamic method in the apparatus described in ([1]). It differed from the usual apparatus for studying secondary processes in that, in addition to the collector of secondary particles, it had a movable probe mounted in it, allowing the intensity of secondary ions leaving the target at different θ to be measured.

Fig. 1. Polar diagrams of the angular distribution of secondary ions during bombardment of a W target heated to 1500° K by K^+ ions with energy $E_0 = 2$ keV. a–$\Phi = 80°$, b–$\Phi = 85°$

Figure 1: Fig. 1. Polar diagrams of the angular distribution of secondary ions during bombardment of a W target heated to 1500° K by K^+ ions with energy $E_0 = 2$ keV. a–$\Phi = 80°$, b–$\Phi = 85°$

Provision was also made for changing the orientation of the target with respect to the incident ion beam.

The investigation of the angular dependence of the energy spectra of secondary ions was also carried out by the dynamic method on the setup described in ([4]). The energy distribution curve of secondary ions was recorded on the screen of an oscillograph with the aid of an electrostatic analyzer of the Hughes–Rojansky type. To amplify the current at the analyzer output, an ion-electron multiplier was used. The possibility was provided of changing the incidence angle of the primary ions and the emission angle of the analyzed group of secondary ions with the aid of an external magnet.

Results of measurements. Polar diagrams characterizing the angular distribution of secondary ions during bombardment of a tungsten target heated to 1500° by K^+ ions with energy $E_0 = 2$ keV are given in Fig. 1. Here, along the movable radius of the polar system are plotted the rela-

of the current to the movable probe I_z to the primary ion current I_0 on an arbitrary scale, while the angles between the polar axis of the system and the movable radii correspond to the emission angles θ of the secondary ions. The dashed circumference is the theoretical function $2R\cos\theta$, where R is the radius of this circumference. Curves a and b were obtained, respectively, at $\Phi = 80$ and 85°. For comparison, curve b has been reduced to the intensity values at $\Phi = 80°$.

Fig. 1. Polar diagrams of the angular distribution of secondary ions during bombardment of a W target heated to 1500° K by K^+ ions with energy $E_0 = 2$ keV. a–$\Phi = 80°$, b–$\Phi = 85°$.

It is seen that the maximum of $I(\theta)$ corresponds to the angles of specular reflection. It was shown that a decrease in the energy of the primary ions leads to a shift of the limiting value of the angle Φ, from which specular reflection begins to be observed, toward smaller Φ. Thus, the experiment shows that the conclusions (7), obtained in considering a model of scattering by a chain of surface atoms, are qualitatively confirmed.

Figure 2 gives a polar diagram characterizing the angular distribution of secondary ions for the case of bombardment of a tungsten target heated to 1500° K by K^+ ions with energy $E_0 = 3$ keV at an angle $\Phi = 80°$. In our cases the angular width of the slit (probe) for the angle φ was greater than Φ; therefore,

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Fig. 2. Comparison of the experimental diagram of the angular distribution of secondary ions (a) with the theoretical one according to (8) (b). $T = 1500^{\circ}$K

Figure 2: Fig. 2. Comparison of the experimental diagram of the angular distribution of secondary ions (a) with the theoretical one according to (8) (b). $T = 1500^{\circ}$K

for comparison, the same polar diagram gives the curve of the dependence of the flux density of scattered (reflected) particles on the angle θ, calculated from the formula:

$$I(\theta) = \frac{3\theta^{3/2}\Phi^{1/2}}{2\pi(\theta^3 + \Phi^3)}, \tag{1}$$

obtained by Firsov (8) in solving the Boltzmann kinetic equation. It is seen that they coincide with one another.

Analogous results were obtained in bombardment of a W target by Na^+, Rb^+, and Cs^+ ions, and also in bombardment of a Mo target by Na^+, K^+, and Rb^+ ions.

In the investigated range of primary-ion energies (1-3 keV) it may indeed be assumed that in scattering the main role is played by an interaction law close to Coulomb' s, and the angles $\Phi = \theta \geq 80^{\circ}$, which corresponds to the conditions for solving the Boltzmann kinetic equation in (8).

Thus, the agreement of the two curves—the experimental and the theoretical—apparently indicates the possibility of explaining such a result also on the basis of the concept of multiple collisions of incident ions with target atoms, since diffusion in the directions of the particle-velocity vector is the result of multiple collisions.

Figure 3 gives an oscillogram of the energy distribution of secondary ions, obtained in bombardment by K^+ ions with energy $E_0 = 2$ keV of a tungsten target heated to 2000° K at $\Phi = \theta = 70^{\circ}$. It is seen that here, in contrast to the case $\Phi \neq \theta$ $(4, 6)$, the intensity

of the monoenergetic part of the peak of singly scattered K^+ ions increased somewhat. This increase, apparently, indicates that the case $\Phi = \theta \gtrsim 70^{\circ}$ favors the emission of multiply scattered ions.

In Fig. 4 a series of oscillograms is given for the energy distribution of secondary ions, obtained at different Φ and θ, but satisfying the condition $\Phi = \theta \gtrsim 70^{\circ}$. Here, too, a tungsten target heated to 2000°K was bombarded with K^+ ions of energy $E_0 = 2000$ eV. Oscillogram 1 was obtained at $\Phi = \theta = 70^{\circ}$, and each subsequent one corresponds to an increase of the angle of incidence and emission by 5°.

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Fig. 3

Figure 3: Fig. 3

Fig. 4

Figure 4: Fig. 4

Fig. 2. Comparison of the experimental diagram of the angular distribution of secondary ions (a) with the theoretical one according to (8) (b). $T = 1500°$K

Fig. 3. Oscillogram of the energy distribution of secondary ions upon bombardment of a W target heated to 2000°K by K^+ ions with energy $E_0 = 2$ keV; $\Phi = \theta = 70°$

Fig. 4. Series of oscillograms of the energy distribution of secondary ions, obtained in the case K^+ on W; $T = 2000°$K; $E_0 = 2$ keV. 1—$\Phi = \theta = 70°$; 2—$\Phi = \theta = 75°$; 3—$\Phi = \theta = 80°$; 4—$\Phi = \theta = 85°$

An increase in Φ or θ, as is known [4, 6], leads to growth of the peak of singly scattered ions, and increasing both simultaneously does so all the more; therefore the comparison of the oscillograms with one another and the measurement of the values of the maximum energy of the secondary ions E_m as a function of Φ and θ were carried out at the same intensity of the peak of singly scattered ions.

It is seen that, with simultaneous increase of the angles Φ and θ, the half-width of the maximum of the singly scattered ions grows faster than in the case when

Φ and θ increase separately ([6]), and this increase occurs mainly through an increase in the intensity of the monoenergetic part of the peak of singly scattered ions. At angles of incidence and reflection close to grazing ($\Phi = \theta \gtrsim 85°$), the value of the maximum energy of the secondary ions E_m becomes close to the value of the initial energy of the primary ions. Such closeness of E_m to E_0 apparently indicates that the situation $\Phi = \theta \gtrsim 85°$ favors an increase in the number of collisions of ions with target atoms and their emergence with a small loss of energy. If it is assumed that an ion is deflected through an angle β as a result of several successive collisions, with a deflection each time through small angles β' equal or close to one another, then it is not difficult to show that $E_m \approx E_0$ ([9–10]).

Thus, consideration of the angular and energy distributions of secondary ions when a target is bombarded by ions at a grazing angle shows that the presence of extremely anisotropic scattered ions is also well explained from the standpoint of multiple collisions of the bombarding ions with a system of free atoms.

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