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STUDY OF THE CRITICAL ANGLE OF CHANNELING OF ACTIVE METAL IONS THROUGH THIN ALUMINUM FILMS

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A B S T R A C T

Spatial distributions of ions (K+, Na+) passed through thin single-crystal Al films with thicknesses from 180 to 600 Å and critical channeling angles were studied. Ion energy varied within E0 = 10−30 keV. It was shown that increasing the primary ion beam energy leads to a decrease in the width of the angular distribution maxima, which is associated with a decrease in the critical channeling angle ψcr. It was found that ψcr for axial channeling does not exceed 4−5◦, and for planar channeling — 9−10◦.

K E Y W O R D S

Critical angle, ion passage, angular distribution, channeling, spatial distribution.

Introduction

Interactions of electrons and ions with energies of 10−100 keV and higher with a solid, in particular the phenomena of scattering and their passage through thin layers of crystals, are widely used in studies of solid-state physics. If the scattering medium is a single crystal, then successive collisions of incident ions with crystal atoms become strongly coupled, which leads to the appearance of many effects due to the ordered arrangement of crystal atoms. The results of experimental and theoretical studies have shown that this nature of interaction, in turn, allows one to obtain information about the structure of the crystal, the nature of the motion of atomic particles in it, defect formation and localization of impurity atoms in the crystal lattice [1–10]. It is known that bombardment with ions of active metals with an energy of 1–100 keV is used to modify surface properties and obtain nanoscale structures with specified physical properties at different depths in the near-surface region of materials [11–14], as well as to study the degree of single-crystallinity of crystals [2,4,7].

When thin single-crystal films are bombarded with ions, some of the ions pass through the sample with a small loss of energy due to axial and planar channeling [3,4,7]. Channeling depends primarily on the angle of incidence of the primary beam on the sample surface. In this case, those ions that fall on the surface at an angle smaller than the critical ψ_{cr} pass through the sample. The angle ψcr between the particle trajectory and the channel axis, at which the guiding effect of a row of atoms on an ion does not disappear, is called the critical channeling angle of the particle [2]. According to Linhard's theoretical estimates, an increase in the energy of the primary ion beam should lead to a decrease in the angle at which the channeling effect begins to manifest itself, i.e., the ion is focused between the atomic rows of the crystal. Theoretically, ψ_{cr} is estimated using Linhard's expressions [2]. For experimental evaluation of ψ_{cr}, it is possible to use the method of studying the spatial distribution of ions, passed through free thin single-crystal films, depending on the polar angle of incidence of the beam, as well as on the azimuthal angle of rotation of the sample. In this work, the critical channeling angles of K^+ and Na^+ ions, passed through single-crystal Al(100) films with a thickness dAl from 180 to 600 A, were experimentally determined. The obtained results were compared with theoretical calculations.

The studies were carried out in an ultra-high-vacuum universal setup with a working chamber vacuum of ~(3−8) 10^{-9} Torr. The surface of the studied sample was cleaned by thermal heating from the back side of the target. The cleanliness of the sample surface was estimated by the disappearance of the carbon and oxygen Auger peaks in the Auger electron spectrum. The angular detection aperture of the Yuz-Rozhansky analyzer was ~ 0.5^0. A manipulator with five degrees of freedom was used in the experiments: rotation of the sample in its plane; tilt with respect to the ion beam; movement of the target in the beam in the vertical and horizontal directions. The drive for each movement is equipped with a scale with a vernier, allowing one to count the rotation and tilt of the target relative to the beam with an accuracy of 0.1^0 and its movement with an accuracy of 0.1 mm. The manipulator allows the target holder to rotate around the axis by 360^0 and shift vertically and horizontally by 20 mm, as well as rotate the target in azimuth. Taking into account the backlash in the worm gears, the absolute installation accuracy of the manipulator is 15′. The ion source allows the sample to be bombarded with ions with an energy of 10 to 35 keV at a maximum current density of 10^{-7} A/cm^2. The ion spot diameter can be adjusted using a single lens within 0.4−2 mm, depending on the task being solved.

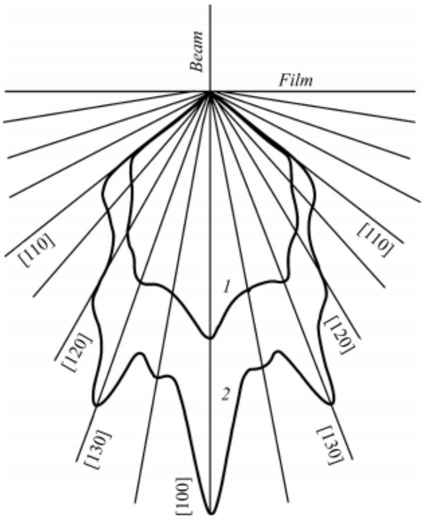

Fig. 1. Polar diagrams of the angular distribution of Na^+ ions passed through a single-crystal Al(100) film (dAl = 450 A) at energies E_0 = 20 (1) and 30 keV (2).

Figure 1 shows the polar diagrams of the angular distribution of Na^+ ions that passed through a single-crystal Al(100) film with dAl = 450 A. When obtaining the polar diagrams of the angular distribution, the direction of the primary ion beam coincided with the direction of [100], the VEU-6 detector was rotated around the 001 axis of the crystal lattice, and the detection plane coincided with the {001} plane. It is evident that the nature of the polar diagrams of the angular distribution is sharply anisotropic. They exhibit clearly defined maxima corresponding to the crystallographic directions [100], [130], [120], [110].

An increase in the primary ion beam energy leads to a decrease in the width of the angular distribution maxima, which is associated with a decrease in the critical channeling angle ψ_{cr}.

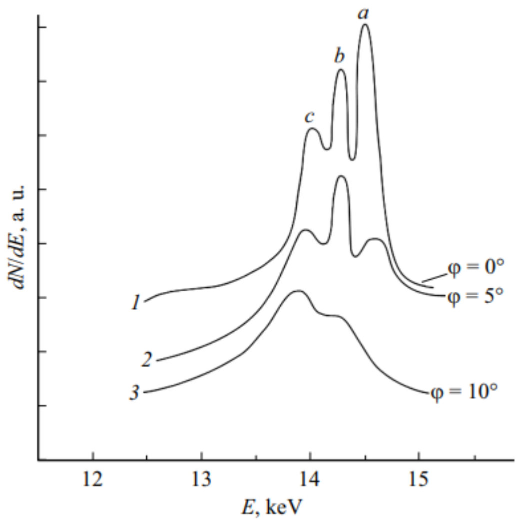

Fig. 2. Energy distribution of Na^+ ions passing through the Al(100) film at ion beam incidence angles $\phi = 0$ (1), 5 (2) and 10^0 (3); dAl = 450A. Primary ion energy 20 keV

Figure 2 shows the energy distribution spectra of Na^+ ions that passed through 450 Å thick Al(100) films. Na^+ ions were directed toward the surface with $E_0 = 20$ keV at different angles (0, 5, and 10◦) relative to the normal. The spectrum obtained with an ion beam incident along the normal to the surface ($\phi = 0^0$) contains all three peaks characteristic of a single-crystal film: the so-called axial (a), planar (b), and diffuse (c) transmission [7]. At $\phi = 5^0$, all three peaks are also detected. However, the intensity of peak a decreases sharply, the half-width of the planar channeling peak increases without a noticeable change in its intensity.

Apparently, the decrease in the number of ions that passed as a result of axial channeling leads to an increase in the number of ions of planar channeling. From the third spectrum ($\phi = 10^0$) it is seen that the maximum of axial channeling practically disappears, planar channeling has a very low intensity, the position of the maximum of random (diffuse) passage shifts toward lower energies, and the half-width of this maximum increases. The latter is due to an increase in the number of ions that have experienced multiple collisions with the target (film) atoms, which leads to an increase in the average energy loss of ions during passage. Based on the analysis of the spectra presented in Fig. 2, it can be assumed that ψ_{cr} for axial channeling is ~ 5^0, and for planar channeling ~ 10^0. The same results were obtained in the case of bombardment of Al (100) with K^+ ions.

Critical channeling angles of active metal ions through thin Al (100) films (in degrees)

Ion	[110]		[100]		[130]		[120]	
	Experiment	Theory	Experiment	Theory	Experiment	Theory	Experiment	Theory
$E_0 = 20$ keV								
Na^+	~ 8.2	8.3	~ 6.6	6.5	~ 4.6	4.4	~ 3.8	3.7
K^+	~ 9.7	9.6	~ 6.6	7.4	~ 5.8	4.4	~ 4.7	4.4
$E_0 = 30$ keV								
Na^+	~ 8.0	8.3	~ 6.6	6.3	~ 4	4.1	~ 3.9	3.4
K^+	~ 8.7	8.6	~ 7.7	7.5	~ 4.9	4.4	~ 4.2	3.6

Based on these experimental data, the critical channeling angles of Al (100) bombarded with Na^+ and K^+ ions were estimated and compared with the calculated data obtained according to the Linhard expression, which applies to relatively low energies (from 10 to 50 keV) (see table):

$$\psi_{cr} = \left[\frac{ca}{d\sqrt{2}} \left(\frac{Z_1 Z_2 e^2}{2\pi d E_0} \right)^{1/2} \right]^{1/2},$$

where c=√3; d—distance between atoms of the chain; Z_1 and Z_2—atomic numbers of the target materials and the ion, respectively; E_0—initial energy; a—shielding parameter (a=0.86φ, φ—potential of a point charge); e—electron charge.

The experimental values of the critical channeling angles ψ_{cr} for a given crystal direction were estimated based on the half-width of the maxima of the angular or spatial distributions of the passed ions. Their comparison showed very satisfactory agreement. It should also be noted that the results of the experiment on the passage of ions through thin layers of crystals confirm the conclusions that an increase in the primary ion beam energy and a decrease in the ion mass lead to a decrease in the critical channeling angle.

The critical angles of channeling of Na^+ and K^+ ions were experimentally estimated using methods of studying the angular dependences of ion passage through free thin Al (100) films. It was shown that ψ_{cr} depends on the mass and energy of ions. The obtained results are in good theoretical agreement with Linhard's calculations. It was shown that ψ_{cr} for axial channeling does not exceed $4-5^0$, and for planar channeling — $9-10^0$

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