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Study of the critical angle of channeling of active metal ions through thin aluminum films

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The spatial distributions of ions (K^+, Na^+) passed through thin polycrystalline and single-crystalline Al films with the thickness from 180 to 600 Åand critical channeling angles have been studied. The ion energies have been varied within the range $E_0 = 10-30$ keV. It has been shown that an increase in the energy of the primary ion beam leads to a decrease in the width of the maxima of the angular distribution, which is associated with a decrease in the critical channeling angle ψ_{cr}. It has been found that the value ψ_{cr} does not exceed $4-50$ for axial channeling and $9-100$ for planar channeling

Keywords: critical angle, passage of ions, angular distribution, channeling, spatial distribution.

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Interactions of electrons and ions with energies of $10-100$ keV and higher with a solid state, in particular, the phenomena of scattering and their passage through thin layers of crystals, are widely used in research for solid state physics. If the scattering medium is a single crystal, then successive collisions of incident ions with crystal atoms become strongly bound, 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 type of interaction, in turn, allows obtaining information about the structure of the crystal, the nature of the movement of atomic particles in it, the formation of defects and the localization of impurity atoms in the crystal lattice [1–10]. It is known that bombardment by active metal ions with an energy of $1-100$ keV is used to modify surface properties and obtain nanoscale structures with desired physical properties at different depths of the near-surface region of materials [11–14], as well as to study the degree of single-crystallinity of crystals [2,4,7].

During the bombardment of thin single-crystal films by ions, the part of the ions due to axial and planar channeling pass through the sample with low loss in energy [3,4,7]. Channeling primarily depends 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 less than the critical ψ_{cr} pass through the sample. The angle ψ_{cr} between the particle trajectory and the channel axis, at which the guiding action of a number of atoms on the ion still does not disappear, is called the critical angle of particle channeling [2]. According to Lindhard's theoretical estimates, the increase in energy of the primary ion beam should lead to the decrease in angle from 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 the Lindhard formulas [2]. To experimentally estimate ψ_{cr}, one can use the method of studying the spatial distribution of ions that have 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 sample rotation.

In this work, the critical angles of channeling of K^+ and Na^+ ions passing through Al(100) single-crystal films with the thickness d_{Al} from 180 to 600 Åare experimentally determined. The results obtained were compared with theoretical calculations.

The research was carried out in the ultrahigh-vacuum universal ion implanter with working chamber vacuum $\sim (3-8) \cdot 10^{-9}$ Torr. The surface of the test sample was cleaned by thermal heating from the rear side of the target. The surface purity of the sample was estimated from the disappearance of the carbon and oxygen Auger peaks in the Auger electron spectrum. The angular detection aperture of the Hughes$-$Rozhansky energy analyser is $\sim 0.5^\circ$. In the experiments, the manipulator with five degrees-of-freedom was used: rotation of the sample in its plane; tilt with respect to the ion beam; movement of the target in the beam in the vertical, horizontal direction. Actuator for each movement is equipped with vernier scale, which makes it possible to count the rotation and inclination of the target relative to the beam with accuracy of 0.1° and its movement with accuracy of 0.1 mm. The manipulator allows rotation of the target holder around the axis by 360° and vertical and horizontal displacement by 20 mm, as well as rotation of the target in azimuth. Taking into account the freeplay in worm-gear drives, the absolute accuracy of the manipulator installation is $15'$. The ion source makes it possible to bombard the sample by ions with energies from 10 to 35 keV at

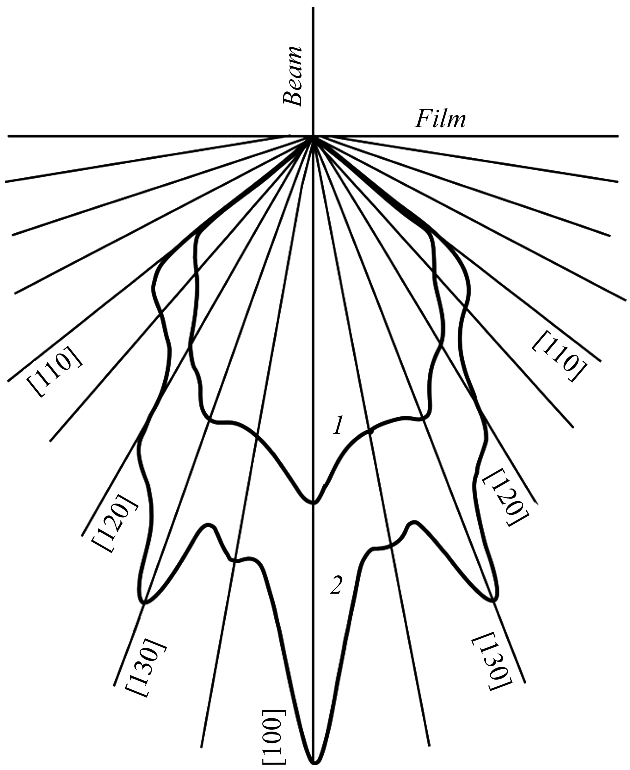

Figure 1. Polar diagrams of the angular distribution of Na^+ ions passing through the single-crystal Al(100) film ($d_{\text{Al}} = 450$ Å) at energies $E_0 = 20$ (*1*) and 30 keV (*2*).

a maximum current density of 10^{-7} A/cm^2. The ion spot diameter can be adjusted using the single lens within 0.4–2 mm depending on the problem being solved.

Figure 1 shows polar diagrams of the angular distribution of Na^+ ions that have passed through the single-crystal Al(100) film with $d_{\text{Al}} = 450$ Å. During obtaining polar diagrams of the angular distribution, the direction of the primary ion beam coincided with the [100] direction, the VEU-6 detector performed around the $\langle 001 \rangle$ axis of the crystal lattice, and the detection plane coincided with the $\{001\}$ plane. It can be seen that the nature of the polar diagrams of the angular distribution is cardinally anisotropic. They exhibit clearly pronounced maxima corresponding to the crystallographic directions [100], [130], [120], [110]. Increasing in the energy of the primary ion beam leads to the decreasing in width of the maxima of the angular distribution, which is associated with decrease in the critical channeling angle ψ_{cr}.

Figure 2 shows the energy distribution spectra of Na^+ ions that have passed through Al(100) films 450 Åthick. The Na^+ ions were directed to the surface with $E_0 = 20$ keV with different angles (0, 5 and 10°) relative the normal. The spectrum obtained when the ion beam is incident along the normal to the surface ($\varphi = 0°$) exhibits all three peaks characteristic of the single-crystal film: the so-called axial-transmission(a), planar transmission(b) and diffuse-transmission(c) [7]. At $\varphi = 5°$ all three peaks are also found. However, the intensity of the a peak sharply decreases, and the half-width of the in-plane channeling peak increases without the noticeable change in its intensity. Apparently, the decrease in the number of ions that have passed as a result of axial channeling leads to increase in the number of planar channeling's ions. It can be seen from the third spectrum ($\varphi = 10°$) that the maximum of axial channeling practically disappears, planar channeling has a very low intensity, the position of the maximum of irregular (diffuse) transmission shifts towards lower energies, and the half-width of this maximum increases . The latter fact is due to an increase in the number of ions that have experienced multiple collisions with atoms of the target (film), which leads to an increase in the average energy loss by ions during their passage.

Based on the analysis of the spectra shown in Fig. 2, it can be assumed that ψ_{cr} for axial channeling is $\sim 5°$, and for planar channeling is ~ 10 ^{circ} The same results were obtained in the case of Al(100) bombardment with K^+ ions.

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 Lindhard formula, which refers to relatively low energies (from 10 to 50 keV) (see table):

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

here $c = \sqrt{3}$; d is distance between chain atoms; Z_1 and Z_2 is atomic numbers of the target material and ion, respectively; E_0 is initial energy; a is shielding parameter ($a = 0.86\phi$, ϕ is point charge potential); e is electron charge.

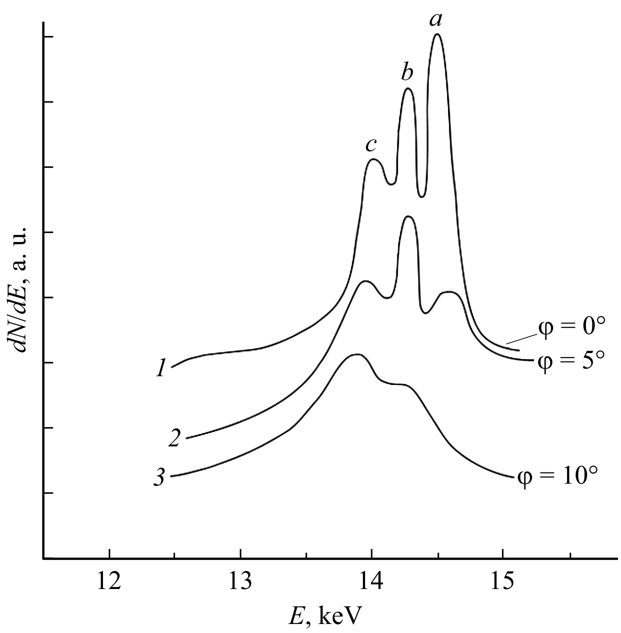

Figure 2. Distribution in energy of Na^+ ions passing through the Al(100) film at ion beam incidence angles $\varphi = 0$ (*1*), 5 (*2*) and 10° (*3*); $d_{\text{Al}} = 450$ Å. Energy of primary ions 20 keV.

Critical angles for channeling 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	~ 7.8	7.4	~ 5.8	5.6	~ 4.7	4.4
$E_0 = 30$ keV								
Na^+	~ 8.0	8.3	~ 7.1	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

Experimental values of the critical channeling angles ψ_{cr} for given direction of the crystal were estimated from the half-width of the maxima of the angular or spatial distributions of the transmitted ions. Their comparison showed a 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 conclusion that the increase in the energy of the primary ion beam and the decrease in the ion mass lead to decrease in the critical channeling angle.

The critical channeling angles Na^+ and K^+ ions are experimentally estimated using the methods of studying the angular dependences of the passage of ions through free Al(100) thin films. It is shown that ψ_{cr} depends on the ion mass and energy. The results obtained agree well with Lindhard's theoretical calculations. It is shown that ψ_{cr} for axial channeling does not exceed 4−5°, and for planar channeling not exceed 9−10°.

Conflict of interest

The authors declare that they have no conflict of interest.

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