Dechanneling of protons in single-crystal tungsten

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The energy spectra of the backward scattering of protons with $E_0 = 6.3$ MeV were used to determine the integral dechanneling functions for the axial (⟨111⟩, ⟨100⟩, ⟨110⟩) and planar ({110}) channels of the tungsten crystal at temperatures 293, 620, and 850 K. The energy scale was converted into a depth scale by using the previously obtained [A. S. Rudnev *et al.*, Phys. Status Solidi A **35**, K23 (1976)] values of the energy losses of the channeled particles. It is shown that the principal dechanneling mechanism at depths $\lesssim 20$ μm is scattering due to thermal vibrations of the atoms in the crystal lattice.

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INTRODUCTION

The integral dechanneling function (the dependence of the fraction of the dechanneled particles on the depth) $\chi(x)$ is an important characteristic of the interaction of charged particles with crystals. Its correct determination is essential both for the study of the mechanism responsible for the knock-out of particles from the channeling regime, and for different applications of the channeling phenomenon in solid-state and nuclear physics.

The theoretical principles of the dechanneling process were expounded in Lindhard's well-known paper.[1] He has shown, in particular, that the main factors that increase the energy $E_\perp$ of the transverse motion of particles moving in the channeling regime are thermal vibrations of the lattice atoms and multiple scattering by the free electrons. In the case of axial channeling, the contribution of the thermal vibrations to the increase of $E_\perp$ is proportional to $u_2^2 d/E_0$, where u_2^2 is the mean squared amplitude of the thermal vibrations in the transverse plane, d is the interatomic distance in the direction of the considered crystallographic axis, and E_0 is the energy of the incident particles. The contribution of the multiple scattering by the free electron is proportional, according to[1], to the interatomic distance d and does not depend on the crystal temperature (see also[2]). In the case of planar channeling, the contribution of the thermal vibrations to the increase of $E_\perp$ is proportional to $\beta = 1 + 4.8 u_2^2/a^2$, [3] where a is the screening radius of the atom.

It can be shown (see, e.g., [4]) that the integral dechanneling function $\chi(x)$ depends on the same combination of parameters (x, u_2^2, d and E_0) as $\Delta E_\perp$. Therefore an experimental study of the behavior of $\chi(x)$ as a function of the crystal temperature for different crystallographic directions and at different energies of the incident particles makes it possible to verify the conclusions of the theory.[1] Attempts at such a verification were repeatedly undertaken.[5–9] The conclusions, however, were contradictory: some of the results[6,7] confirm the conclusions of the theory,[1] while others[8,9] disagree.

The integral dechanneling function $\chi(x)$ was determined in experiments[5–9] from the normalized energy spectra

$$\chi'(E) = Y_c(E)/Y_n(E), \tag{1}$$

where E is the energy of the particles emitted from the crystal, $Y_c(E)$ is the energy spectrum of the backward scattering of the particles for the case when the direction of the incident beam coincides with one of the high-symmetry crystallographic directions, and $Y_n(E)$ is the backward-scattering energy spectrum obtained for arbitrary orientation of the crystal relative to the beam. To obtain the function $\chi(x)$ from $\chi'(E)$ it is necessary to know the energy losses of the particles that move in the channeling regime from the point of entry into the channel to the dechanneling point. Since the cited papers[5–9] contain no systematic data on the energy losses of these particles, it was assumed that the energy losses of the particles moving in the channeling regime are proportional to the normal energy losses, and the proportionality coefficient is independent of the particle energy or of its transverse energy (or the dechanneling depth). Obviously, this is a rather crude approximation.[2,10]

The question of the dependence of the channeled-particle energy losses on the dechanneling depth has already been considered in detail.[11–12] It was shown that the energy losses of channel d particles depend strongly on the dechanneling depth. In particular, the question was also considered of the correctness of the determination of the integral dechanneling function from the backward-scattering energy spectra, and it was shown that determination of the function $\chi(x)$ from relation (1) is generally speaking only approximately correct (see also[14]). It follows, however, from[12] that in the particular case of channeling of protons with energy ~ 6 MeV in a tungsten crystal the error in the determination of the integral de-

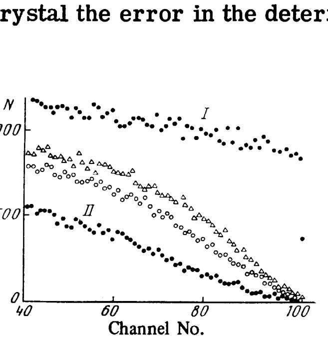

FIG. 1. Proton backscattering energy spectra: II—incident beam aligned with the axial direction ⟨111⟩ of the W crystal, measured at $T = 293$ (●), 620 (○) and 850 K (△), I—for the case of non-oriented crystal; N—number of counts in channel.

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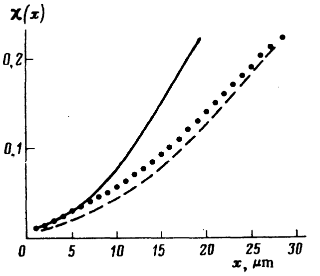

FIG. 2. Dependence of the values of $\chi(x)$ on the depth for the axial direction ⟨111⟩ of the W crystal, as obtained from the proton backscattering spectra using the function $\overline{m}(x)$ (●), $m=1$ (solid curve) and $m=0.35$ (dashed curve). $T=293$ K.

channeling function from relation (1) does not exceed the experimental errors. The problem of determining the integral dechanneling function reduces therefore in this case to a correct conversion of energy into depth.

We present in this paper the results of an investigation of dechanneling of protons with $E_0=6.3$ MeV in a tungsten crystal. These results were obtained with account taken of the dependences of the mean relative energy losses of the channeled particles on the dechanneling depth. Preliminary results of these investigations have already been published.[15]

MEASUREMENT RESULTS

The experiment was performed on a proton beam from a 120 cm cyclotron. The proton energy was 6.3 MeV. The energy scatter in the beam did not exceed 60 keV, and the beam divergence angle was 0.025°. A single-crystal tungsten target was mounted on a triaxial goniometer equipped with a heater. The crystal temperature was measured with a thermocouple and was maintained constant with ± 1% during the measurements. The beam was monitored by recording the protons scattered by a tantalum foil that blocked the beam periodically.

The energy spectra of the scattered protons were recorded with a semiconductor spectrometer having an energy resolution $\lesssim 20$ keV. The proton backward-scattering energy spectra, for the case when the direction of the incident beam coincided with the ⟨111⟩ axial direction of the tungsten crystal and measured at temperatures $T=293$, 620, and 850 K, are shown in Fig. 1. Analogous spectra were obtained for the axial ⟨100⟩ and ⟨110⟩ channels and for the planar {110} channel.

Figure 2 shows the values of the integral dechanneling function for the ⟨111⟩ axial channel, obtained from spectra measured at $T=293$ K. The points show the values of $\chi(x)$ obtained with the aid of relation (1) with conversion from energy to depth by using the dependence of the average relative energy losses of the channeled particles on the dechanneling depth (the functions $\overline{m}(x)$[16]). The energy-to-depth conversion was effected graphically with the aid of the relation

$$x=\frac{1}{C_2[k_p+\overline{m}(x)]}\left[1-\left(\frac{E}{E_0}\right)^{3/2}\right], \tag{2}$$

where $k_p=k/p^{3/2}$, $k=\cos\theta_1/\cos\theta_2$, p is a coefficient that takes into account the energy lost to the recoil of the scattering atom, $C_2=0.012\ \mu\mathrm{m}^{-1}$, θ_1 and θ_2 are the angles between the normal to the target surface and the incident-beam and detection directions, respectively, and E_0 is the energy of the incident particles.

For comparison, Fig. 2 shows the values of $\chi(x)$ obtained from the same spectra using for the energy-to-depth conversion the value $m=1$ corresponding to normal energy losses (solid curve), and the value $m=0.35$ corresponding to the energy losses of well-channeled particles (dashed curve). It is seen from the figure the method of converting energy into depth influences substantially the $\chi(x)$ dependence determined from the spectra. The curve obtained by using $m=1$ practically coincides at small depths ($x\leq 5\ \mu$m) with $\chi(x)$ determined when $\overline{m}(x)$ is taken into account, but at depth ~20 μm the discrepancy reaches 60–70%. The curve obtained using $m=0.35$ is in better agreement at larger depths with the $\chi(x)$ obtained with $\overline{m}(x)$ taken into account, but at a depth ~5 μm the discrepancy amounts to ~50%.

The influence of the method used to convert energy into depth influences substantially the results of the determination of the values of $\chi(x)$ also at other crystal temperatures. This is clearly seen from Fig. 3, which shows plots of $\chi(x)-\chi(0)$ against depth, obtained by using the functions $\overline{m}(x)$, $m=1$, and $m=0.35$ for energy-to-depth conversion at crystal temperatures $T=293$, 620 and 850 K.

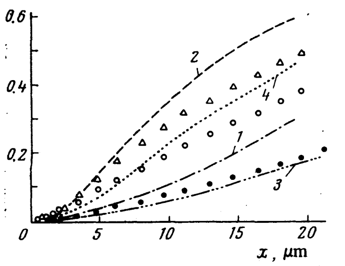

FIG. 3. Plot of $\chi(x)-\chi(0)$ vs depth for the axial direction ⟨111⟩ of W crystal. The values marked ●, ○, and △ were obtained using the function $\overline{m}(x)$ at $T=293$, 620, and 850 K, respectively. Curves 1 and 2 were obtained from the same spectra using $m=1$ at $T=203$ and 850 to convert from energy to depth. Curves 3 and 4 were obtained using $m=0.35$ at $T=293$ and 850 K.

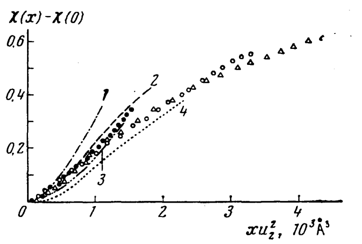

FIG. 4. Plots of $\chi(x)-\chi(0)$ on the parameter xu_2^2 for the axial direction ⟨111⟩ of the W crystal, obtained using $\overline{m}(x)$ at $T=293$ (●), 620 (○), 850 K (△); $m=1$ at $T=293$ (1), 850 K (2); $m=0.35$ at $T=293$ (3), 850 K (4).

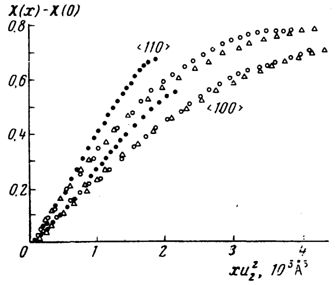

FIG. 5. Plots of $\chi(x)-\chi(0)$ against the parameter xu_2^2 for the axial directions ⟨100⟩ and ⟨110⟩ of the W crystal. The energy-to-depth conversion was effected by using the function $\overline{m}(x)$. $T=293$ (●), 620 (○), 850 K (Δ).

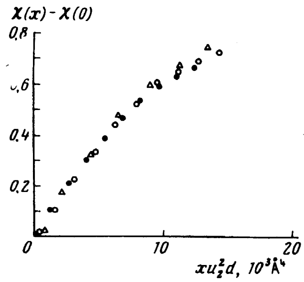

FIG. 7. Plot of $\chi(x)-\chi(0)$ against the product xu_2^2d for axial directions of the crystal W: ⟨111⟩ (●), ⟨100⟩ (○) and ⟨110⟩ (Δ) at $T=620$ K. The energy-to-depth conversion was with the aid of the function $\overline{m}(x)$.

The use of various methods of changing from the energy scale to the depth scale when determining the integral dechanneling function leads to substantially different dependences of $\chi(x)-\chi(0)$ not only on the depth but also on the crystal temperature. Figure 4 shows the values of $\chi(x)-\chi(0)$ for the axial direction ⟨111⟩, obtained using different methods of energy-depth conversion, as functions of the parameter xu_2^2. The mean squared amplitude u_2^2 of the thermal vibrations of the lattice atoms in a plane perpendicular to the ⟨111⟩ axis was calculated from the total mean squared vibration amplitude determined by the Debye model (see, e.g., [2]). It is seen from the figure that the values of $\chi(x)-\chi(0)$ obtained using $\overline{m}(x)$ at depths $x \leq 20$ μm fit a single curve. On the other hand if the values $m=1$ and $m=0.35$ are used for the energy-to-depth conversion, then the values $\chi(x)-\chi(0)$ diverge at all depths.

Analogous results were obtained for the axial channels ⟨100⟩ and ⟨110⟩. Figure 5 shows plots of $\chi(x)-\chi(0)$ for the axial directions ⟨100⟩ and ⟨110⟩ against the product xu^2, as obtained by using the functions $\overline{m}(x)$ for these channels.[16] It is seen from the figure that in these two cases the values of $\chi(x)-\chi(0)$ obtained at different crystal temperatures fit on one curve in the region of small depths.

Figure 6 shows the dependence of the values of $\chi(x)-\chi(0)$ obtained at various crystal temperatures on the product xu_2^2d for the axial direction ⟨111⟩, ⟨100⟩, and ⟨110⟩ of a tungsten crystal. The energy-to-depth conversion was with the aid of the functions $\overline{m}(x)$. It is seen from the figure that the values of $\chi(x)-\chi(0)$ obtained at various temperatures and for different axial crystal directions contract to a single curve at $x \lesssim 20$ μm.

By way of example, Fig. 7 shows the values of $\chi(x)-\chi(0)$ obtained at $T=620$ K for different axial directions, as functions of the product xu_2^2d. It is seen in this figure that the values of $\chi(x)-\chi(0)$ for different axial channels practically coincide for all depths.

The values of $\chi(x)-\chi(0)$ for the case of planar channeling in the {110} direction are shown in Fig. 8. The abscissas in this figure are the values of the parameter $x\beta$. Energy-to-depth conversion was with the aid of the function $\overline{m}(x)$ for the planar channel {110}.[16] In this case, too, the values of $\chi(x)-\chi(0)$ obtained at various crystal temperatures agree in the region of small depths.

DISCUSSION OF RESULTS

The results obtained in the present paper for axial channeling confirm Lindhard's conclusions that various mechanisms contribute to particle dechanneling. The agreement between the plots of $\chi(x)-\chi(0)$ against xu_2^2 for different crystal temperatures and against xu_2^2 for different temperatures and different axial directions in the crystal at depths $\lesssim 20$ μm (Figs. 4–6) gives grounds for stating that the principal dechanneling mechanism in this depth region (at the proton energy considered in this paper) is the scattering due to thermal vibrations of the lattice atoms. The assumption that the discrepancy be-

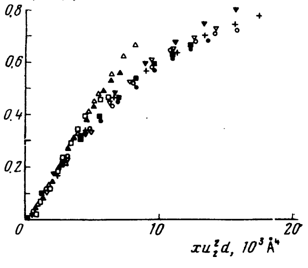

FIG. 6. Plot of $\chi(x)-\chi(0)$ against the product xu_2^2d for axial directions of the crystal W: ⟨111⟩ ($T=293$ (□), 620 (■), 850 K (●)); ⟨100⟩ ($T=293$ (▲), 620 (▽), 850 K (○)) and ⟨110⟩ ($T=293$ (Δ), 620 (▼), 850 K (+)). The energy-to-depth conversion was with the aid of the function $\overline{m}(x)$.

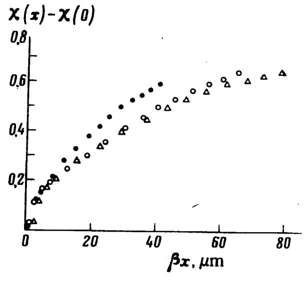

FIG. 8. Plot of $\chi(x)-\chi(0)$ against the parameter $x\beta$ for the planar channel {110} of a W crystal at $T=293$ (●), 620 (○) and 850 K (Δ), The energy-to-depth conversion was with the aid of the function $\overline{m}(x)$.

tween the curves at depths $x > 20$ μm is due to the increased contribution made to the dechanneling by multiple scattering of protons by free electrons[17] is confirmed by our results. The values of $\chi(x) - \chi(0)$ as functions of $x u_2^2 d$, corresponding to different axial direction at the same temperature, coincide at all depths (Fig. 7). This agrees with the predictions of the theory, [1] which postulates that the contribution made to the dechanneling processes as a result of multiple scattering by free electrons is independent of the crystal temperature and is significant at low transverse energies of the channeled particles (it is obvious that particles with low initial transverse energy drop out of the channeling regime at large depths).

Our results for the case of planar channeling can also be explained within the framework of the existing theoretical premises concerning the dechanneling process.[3] The agreement between the values of $\chi(x) - \chi(0)$ obtained at various crystal temperatures for the planar channel $\{110\}$ as functions of the product $x\beta$ (Fig. 8) at depths $x < 20$ μm confirm the theoretical conclusions[3] that at these depths the principal mechanism responsible for the knock-out of the particles from the planar channeling regime is scattering due to thermal vibrations of the atoms.

Our present results give grounds for assuming that the most probable cause of the various conclusions drawn from experimental results of like type[6-9] are the differences in the method of energy-to-depth conversion. In the cited papers they used the connection between E and x obtained in[5]. This connection presupposes that the energy lost by the channeled particles from their entry into the channel to the dechanneling point are known. In a number of papers[6,7] the energy losses of particles moving in the channeling regime were assumed equal to the energy losses of well-channeled particles. Other workers[8,9] have assumed that the energy losses of particles moving in the channeling regime are equal to the normal energy losses. Figures 2–4 show how the functions $\chi(x)$ depend on the method of energy-to-depth conversion. On the basis of the curves in these figures it can be concluded that the ratio of the energy of the particles moving in the channeling regime to the normal energy losses, $S_c(E)/S_n(E)$, should itself be dependent on E and on $E_\perp$.

All the results presented in the present paper show that an important role in the correct determination of the integral dechanneling function is played by the function $\overline{m}(x)$ derived by us previously, [11-13,16] which represents the dependence of the average relative energy losses of the channeled particles on the dechanneling depth. The function $\overline{m}(x)$ is important not only for a correct transformation of the energy scale in Eq. (1) into the corresponding depth scale. The behavior of the function $\overline{m}(x)$ determines the possibility of using relation (1) to determine the integral dechanneling function. At certain combinations of the energy and of the sort of bombarding particles and the crystal properties, it is not excluded that the behavior of the function $\overline{m}(x)$ is such that a more complicated method is necessary to determine the function $\chi(x)$. [12]

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