Effect of exit surface on neutral fraction in mega-electron-volt hydrogen beams transmitted through aluminum epitaxial foils under a planar channeling condition

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Neutral fractions are measured for $(0.4-0.8)$ MeV H^+ ion beams transmitted through aluminum epitaxial foils under the (100) planar channeling condition. Two foils are prepared: the first $(\Theta=90°)$ is almost perpendicular to the direction of the beam and the second $(\Theta=30°)$ is inclined at 60° compared with the first. The measured neutral fractions, which are in the 10^{-3} range, exhibit a minimum at the (100) channeling direction, however, the channeling effect is enhanced for the foil with $\Theta=30°$. The fraction is calculated for the two foils from the equilibrium fraction and the charge exchange between the ions and the surface atoms in a vacuum. Both the equilibrium fraction and the charge exchange depend on the exit positions of ions from the midplane of the channel. The measured energy dependence of the ratio (channeling/random) of the fractions is reproduced by calculation. Thus the results indicate that the transmitted charge-state distributions are modified by the charge exchange after the emergence of ions in a vacuum.

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I. INTRODUCTION

The interactions of ion beam with solids or solid surfaces have been studied for many years. The charge-state fractions of energetic light ions are the most extensively investigated in this field [1,2]. The impinged ions undergo charge-exchange collisions and the charge-state distributions of the ions grow in the foil for their equilibrium ones. It is believed that the ions emerge from the foil surface with almost the same charge-state distributions as in the foil, and that the surface plays no special role [3]. However under certain conditions, the ions emerging from the surface of the foil must be influenced by the interaction of ions with the atoms on the surface, hence the charge-state distribution could be changed from the one inside the foil. The interaction may be a so-called "post-foil" interaction or a continuous scattering with the surface atoms due to electromagnetic field along the passage. If interactions change the charge-state distributions in the vacuum significantly from those in the foil, the effect must be taken into accounts.

Although a fraction of the charge state of MeV ions with electrons smaller than 10^{-3} is hard to measure with good statistics, it is sensitive to the ion scattering on surface atoms. Because of small binding energy and large orbital radius of the outermost electron, the electron is lost during a comparatively large impact-parameter collision. Thus the charge state is easily affected by the geometry relative to the surface, i.e., the angle between the ion beam in the vacuum and the surface. For example, the fraction of sub-MeV hydrogens in a proton beam at the glancing angle incident to a crystal surface is in the order of 10^{-3} and is about 20% of the case where the beam is transmitted by the foil [4]. The decrease to 20% is notable. This is contrast with the case where the He^+ fraction in an MeV He ion beam scattered at the glancing angle incidence is in the order of 10^{-1} and the fraction is about 50% of that where the beam is transmitted by the foil [4–6]. Therefore in the investigation of the small fraction of the charge states of ions, the effect of the surface scattering is expected to be significant.

Since the neutral fraction in the transmitted sub-MeV proton beam is in the order of 10^{-3}, it is large enough to measure within the relative error of 10%. Thus the fraction measured in one set of conditions can be compared with those in a different set of conditions in order to determine information about the surface scattering. All events which create neutrals measured in fast proton beams are believed to happen at the emergence from the foil surface, because no bound states of hydrogen exist in the foil. However, for the neutral fraction, many experimental results have been reported where the fraction can be explained by treating it as if it grows in the foil, i.e., survival fraction and the energy losses of H^0 depend on the thickness of the foil [3,7,8].

We have measured the 10^{-3} range-neutral fraction in $(0.3-0.6)$ MeV H^+ beam transmitted through an Al-polycrystalline foil whilst changing exit angles between the beam direction and the foil surface from 90° to 30° [9]. The fraction slightly decreased at the angle of 30° from that of the initial one at 90°. This is due to the large electron loss probability during collisions distant from the surface, where the electron capture does not occur. A numerical estimate shows that the ground state hydrogens contributes about half of the decrease and that of the excited state hydrogens covers the remainder. Although the amount of the excited state hydrogens is small, the electrons in the excited states are removed more easily during collisions distant from the surface [9].

Previously, the neutral fraction in an MeV H^+ ion beam after channeling through Au crystal has been reported [10]. It is known that the charge-state fraction of the measured ions is determined by the exit position, i.e., the distance from the midplane in the channel [5]. Thus the neutral fraction for the channeling ions which depends on the exit positions is not an equilibrium one in the random solid. When the ion exits from the surface with a small angle, the position determines the outward trajectory, and thus the following collisions with target atoms. Therefore it is expected that the charge exchange in the vacuum between the emerged ions and the

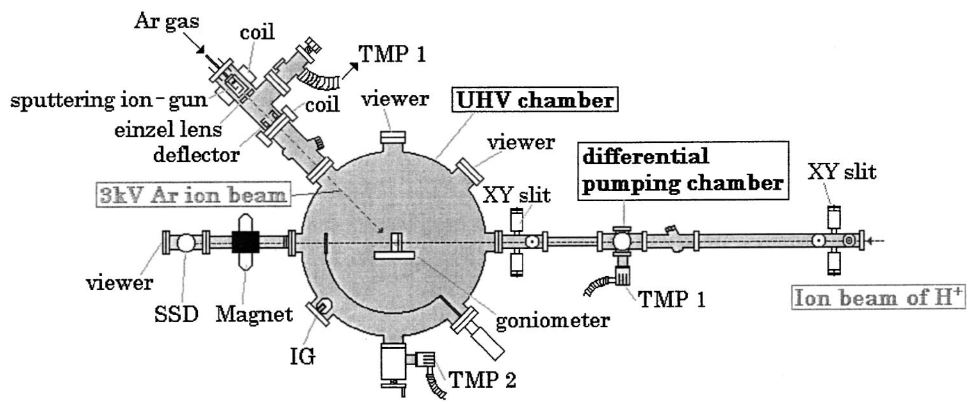

FIG. 1. Experimental setup.

target atoms must depend on the exit position. Thus the interaction between the emerged ions and the surface atoms may also change the fraction in a vacuum depending on the impact parameters between them. In this work, we have investigated the surface scattering effect on the neutral fraction for the channeling ions. The neutral fraction of MeV H^+ ion beams transmitted through two different Al epitaxial foils under the (100) channeling condition has been measured and compared. The first foil ($\Theta=90°$) is almost perpendicular to the beam direction and the second ($\Theta=30°$) is inclined at 60° compared with the first one. The ratios of the neutral fraction at the (100) planar channeling direction to that at the random direction measured at the two foils are compared with calculated ones respectively.

II. EXPERIMENT

A. Experimental procedure

In order to use them in the channeling experiments, Al epitaxial foils were prepared by vacuum evaporation on the KCl (001) and were carefully checked by the transmission electron microscope (HITACH; H-300) to have a range of the sing1e crystal of several hundred μm. Two sets of the two foils were used in the experiments and their thicknesses were 4000–6000 Å. The main parts of the experimental setup are schematically shown in Fig. 1. The two foils put on 1 mm ϕ holders were mounted up and down on a goniometer in a 3×10^{-10} Torr UHV chamber evacuated by an ion pump. The first is almost perpendicular to the beam direction ($\Theta=90°$) and the second is inclined at 60° compared with the first ($\Theta=30°$). The azimuthal angle of the second foil was carefully adjusted so that the incident beam direction was along the (100) crystallographic planes in the foil by a rotation of the goniometer around the vertical axis. In this configuration, other low index planes do not match the beam direction for the second foil.

The oxide layer on the surface of the foils was estimated to be 100 Å by Rutherford backscattering for the polycrystalline Al foils which had been made by the vacuum evaporation [9,11]. In order to remove the oxide layer of the foils, the foils were irradiated with 2–3 keV Ar^+ beams and sputtered more than 100 monolayers. The sputtered thickness was estimated by the integrated irradiation dose monitored by the beam currents from the target foil and the sputtering yield reported by Yamamura and Tawara [12]. The base pressure during this rough sputtering was 10^{-8}–10^{-7} Torr after being evacuated by two turbo-molecular pumps (TMP's). After this, the Ar gas flow was reduced and several monolayers of Al were removed in 10^{-9} Torr UHV evacuated by the ion pump. After the sputtering, the targets were annealed at 250–300 °C more than 8 h in 10^{-10} Torr. This procedure of the sputtering and the annealing in UHV was after that indicated in Ref. [4].

A beam of (0.4–0.8)-MeV H^+ ions accelerated by the 1.7 MV tandem Van de Graaff accelerator of Nara Women's University was collimated to less than 0.1 mm$\times$0.1 mm by two sets of slits and was directed at one of the targets. The penetrating ion beam was selected by an aperture with an acceptance half angle of 0.7 mrad placed at the incident beam direction and was detected by a solid state detector (SSD). Rotating the target foil by the goniometer around the vertical axis ±several degrees, the (100) channeling direction was detected. The neutral fraction in the detected beam was measured by removing H^+ ions by a magnet which was placed upstream of the SSD. The magnet and counters were driven sequentially by a gate-pulse generator controlled by a personal computer.

B. Experimental results

Figure 2 shows examples of the energy spectra of ions detected after the collision of 0.6 MeV H^+ ions. The figures in the left column show those for $\Theta=90°$ and those in the right column show those for $\Theta=30°$. Both Fig. 2(a) figures correspond to the incidence of the random direction and both Fig. 2(c) figures are for the (100) channeling incidence. Both Fig. 2(b) figures are those for several mrad off from the (100) channeling case. The higher energy peak at about 600 keV in each spectrum corresponds to the incident beam which penetrated small pin holes on the epitaxial foils. The lower energy peak corresponds to the ions transmitted by the foil.

The neutral fractions for the channeling-ion energy, 568±10 keV, were measured and are shown in Fig. 3 with the ion yields. The transmitted beam intensity increases due to a channeling effect when the foils are tilted as the beam

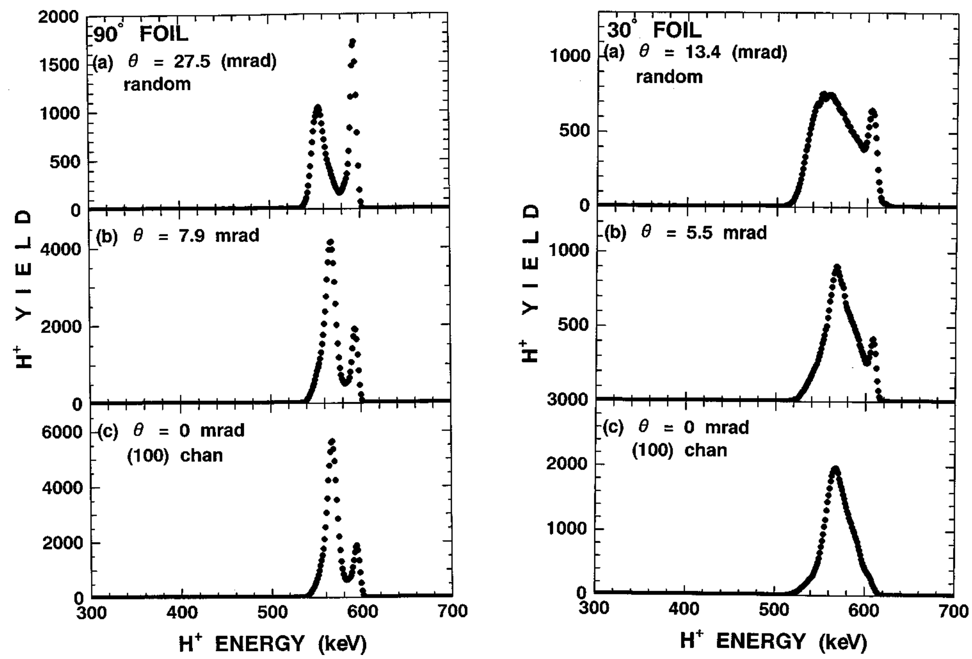

FIG. 2. Examples of the energy spectra. The left column shows those for the foil at $\Theta=90°$ and the right column shows those for $\Theta=30°$. The top figures (a) show those at the random incidence. The bottom figures (c) show those at the (100) channeling incidence and the middle (b) are those for the angle θ several milliradians off from the (100) channeling incidence.

direction becomes parallel to the low index planes. At that time, the ion trajectories are broadly peaked at the midplane in the channel and the small impact-parameter collisions which result in large angle scattering and large energy losses are lessened. Generally, the neutral fraction also decreases for the channeling ions because of the reduction of the small impact-parameter collisions. The ion yield distribution measured at $\Theta=90°$ has small peaks at the tail of the main peak, which are due to the overlaps of some low-index crystallographic planes at an angle of almost 90°. The width of the yield peak for the (100) channeling at $\Theta=90°$ is larger than that at $\Theta=30°$. This depends on the direction of measurement along the angle θ, which was not perpendicular to the (100) plane. The angular dependence shown in Fig. 3(a) was made on the plane between the (110) and (210) planes, which crosses the (100) plane with an angle of about 40°. The neutral fractions for both foils decrease at $\theta=0$, i.e., at the (100) channeling. The channeling effect on the fraction at $\Theta=30°$ is found to be enhanced more than that at $\Theta=90°$. The fraction at $\Theta=30°$ for the random incidence is also smaller than that at $\Theta=90°$, which is a similar result to that reported for polycrystalline Al foil [9].

The difference in perfectness of the crystal of the two foils used is not considered in the results shown in Fig. 3. Thus we obtained the neutral fraction, $\Phi^{\Theta}_{CHN}(\theta)$, for the channeling ions at the angle θ by

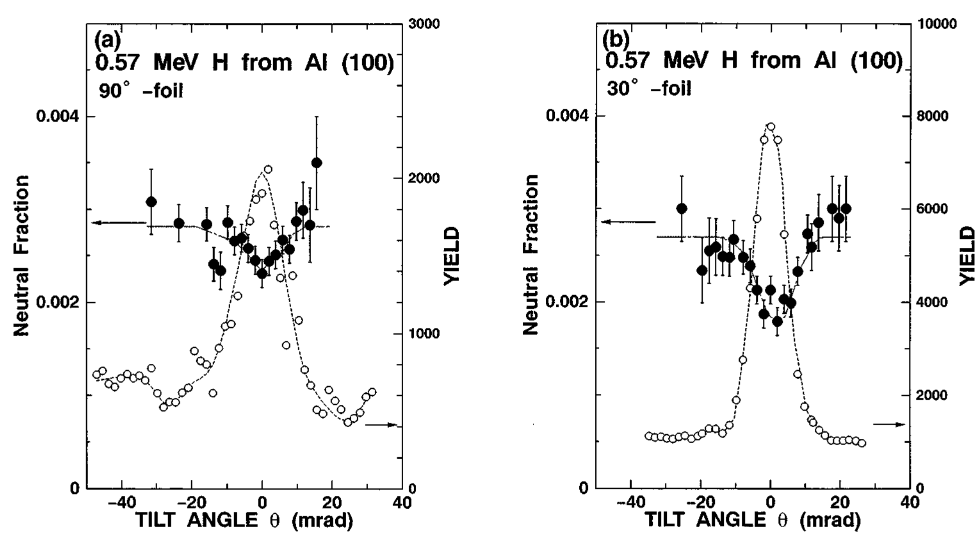

FIG. 3. The θ dependence of the neutral fractions (closed circles) for the ions channeling through with energy of 568 ± 10 keV. The penetrated ion yields are also shown (open circles). (a) $\Theta=90°$ and (b) $\Theta=30°$.

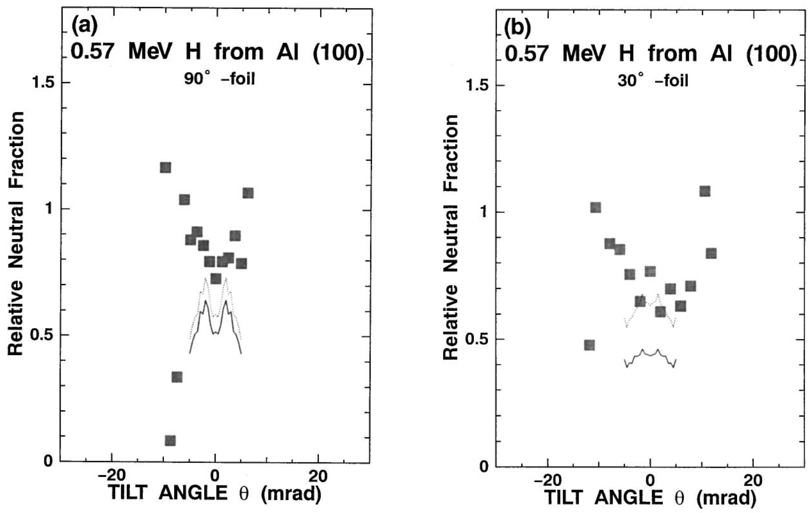

FIG. 4. The θ dependence of the results of the normalized fraction (squares), i.e., $\Phi^{\Theta}_{CHN}(\theta)/\Phi^{\Theta}_{mes}(\theta_{RND})$. (a) $\Theta=90°$ and (b) $\Theta=30°$. For obtaining the calculated normalized fraction, the calculated neutral fractions at the random incidence were those obtained in Ref. [9]. In the figure (a) for comparison with the calculated ones, the angles of the experimental results are plotted on the θ axis after they are multiplied by a factor of 0.6. The solid lines show the calculated results with the surface scattering, and the dotted lines show those without the surface scattering.

$$\Phi^{\Theta}_{CHN}(\theta)=\frac{\Phi^{\Theta}_{mes}(\theta)-\Phi^{\Theta}_{mes}(\theta_{RND})\times F^{\Theta}_{RND}(\theta)}{1-F^{\Theta}_{RND}(\theta)}, \qquad (1)$$

where Θ corresponds to 90° or 30°, $\Phi^{\Theta}_{mes}(\theta)$ is the measured neutral fraction at the angle θ, $\Phi^{\Theta}_{mes}(\theta_{RND})$ is the measured neutral fraction at the random direction θ_{RND}, and $F^{\Theta}_{RND}(\theta)$ is the random-ion fractional yield in the detected ions. The random-ion fractional yields were estimated under the assumption that the random yields do not depend on the angle θ. The results of $\Phi^{\Theta}_{CHN}(\theta)$ are shown in Fig. 4 after being normalized by the neutral fraction at the random direction $\Phi^{\Theta}_{mes}(\theta_{RND})$. Although the results have not changed so much from $\Phi^{\Theta}_{mes}(\theta)$ shown in Fig. 3 and have scattered due to the statistical errors, it is found that the valleys become slightly deeper and wider than $\Phi^{\Theta}_{mes}(\theta)$. Thus it is expected that the contribution from the random ions is eliminated and the angular dependence of the neutral fraction is expressed more accurately using $\Phi^{\Theta}_{CHN}(\theta)$. In Fig. 4(a), the measured angles are plotted after they are multiplied by 0.6 on the θ axis in order to correct the direction of the scanning axis to be perpendicular to the (100) plane.

By changing the energy of H^+ beam from 0.4 MeV to 0.8 MeV, the energy dependence of the channeling effect on the neutral fractions was measured. The measured energy window was ±10 keV around the peak energy of the channeled ions. The channeling effect which appears in Fig. 4 is observed for both foils in this energy range. However, the effect is different between the two foils. Figure 5 shows the normalized fractions at $\theta=0$, $\Phi^{\Theta}_{CHN}(0)/\Phi^{\Theta}_{mes}(\theta_{RND})$. For the foil of $\Theta=90°$, the ratio is 0.8 ± 0.15 and does not really depend on the energy. For the foil of $\Theta=30°$, the ratio is less than 0.4 at the low energy and it increases with increasing energy to approach that of the foil with $\Theta=90°$. These results are quite different from the results reported by Gaillard *et al.* [10]. They used Au foil thin enough that they can define the trajectory H^+. The surface of the Au foil was used without cleaning, and it was found that the effect of channeling disappeared as the energy of H^+ decreased.

III. CALCULATION OF NEUTRAL FRACTION WITH CHANNELING-ION TRAJECTORIES

The experimental results show that the neutral fraction has a minimum at the (100) channeling direction, which is similar to the result reported by Gaillard *et al.* [10]. The channeling effect on the fraction at $\Theta=30°$ is found to be enhanced. Further, the enhanced effect for the foil of Θ

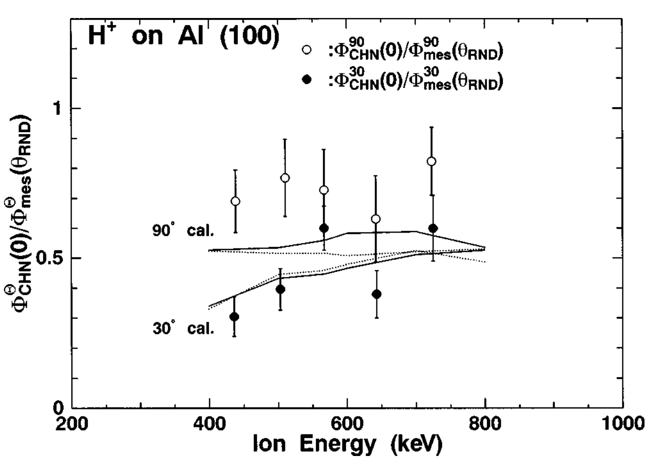

FIG. 5. The incidence-energy dependence of the normalized fractions at the channeling direction, i.e., $\Phi^{\Theta}_{CHN}(0)/\Phi^{\Theta}_{mes}(\theta_{RND})$. The open circles show those for $\Theta=90°$, and the closed circles show those for $\Theta=30°$. The dotted lines show the calculated results for the ions of $\theta=0$, and the solid lines show those averaged over the all channeling ions.

$=30°$ starts to decline with increasing energy. These results may be related to electron loss and electron capture at the surface, when the ions emerge from the planar channel in the foil. In order to inspect the interaction of the penetrating ions with the surface atoms, a computer simulation was performed using a traditional simplified trajectory calculation for the channeling ions and the impact-parameter-dependent probabilities of the charge exchanges for the ground state hydrogen.

A. Calculation of the channeling-ion trajectories

The trajectories of the ions were calculated under the continuum planar potential using the Molière approximation of the Thomas-Fermi type. The ions which approach the (100) plane within a fixed region were regarded as the dechanneling ions and rejected. For this critical distance for the dechanneling, we chose 0.6 a_{TF} and the final results were compared with the results for 0.6 $a_{TF} \sim 1.2$ a_{TF} where a_{TF} is the Thomas-Fermi screening radius. Although a slight dependence on the critical distance was observed in the θ dependence of the fraction, it was not significant in the following discussion.

The stopping power for the channeling ion was assumed to be given by

$$S(x) = S_0 - S_1 + S_1 \cosh\left(\frac{0.3}{2\ a_{TF}}x\right), \tag{2}$$

where x is the distance from the midplane of the channel and S_0 and S_1 are constants. The constant S_0 corresponds to the stopping power at the midplane [13,14]. By integrating this stopping power along x and putting the integral to be equal to the stopping power for the random incidence, S_R, we have obtained the relation

$$S_R = S_0 + 0.1\ S_1. \tag{3}$$

For S_R, we have used the one compiled by Ziegler [15]. By using this relation, the parameters S_0 and S_1 were obtained to fit the energy loss of H^+ channelled through two foils ($\Theta=90°$ and 30°), respectively. For example, for a 0.6 MeV proton beam, the data set of $S_R=6.4, S_0=3.8\pm0.2, S_1=26\pm2$ eV/Å gives a reasonable measure of energy losses of the channeling ions for both of the foils.

The multiple-scattering angle of ions due to the collisions with electrons in the channel was calculated by integrating the small deflection angle $\Delta\phi$ along a trajectory length l. Using the impulse approximation, the magnitude of the deflection angle is

$$\Delta\phi = \sqrt{\frac{m\Delta E(l)}{M_p E}}, \tag{4}$$

where m is the mass of electron, $\Delta E(l)$ is the energy loss of H^+ in the trajectory of length l, M_p and E are the mass and the energy of H^+, respectively. The positions x's at the exit surface and the total scattering angles of the ions were calculated under this multiple scattering. The set of the exit positions of ions which can be detected by the experimental acceptance angle, was a final result of this trajectory calculation. This position is denoted $x_i^0(\theta,\Theta)$ in the following, where i is the trajectory number. Thus in this calculational scheme, the dependence of x_i^0 on the angle Θ is due only to the foil thickness.

B. Calculation of the neutral fraction

The neutral fraction of MeV H^+ moving parallel to the crystal plane at the distance x from the midplane in the channel is given by

$$\Phi_0(x) = q_c(x)/[q_l(x) + q_c(x)] \approx q_c(x)/q_l(x), \tag{5}$$

where $q_c(x)$ and $q_l(x)$ are the electron capture and electron loss probabilities respectively for the unit length of the trajectory at the distance x [5]. The wavelength of the oscillation of the channeling trajectory is several hundred Å, which is larger than the mean free path of the charge exchange (several Å). Thus the trajectory of the channeling ion can be approximated to the one parallel to the plane at the inside of the exit surface and we have approximated that the neutral fraction of the exit ions at the emergence is given by Eq. (5).

For the probabilities $q_c(x)$ and $q_l(x)$, we have used those obtained by the first order perturbation theory. The detail of the charge-exchange probabilities is described in Refs. [6,9,16]. In order to be used in this work, the impact parameter dependent probabilities calculated in Ref. [9] were integrated along the axis perpendicular to the beam direction and parallel to the crystal plane. Then, those probabilities are translated to the ones depending on the distance from the midplane of the channel. In Fig. 4, the calculated results of the angle θ dependence of the normalized neutral fraction using Eq. (5) are shown by dotted lines. The calculated results were sharply structured. The main reason for this disagreement is that the multiple scattering due to collisions with target atoms (screened nuclei) was not treated here. Taking this into consideration, the results may be smeared.

In addition to the check of the angular dependence in the comparison between the results for the two foils of $\Theta=90°$ and 30°, the dependence of the calculated neutral fraction on the two foil thickness used was confirmed to be same. The foil for $\Theta=30°$ is about two times thicker than that for $\Theta=90°$ because of its inclination. Since the multiple scattering due to the collisions with electrons has been treated here, the neutral fractions for the two foil thickness are almost same and are also independent of the deviation of the foil thickness from their mean value. The independence of the foil thickness is due to the fact that the calculated exit positions of detected ions are smeared during several oscillations.

We have treated the surface effect as follows. The neutral fraction of ions which exit from the channel is modified in the vacuum in collisions with atoms on the surface. In this work, the final fraction of ions through the foil of Θ (90° or 30°) is obtained by

$$\Phi^{\Theta}(\theta) = \frac{\sum_{i=1}^{n} \Phi^{\Theta}(x_i^0(\theta,\Theta))\,\delta(\theta_i^s < \Delta)}{\sum_{i=1}^{n} \delta(\theta_i^s < \Delta)}, \tag{6}$$

where x_i^0 is the exit position of the trajectory i, which is a function of the angles θ and Θ. The θ_i^s is the scattering angle of the trajectory i and Δ shows the acceptance angle of detected ions. The delta function means the condition to detect the ion penetrated along the trajectory i. Thus the denominator is the total number of the ions detected and the numerator is the sum of the neutral fractions of the ions detected. The number of trajectories calculated, n, was more than 4000 for each value of θ and Θ.

The neutral fraction of the ion i in the numerator of Eq. (6), $\Phi^{\Theta}(x_i^0(\theta,\Theta))$, is estimated by

$$\Phi^{\Theta}(x_i^0(\theta,\Theta)) = [\Phi(x_i^0) + F_c(x_i^0,\Theta)] \times F_s(x_i^0,\Theta), \quad (7)$$

where $\Phi(x_i^0)$ is the neutral fraction of the exit ions at the emergence on the surface given by Eq. (5) and $F_c(x_i^0,\Theta)$ and $F_s(x_i^0,\Theta)$ are the electron capture probability of the H^+ and the survival probability of H^0 following the emergence at the exit position x_i^0 with the exit angle measured from the surface Θ, respectively. These two probabilities were obtained by a Monte Carlo simulation using the impact parameter dependent electron capture and electron loss probabilities as follows.

For the given Θ, the random exit positions on the surface, (x_j^0,y_j^0) are given by the random numbers, where the coordinate y_j^0 is along the direction perpendicular to that of x_j^0. Thereafter the next summations over the surface atoms, k, which were impacted by the ion being in the vacuum, were calculated:

$$Q_c(x_j^0,\Theta) = \sum_k P_c(b_k((x_j^0,y_j^0),\Theta)) \quad (8)$$

and

$$Q_l(x_j^0,\Theta) = \sum_k P_l(b_k((x_j^0,y_j^0),\Theta)), \quad (9)$$

where $b_k((x_j^0,y_j^0),\Theta)$ is the impact parameter between the ion and the surface atom and $P_c(b_k((x_j^0,y_j^0),\Theta))$ and $P_l(b_k((x_j^0,y_j^0),\Theta))$ are the impact parameter dependent electron capture and loss probabilities, respectively. Using the functions, the two probabilities in Eq. (7) were given by

$$F_c(x_i^0,\Theta) = \frac{\sum_{j=1}^{m} Q_c(x_j^0,\Theta)\,\delta(x_i^0 < x_j^0 < x_i^0 + \Delta x)}{\sum_{j=1}^{m} \delta(x_i^0 < x_j^0 < x_i^0 + \Delta x)} \quad (10)$$

and

$$F_s(x_i^0,\Theta) = 1 - \frac{\sum_{j=1}^{m} Q_l(x_j^0,\Theta)\,\delta(x_i^0 < x_j^0 < x_i^0 + \Delta x)}{\sum_{j=1}^{m} \delta(x_i^0 < x_j^0 < x_i^0 + \Delta\, x)}, \quad (11)$$

where m is the number of the exit positions, x_j^0, which was 1000. The Δx shows the window of the position, which was 0.01 times the interplanar distance of the (100) planes. Thus the x_i^0 in Eqs. (10) and (11) and in the right-hand side of Eq. (7) divides the (100) channel into a hundred parts. The denominators are the total numbers of ions which exit at $x_i^0 \sim x_i^0 + \Delta x$ and the numerators are the numbers of the ions which capture electron and loss electron at the surface, respectively.

In Eqs. (8)–(11), only collisions that occur when the ion is in the vacuum are treated. Here, electron capture does not have to occur before electron loss. Thus using Eqs. (10) and (11) in Eq. (7) causes an error due to the electron capture that occurs when H^+ ions are apart from the surface. However, since the electron capture contributes at small impact parameters, most of the electron loss treated here was considered to occur after the electron capture. Examples of the probabilities for $\Theta = 90°$ and 30° are shown in Fig. 6 for 568 keV ions. The survival probabilities are large for the ions exiting from the midplane of the channel and the electron capture probabilities are large for the ions exiting near the plane.

The results of Eq. (6), the normalized neutral fractions modified by the surface scattering, are shown in Fig. 4 by solid lines. Comparison of the solid lines and the dotted lines, i.e., the calculated results without taking into consideration the surface effect, shows that the channeling effect is enhanced by taking into consideration the surface scattering. The calculated result of the angular dependence for $\Theta = 90°$ was sharply structured.

For a comparison of the energy dependence, in order to remove the structural effect of the calculated θ dependence, the dependence was not only calculated at $\theta = 0$, but also calculated for all channeling ions and averaged. The results of the energy dependence of the normalized fraction are shown in Fig. 5. The averaged ones do not differ greatly from those for $\theta = 0$. The calculated results for $\Theta = 90°$ are smaller than those measured. However, the results are not dependent on the energy. For $\Theta = 30°$, the calculated results increase with increasing energy and approach those for $\Theta = 90°$. Thus observed results of the energy dependence of the normalized fraction for the both Θ are well reproduced by this simple calculation.

IV. DISCUSSION

From the comparison of the calculated θ dependence with the measured one as shown in Fig. 4, it is found that the calculated relative neutral fractions were smaller than those measured. This is not the case for $\Theta = 30°$ for all energies of ions treated in this work, which can be seen in Fig. 5. However, the calculated results depend sharply on the angle θ contrary to the measured ones. The disagreement would be caused by the rough model for the trajectory calculation of the channeling ions. In this calculation, the interaction between the ions and target atoms was approximated to be a planar potential and the multiple scattering with the screened nucleus of the target atoms was not treated. However the present epitaxial foils are thick enough for the channeling ions to oscillate several times. Since the multiple scattering during several channeling oscillation smears the exit positions of the detected ions from the foil more than that of the calculated one, the measured neutral fraction could not have a sharp θ dependence.

Although the trajectory calculation was simple, the results

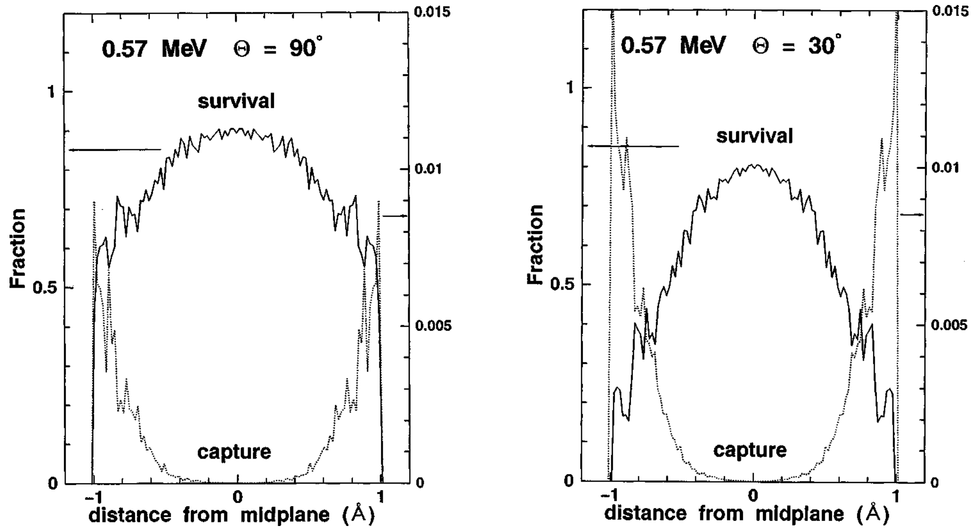

FIG. 6. Examples of the calculated probabilities for the electron capture of H^+ (dashed lines) and the survival of H^0 (solid lines) at the surface. The ion energy is 568 keV. (a) $\Theta=90°$ and (b) $\Theta=30°$.

of the calculation reveal some important information. In Fig. 4 we show by dotted lines the calculated results under the assumption, that the effect of the scattering at the surface is ignored, i.e., $F_c=0$ and $F_s=1$. The dotted lines oscillate around 0.6 for both Θ. Taking the scattering with the surface atoms into consideration, the relative fraction for $\Theta=30°$ decreases more than that for $\Theta=90°$. Therefore, the experimentally observed enhanced channeling effect at $\Theta=30°$ on the relative fraction would be due to the modification by the collisions with surface atoms in the vacuum. Figure 6 shows that the probability for the electron capture at $\Theta=30°$ is large compared with that at $\Theta=90°$, however, the survival probability of H^0 is also small at $\Theta=30°$. This causes the difference between the relative fractions for $\Theta=30°$ and 90°. The final results indicate that the modification at the surface for $\Theta=30°$ is larger than that for $\Theta=90°$.

Both the electron-capture and electron-loss probabilities increase as the ion energy decreases. Thus the modification at the surface for $\Theta=30°$ is expected to be enhanced as the ion energy decreases. While for $\Theta=90°$, the modification is not so significant in this energy range and the surface is regarded as playing no special role, thus the energy dependence of the relative fraction is not expected. Figure 5 shows that the energy dependence observed in the measured normalized fraction can be well approximated by this simple calculation.

We have checked that the calculated results do not change significantly by using other conditions of the parameters of the trajectory calculation. First, we changed the parameters for the dechanneling. Although the relative fraction for both foils decreases with increasing critical distance for the dechanneling, the obtained energy dependence was similar to the present one. In choosing the distance to be twice the present calculation, 1.2 a_{TF}, the both curves fall about 0.1. Secondly, we multiplied the multiple-scattering angle by a factor, because the calculated angle was too small to reproduce the monotone θ dependence of the relative fraction. The increasing multiple-scattering angle caused a decrease in the relative fraction at the lower energy of the foil at $\Theta=30°$. Although we have calculated using a factor of less than 2, the results for the higher energy side of the foil of $\Theta=30°$ and those for the foil of $\Theta=90°$ are conserved.

V. CONCLUSION

Neutral fractions are measured and compared for (0.4–0.8) MeV H^+ ion beams after channeling through two Al epitaxial foils under the (100) channeling condition. The measured neutral fractions exhibit minima at the (100) planar channeling direction. The channeling effect is enhanced for the foil at $\Theta=30°$. The fraction is calculated for the two foils by using the calculated data sets of the position-dependent equilibrium fraction and the position-dependent charge-exchange probabilities between the exit ions and the surface atoms. The measured energy dependence of the relative fraction is reproduced by the calculation. The enhanced effect in the relative fraction measured at $\Theta=30°$ was concluded to be due to the modification by the collisions of ions with surface atoms.

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