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Energy loss of channeled 290 MeV/u C^{6+} ions in a Si crystal

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Abstract

We have succeeded in observing the channeling of 290 MeV/u C^{6+} ions in a Si crystal. Under $\langle 1\,1\,0\rangle$ axial, and $(0\,0\,4)$, $(2\,\bar{2}\,0)$ and $(1\,\bar{1}\,1)$ planar channeling conditions, energy loss of the channeled ion in the Si crystal was observed. We also calculated the trajectory dependent stopping power for planar channeling ions, which employs mean and local electron densities evaluated adopting the Molière potential. Calculated energy loss spectra were found to reproduce the experimental results quite well. © 1998 Elsevier Science B.V.

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1. Introduction

Channeling phenomena and related effects in the energy region below several MeV/u have been extensively investigated [1–5]. However, the study of channeling phenomena with relativistic heavy ions have been scarcely performed. Energy loss of channeling ions is known to be smaller than that of ions for random injection, because the channeling ions move in the space where the target electron density is low. Measuring the energy loss of channeled ions is a general method to study channeling. In the relativistic energy region, however, it is difficult, because the lost energy in the target is much smaller than the incident energy.

We adopted a totally depleted silicon detector (SSD) as a target crystal and measured the deposited energy to it for random injected and several channeling conditions. The experimental results are reported in Section 2. Bethe–Bloch stopping power formula for random injected ions and the stopping power formula for channeling ions are introduced in Section 3. It is noted that the energy deposition to the SSD is a little different from the energy loss in it, because some scattered electrons escape from the target when their ranges are larger than the distance between the collision point and the surface of the target. For high energy ions, the escape probability of energetic electrons increases, and the difference between the energy loss and the energy deposition becomes considerable. The kinematical maximum energy

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of a binary encounter electron amounts to about 0.7 MeV, the range of which in Si is about 1 mm for 290 MeV/u ions. The energy of escaped electrons was simulated, and the result is reported in Section 4.1.

We calculated the trajectory dependent stopping power for planar channeling ions by adopting Lindhard's formula [6] in Section 4.2, and the experimental results are compared with the simulation in Section 5. The relation between the stopping power and the oscillation amplitude of planar channeling ions was obtained from the simulation.

2. Experiment

Channeling experiments with relativistic heavy ions require a beam with a small angular divergence. The critical angle of 290 MeV/u bare C ions for Si ⟨1 1 0⟩ axial channeling is ∼0.45 mrad. We have developed a parallel beam with a single collimator by tuning a series of a doublet and a triplet quadrupole-magnetic lenses located upstream from the collimator. A cylindrical collimator made of iron has a length of 50 mm, and an inner diameter of 1 mm ϕ. A beam divergence as small as 0.15 mrad was achieved in the best condition. To measure the energy loss of the ions in a Si crystal, an SSD was installed on a goniometer as a target crystal, and was used as a detector for energy loss at the same time. The active area of the SSD is 450 mm^2, with the depletion layer of 524 μm. It is noted that the thickness is about half of the maximum range of the binary electrons. We evaluated the energy loss from the energy deposition to the SSD. At 1.5 m downstream from the SSD, a 2-dimentional position sensitive detector (PSD) was placed to measure the angular spread of the transmitted beam. The active area of the PSD is 20 mm × 20 mm. The goniometer can be rotated around three orthogonal axes with a precision of 0.001°.

The crystal orientation was pre-determined by X-ray diffraction with a precision of about 1° in advance. The SSD was rotated around two orthogonal axes by 0.02° (0.35 mrad) steps near the ⟨1 1 0⟩ direction while monitoring signals from the SSD and the PSD. When a planar channeling condition is realized, intensities in the region of lower deposited energy to the SSD and those near the center of the PSD increase simultaneously. Using orientations obtained for several planar channelings, we determined the ⟨1 1 0⟩ axial directions accurately.

The spectra of the deposited energy to the SSD for random, axial and planar channeling conditions are shown in Fig. 1. The peak position of the spectrum for random injection is 11.8 MeV. In the channeling conditions, the spectra consist of two peaks. The peaks in the lower and higher energy regions correspond to channeling and non-channeling ions, respectively. For the ⟨1 1 0⟩ axial channeling, channeling ions are dominant, which appear at 5.8 MeV in the spectrum of energy deposition. For planar channeling cases, non-channeling ions are dominant, because the critical angles of these planar channelings are smaller than that of the ⟨1 1 0⟩ axial channeling. The critical an-

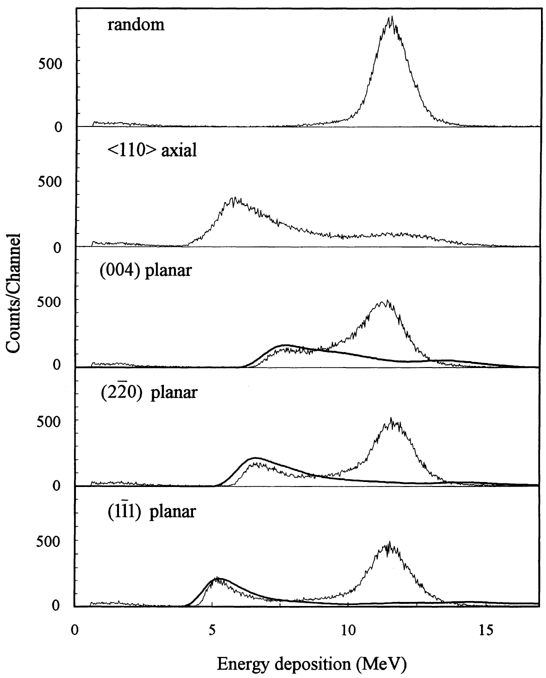

Fig. 1. Spectra of deposited energy to the SSD for random, ⟨1 1 0⟩ axial, (0 0 4), (2 $\bar{2}$ 0) and (1 $\bar{1}$ 1) planar channeling conditions. Thin lines are experimental results, and thick lines are simulations.

gles of (0 0 4), $(2\,\overline{2}\,0)$ and $(1\,\overline{1}\,1)$ planar channelings are 0.09, 0.11 and 0.14 mrad, respectively. It is noted that the positions of non-channeling peaks are slightly different from the random case. The peak positions for (0 0 4), $(2\,\overline{2}\,0)$ and $(1\,\overline{1}\,1)$ planar channeling ions are 7.7, 6.6 and 5.2 MeV, respectively. The shape for planar channeling ions also depends on the selected channeling plane.

3. Theory

The Bethe–Bloch stopping power formula is useful to evaluate the energy loss of fast (but non-relativistic) ions [7,8]. In the case of relativistic ions, some corrections are necessary, in which case, the stopping power formula is given by

$$S_{\mathrm{r}} = \frac{4\pi N Z_1^2 Z_2 e^4}{mv^2}(L_0 + \Delta L_{\mathrm{Bloch}} + \Delta L_{\mathrm{Mott}}), \qquad (1)$$

where N is the atomic density of the target, $Z_1 e$ and $Z_2 e$ are the charges of the projectile and target atom, respectively, m is the electron rest mass, v is the velocity of the projectile,

$$L_0 = \ln\left(2mv^2\gamma^2/I\right) - \beta^2,\ \beta = v/c,\ \gamma = 1\sqrt{1-\beta^2},$$

and I is the mean ionization energy of the target atom. The second term is the Bloch correction term, and the last term is originated in adopting the Mott cross section instead of the Rutherford cross section [9,10]. In the present case, the contributions of $\Delta L_{\mathrm{Bloch}}$ and ΔL_{Mott} to the total stopping power are ~0.07% and ~0.5%, respectively, and these correction terms are small enough to be neglected.

The stopping power can be divided into two parts. One part corresponds to close collisions, and the other is originated from the plasma resonance by distant collisions. The equipartition rule suggests that the contributions of these two parts are equal [11], and the half of $-\beta^2$ term in L_0 is originated in distant collisions, and the other half is from close collisions.

Channeling ions pass through the space where the electron density is low, and the energy loss of them is smaller than that of ions for random injection. Lindhard proposed a position dependent stopping power formula, which is given by

$$S(r) = S_{\mathrm{r}}\left[(1-\alpha) + \alpha\frac{n_{\mathrm{e}}(r)}{Z_2 N}\right], \qquad (2)$$

where S_{r} is the random stopping power, $n_{\mathrm{e}}(r)$ is the electron density at position r, and α is a fraction of the contribution from close collisions, which is $1/2 \leqslant \alpha \leqslant 1$. Lindhard proposed that α is close to 1/2 at very high velocity [6]. The first and second terms in Eq. (2) correspond to the contributions from distant and close collisions, respectively. The contribution from close collisions depends on the local electron density. On the other hand, the contribution from distant collisions is expected to be independent of the ion trajectory, because an effective impact parameter of the distant collision is ~10 Å, which is larger than the interplanar distance particularly in the present experimental conditions. Therefore, adoption of Eq. (2) is considered to be meaningful. We have analyzed the observed stopping power of planar channeling ions employing Eq. (2).

4. Simulation

4.1. Energy of escaped electrons from SSD

The experimental value of the energy deposition for random orientation is 11.8 MeV, compared with 12.84 MeV, the prediction of Eq. (1). In such high energy cases, effects of pulse height defect originated in the recombination of electron–hole pairs are small enough to be neglected. The difference between these values is ~1 MeV, which may be mainly attributed to escape of energetic electrons. To evaluate the amount, Monte Carlo simulation was performed in the following manner.

A path length of the incident ion between collisions, a scattering angle and a received energy of the scattered electron are given at random. The decrease of the ion energy is neglected, because the energy loss is ~0.4% of the incident energy. The collision cross section we adopted is the Rutherford cross section with relativistic correction, which is given by

$$\frac{d\sigma}{dT} = \frac{2\pi Z_1^2 e^4}{mv^2 T^2}\left(1 - \frac{\beta^2 T}{2mv^2\gamma^2}\right), \tag{3}$$

where T is an energy transfer to an electron. When the extrapolated range of the electron $R(E)$ with recoil energy E is larger than the distance l from the collision point to the surface of the SSD, the electron is assumed to escape from the SSD with an energy $E_{\rm out}$, which is given by

$$R(E_{\rm out}) = R(E) - l. \tag{4}$$

The sum of $E_{\rm out}$ for electrons per ion corresponds to the difference $E_{\rm r}$ between the energy loss and the energy deposition for the random case.

The result of the simulation is shown in Fig. 2. The peak positions of simulated energy loss and energy deposition are 13.26 and 12.70 MeV, respectively, and the difference is 0.56 MeV. The simulated energy loss is a little larger than the value 12.84 MeV obtained from Eq. (1). Here, all processes of energy transfer are assumed as binary collisions. As a result, the total energy loss is not very accurate, however, the value of 0.56 MeV derived by this simulation is reliable, because the escaped electrons are produced only by close collisions. It is then concluded that the energy deposition is 12.28 MeV, which is comparatively close to the experimental value.

The FWHM for the experimental energy deposition for the random case is ∼1.4 MeV, and is a little larger than that for simulated energy deposition of ∼1.1 MeV. The reason is possibly the influence of the fragments of C ions produced by collisions with the collimator. In the simulation, the FWHM for the energy deposition is narrower than that for the energy loss. An average number of escaped electrons is 2.2 per ion. It is interesting to note that a small number of electrons with high energies escape from the target, which effectively reduces the energy straggling, and accordingly improves the energy resolution of SSD.

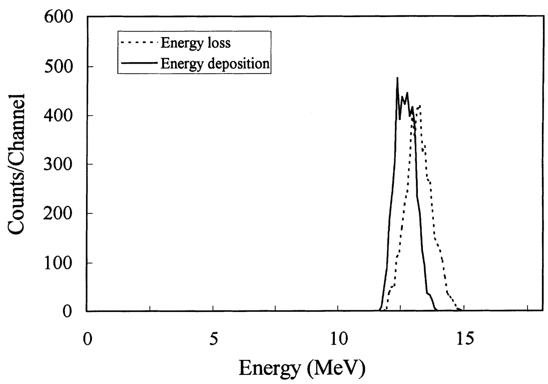

Fig. 2. Spectra of simulated energy loss (dotted line) and energy deposition (solid line) for the random direction.

4.2. Energy loss of planar channeling ion

Planar channeling ions move in the space between two planes with various trajectories. The stopping power for planar channeling ions depends on the trajectory. Trajectories of channeling ions are calculated solving the Newton equation for the Molière potential. Dechanneling effect is not taken into account in this simulation. A stopping power for a trajectory can be obtained by integrating the local stopping power along the trajectory. In the present condition, the number of oscillations is more than 100, which was estimated from the critical angle of channeling. Therefore, the stopping power of channeling ions can be approximated to that for one oscillation. According to Eq. (2), an effective electron density $\overline{n_{\rm e}^*}(z_{\max})$ along the trajectory with an oscillation amplitude $z_{\max}$ is defined as

$$\overline{n_{\rm e}^*}(z_{\max}) \equiv (1-\alpha)Z_2N + \alpha\overline{n_{\rm e}}(z_{\max}), \tag{5}$$

where $\overline{n_{\rm e}}(z_{\max})$ is the average electron density along the ion trajectory, and is written as

$$\overline{n_{\rm e}}(z_{\max}) = \frac{4}{T_{\rm osc}}\int_0^{z_{\max}} \frac{n_{\rm e}(z)}{v_\perp(z)}\,dz, \tag{6}$$

where $T_{\rm osc}$ is the period of the oscillation, and $v_\perp(z)$ is the ion velocity perpendicular to the planar channel at position z. For a fixed trajectory, we can calculate the energy loss and the energy straggling employing Eq. (5) and can obtain the energy loss spectrum of the channeling ion. The spectrum of each trajectory is represented by the Gaussian distribution, because the number of collisions is sufficiently large. The energy loss spectrum of the planar channeling ions is constructed with energy loss spectra of the ions for various trajectories.

The parameter α, which is the fraction of the contribution from close collisions, is determined so that the peak position of the spectrum for the channeling ions agrees with the experimental result.

5. Results and discussion

We calculated the energy of escaped electrons for random injection, E_r, by the Monte Carlo simulation in Section 4.1. For channeling ions, the contribution from close collisions to the stopping power is less than that for random cases, and the probability of production of energetic electrons which escape from the SSD is reduced. The energy of escaped electrons for channeling condition E_c is considered to be proportional to the average electron density along the trajectory, which is estimated to be $E_c \sim (\overline{n_e}(z_{\max})/Z_2N)E_r$. The value of E_c should be subtracted from the simulated energy loss value for each trajectory.

The spectra which are drawn by thick lines in Fig. 1 are the results of the simulation. The values of α are ~0.69, ~0.70, and ~0.76 for (0 0 4), (2 $\bar{2}$ 0) and (1 $\bar{1}$ 1) planar channelings, respectively. These values are larger than 1/2, and depend on the interplanar distance. The peak for non-channeling ions does not appear, because the dechanneling effect is not included in the simulation. The components in the tail to higher energy region are channeled ions with quite large oscillation amplitudes and those passed across the crystal planes. If the dechanneling effect is taken into account, these components will form the large peak at the position for random injected ions, which are actually observed in the experiment. The widths of the peak for channeling ions, which depend on channeling planes, are reproduced by the simulation quite well. As α are determined, the relations between the stopping power of channeling ions and the oscillation amplitude for several planar channelings were obtained, which are shown in Fig. 3. Interplanar distances for (0 0 4), (2 $\bar{2}$ 0) and (1 $\bar{1}$ 1) plane of a Si crystal are 1.36, 1.92 and 3.14 Å, respectively. The stopping power gradually increases with the growth of the oscillation amplitude near the channel center. When the amplitude approaches to half of the interplanar distance, the stopping power increases rapidly, and exceeds the random stopping power, that is 245 MeV/cm.

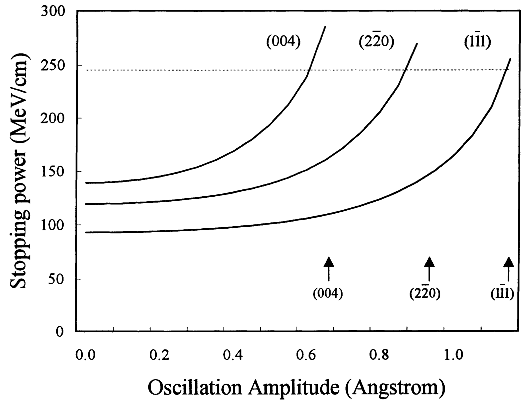

Fig. 3. Relations between stopping power and oscillation amplitude for (0 0 4), (2 $\bar{2}$ 0) and (1 $\bar{1}$ 1) planar channeling 290 MeV/u C^{6+} ions. Dotted line indicates random stopping power, and arrows indicate positions of channel walls.

We calculated the stopping power of channeling ions by Eq. (2), which is comparatively simple. The formula does not include the crystal lattice structure. However, the experimental results were reproduced quite well by employing the fitting parameter α. Esbensen and Golovchenko [12] derived a stopping power formula for channeling ions. Their formula includes the correction term $C(\boldsymbol{b})$, which depends on the impact parameter $\boldsymbol{b}$. Impact parameter dependent stopping power for channeling ions was investigated also by other groups [13,14]. Crawford and Nestor, Jr. calculated the stopping power more accurately, and their formula can be applied to high-Z crystals. Esbensen et al. [15] have shown that the correction term $C(\boldsymbol{b})$ is substantial even for 15 GeV/c protons and pions. We are developing the simulation program which takes into account the correction term $C(\boldsymbol{b})$ at present.

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