Transmission of Fast Protons through Si Single Crystals

By

Kazuho SONE* and Fumio FUKUZAWA**

(Received March 31, 1972)

Abstract

Transmission of 3.0 MeV protons through Si single crystal foil has been studied. From the energy spectra of transmitted protons, stopping powers of Si along <111> axis and {110} plane have been found to be 0.54 and 0.65 times that of random direction, respectively. Photographs of the transmission patterns observed on a ZnS screen are shown, and some interesting features are pointed out.

1. Introduction

Transmission of charged particles through thin crystals is one of the interesting experiments of channeling. Many experiments have been made on the detailed energy loss spectrum[1~35]. Reviews of this subject have been given by Datz *et al.*[36] and Nelson[37]. It has well been established that when the ions are incident parallel to the channeling direction the energy loss due to electronic stopping is smaller than that in amorphous medium. The specific energy loss along the channeling direction becomes approximately 50% of normal one[1,2,5,7,9,11~13,18,30,37]. This effect is larger in axial channeling than in planar channeling. Planar channeling, however, is easier for theoretical treatment due to the capability of reduction to two-dimensional problem, and series of extensive studies on planar channeling have been made by Datz *et al.* and Robinson *et al.*[7,20,24,33,34,35,38].

In this paper, is reported the experiment on the energy spectra of protons transmitted through Si single crystal foil in the direction of <111> and {110} channels, and are shown the photographs of the transmission patterns observed on a ZnS screen.

* Institute of Atomic Energy, Kyoto University.
** Department of Nuclear Engineering.

2. Experimental Procedures

Fig. 1 shows schematically the experimental arrangement. Monoenergetic beams of H^+ or H_2^+ ions were obtained from the Van de Graaff accelerator of Kyoto University. These beams were collimated to reduce the angular spread to less than 0.05° by using two identical two-dimension-slits which were two meters apart. The opening of the slit 1 and silt 2 were finally adjusted to be $1\times1\,mm^2$ and $0.5\times0.5\,mm^2$, respectively. The movable slit 3 having the aperture of 0.2 mm in diameter was placed at 5 cm in front of the target, and was used to adjust the beam current on the target. A Si single crystal foil with specific resistance of 1000 Ω·cm was mounted on a goniometer which has two independent angular variables (θ, ϕ) with accuracy of 0.025°. Two solid-state detectors, SSD 1 and SSD 2, were used to detect the transmitted protons (0°) and the back-scattered protons (135°), respectively. SSD 2 was a monitor detector for the incident ion beam. SSD 1 has a vertical slit of width 0.5 mm. The energy resolution of the detecting system was approximately 30 keV. Energy spectra for transmitted and back-scattered protons were analysed with a 256-channel pulse-height-analyzer (PHA). The accurate orientation of the single crystal target with respect to the incident beam axis was determined by measuring the variation of the yield of transmitted protons for the continuously varied angle of rotation ϕ. The noise-level of the measuring system was approximately 20 keV. The scattering chamber and the beam duct were evacuated to pressure of 8×10^{-7} Torr and 2×10^{-6} Torr, respectively.

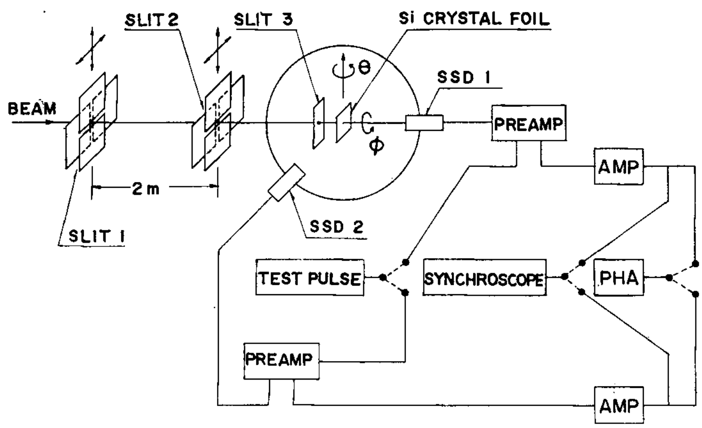


Fig. 1. Experimental arrangement.

In case of observation of the transmission patterns, SSD 1 was removed and a ZnS screen with diameter of 40 mm was placed at the glass window of the scattering chamber. The ZnS screen was about 20 cm apart from the crystal foil. Transmission patterns on the ZnS screen were observed through the glass window and photographed with ASA 100 films under f=1.8 and an exposure time of 20 sec.

The effective area of the Si single crystal foil was approximately $5\times5\ mm^2$, and the crystal surface was almost parallel to a {111} plane. In order to make a thin crystal foil, we used the surface etching technique as shown below. The mixture of two kinds of acid HNO_3 and HF with the ratio of 5:3 was cooled to 0°C. A thick Si single crystal was put into this etching solution, and was taken out after 1~2 min. As the crystal must not be exposed to the air in the midst of etching, the etched crystal was washed in the purified water as soon as possible. It is recommended to agitate slowly the etching solution in order to prevent the sticking small voids on the crystal surface. The etching solution after use is colored light brown, and must not be used for mirror polishing of the crystal. It is important to renew the etching solution frequently.

In order to make a thin crystal foil with a firm frame, the following method was tried. First, a slice of a silicon crystal of about 0.5 mm thick was processed by mirror polishing on both sides. This polished slice was stuck to a teflon plate with melted paraffin on the fringe of the slice (Fig. 2 a)), and was steeped in the etching solution. In this way a target foil of about 5 mm in diameter with a firm frame was easily made. Paraffin is removed completely by a bath of the boiling ethanol.

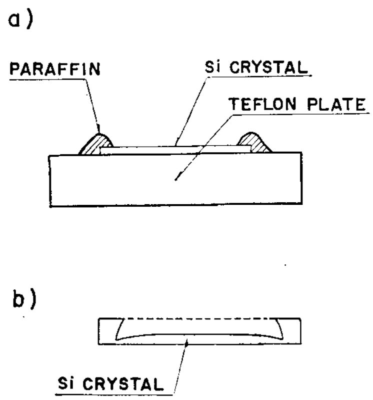


Fig. 2. Production of a thin crystal foil with a firm frame.

3. Results

Fig. 3 b) shows the energy spectra of transmitted protons whose incident

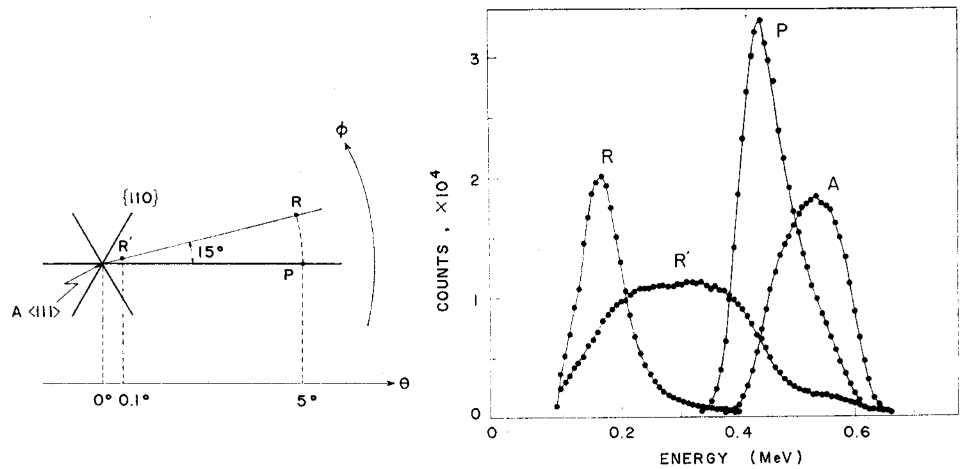


Fig. 3. Energy spectra of transmitted 1.0 MeV protons through the Si crystal foil.

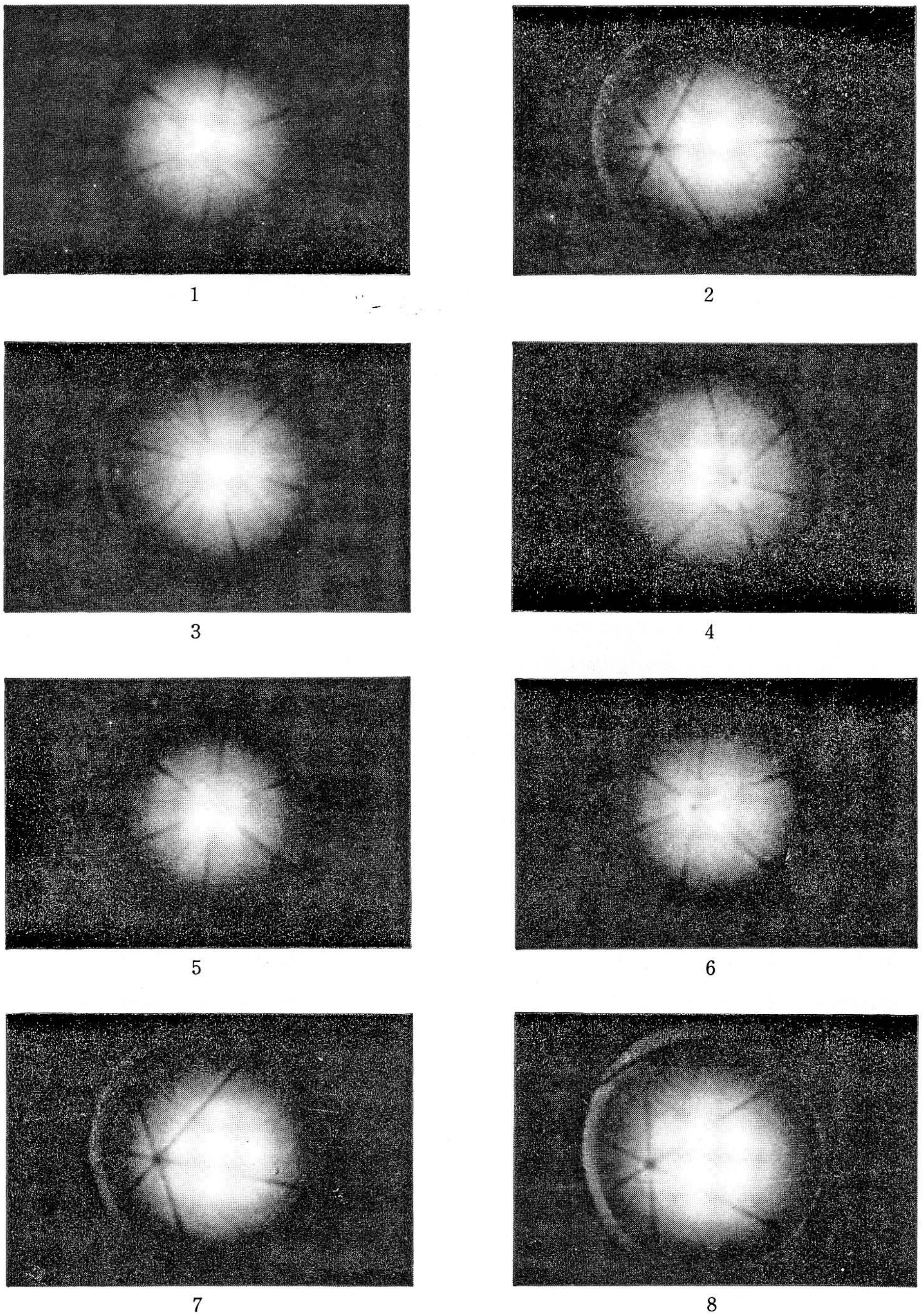
energy was 1.0 MeV, and whose angles of incidence were given in Fig. 3 a). The directions of the incident beam were parallel to the <111> axis for A and to the {110} plane for P. On the other hand, R corresponds to the random incidence, and R′ to the slightly inclined direction to the <111> axis. As was expected, energy loss at A is the smallest of all directions. Energy losses ΔE_A, ΔE_P and ΔE_R are given as follows:

$$E_A = S_A d = 0.46 \text{ (MeV)}$$
$$E_P = S_P d \sec 5.0° = 0.56 \text{ (MeV)}$$
$$E_R = S_R d \sec 5.0° = 0.86 \text{ (MeV)},$$

where d is the thickness of the crystal foil, and S_A, S_P and S_R are stopping powers of Si crystal for 1.0 MeV protons at A, P and R directions, respectively. From these equations we obtain $S_A/S_R = 0.54$ and $S_P/S_R = 0.65$. By using $S_R = 43.5$ (keV/μm), we obtain $S_A = 23.5$ (keV/μm), $S_P = 28.3$ (keV/μm) and $d = 20\ \mu$m.

Transmission patterns of 3.0 MeV protons observed on the ZnS screen, are shown in Photos. 1-8. In these photographs, the part of high density of transmitted protons become white. Therefore, channeling lines are white, while blocking lines are dark. Each photographs were taken under the following conditions as for the incident direction of proton beam.

Photo. 1 : parallel to the <111> axis,
Photo. 2 : 2.2° to the <111> axis and parallel to the {110} plane,
Photo. 3 : 0.2° to the <111> axis and parallel to the {110} plane,
Photo. 4 : 0.9° to the <111> axis and parallel to the {110} plane,



Photos. Transmission patterns. For the incident direction, see text.

Photo. 5 : 0.4° to the $\langle 111 \rangle$ axis and off the {110} plane,
Photo. 6 : 0.8° to the $\langle 111 \rangle$ axis and off the {110} plane,
Photo. 7 : random direction,
Photo. 8 : parallel to {112} plane.

It is clearly seen in Photo. 1 that the axially channeled spot has a sixfold symmetry corresponding to leakage of protons into six {110} planar channels. When the angle of incidence is increased, the axially channeled spot fall out in its center region and becomes a white ring with radial streamers of leakage (Photos. 5 and 6). And, finally, axial and planar blocking appear as a dark spot and dark lines on the background of random protons (Photos. 2, 7 and 8). In this case, white lines are apparently observed on the one side of dark lines.

4. Discussion

Since the random component results from a series of statistically independent deflections of the incident protons, energy and angular distributions of this component are expected to be Gaussian type. We find from Fig. 3 b) that the energy spectrum at R is not pure Gaussian. This deviation is mainly due to the channeled component through {110} channels, which could not be rejected by our vertical slit of SSD 2. Fortunately, the contribution of this channeled component is not so large as to shift the peak position of the energy spectrum. On the other hand, the energy spectrum at R′ contains too many components to be analyzed. In order to obtain the significant information about energy spectrum in this direction, a pin-hole slit, for example, is necessary to define distinctly the outgoing direction.

As for transmission patterns, there are many interesting features to be considered. Leakage of axially channeled protons to planar channels and spreading of the planar channeled protons along that plane should give the valuable information about the motion of channeled protons. The ring spot obtained in case of small incident angle to the $\langle 111 \rangle$ direction may be explained by considering the motion of incident protons in an approximately cylindrical potential[39]. Asymmetrical white-dark contrast observed in planar blocking raise the problems on the random-to-channel transition. Before to treat these problems quantitatively, one must measure the energy and angular distribution of transmitted particles at every local positions on the patterns.

Acknowledgements

We would like to thank Messrs. K. Ohnishi and T. Yada for help with the

experiments.

References

1) C. Erginsoy, H. E. Wegner and W. M. Gibson : Phys. Rev. Letters, **13**, 530 (1964).
2) A. R. Sattler and G. Dearnaley : Phys. Rev. Letters, **15**, 59 (1965).
3) S. Datz, T. S. Noggle and C. D. Moak : Phys. Rev. Letters, **15**, 254 (1965).
4) S. Datz, T. S. Noggle and C. D. Moak : Nucl. Instrum. Methods, **38**, 221 (1965).
5) W. M. Gibson, C. Erginsoy, H. E. Wegner and B. R. Appleton : Phys. Rev. Letters, **15**, 357 (1965).
6) B. W. Farmery, R. S. Nelson, R. Sizmann and M. W. Thompson : Nucl. Instrum. Methods, **38**, 231 (1965).
7) H. O. Lutz, S. Datz, C. D. Moak and T. S. Noggle : Phys. Rev. Letters, **17**, 285 (1966).
8) G. F. Hamilton and A. R. Quinton : Phys. Letters, **22**, 312 (1966).
9) F. H. Eisen : Phys. Letters, **23**, 401 (1966).
10) C. D. Moak, H. O. Lutz, L. B. Bridwell, L. C. Northcliffe and S. Datz : Phys. Rev. Letters, **18**, 41 (1967).
11) A. R. Sattler and G. Dearnaley : Phys. Rev., **161**, 244 (1967).
12) B. R. Appleton, C. Erginsoy and W. M. Gibson : Phys. Rev., **161**, 330 (1967).
13) M. Mannami, F. Fujimoto and K. Ozawa : Phys. Letters, **26A**, 201 (1968).
14) E. S. Machlin, S. Petralia, A. Desalvo, G. F. Missiroli and F. Zignani : Nuovo Cimento, **55B**, 263 (1968).
15) E. T. Shipatov and B. A. Kononov : Atomnaya Energiya, **25**, 439 (1968).
16) W. M. Gibson, J. B. Rasmussen, P. Ambrosius-Olesen and C. J. Andreen : Canad. J. Phys., **46**, 551 (1968) ; Canad. J. Phys., **47**, 1756 (1969).
17) F. H. Eisen : Canad. J. Phys., **46**, 561 (1968).
18) G. Dearnaley, I. V. Mitchell, R. S. Nelson, B. W. Farmery and M. W. Thompson : Phil. Mag., **18**, 985 (1968).
19) L. T. Chadderton and F. H. Eisen : Phil. Mag., **20**, 195 (1969).
20) S. Datz, C. D. Moak, T. S. Noggle, B. R. Appleton and H. O. Lutz : Phys. Rev., **179**, 315 (1969).
21) F. W. Martin : Phys. Rev. Letters, **22**, 329 (1969).
22) M. Kaminsky : Phys. Rev. Letters, **23**, 819 (1969).
23) F. Fujimoto, K. Komaki, K. Ozawa, M. Mannami and T. Sakurai : Phys. Letters, **29A**, 332 (1969).
24) S. Datz, C. D. Moak, B. R. Appleton, M. T. Robinson and O. S. Oen : Proc. Intern. Conf. Atomic Collision Phenomena in Solids, Brighton, ed D. W. Palmer, M. W. Thompson and P. D. Townsend (North-Holland Publishing Co., Amsterdam, 1970) p. 374.
25) G. J. Clark, D. V. Morgan and J. M. Poate : *ibid*, p. 388.
26) L. T. Chadderton and F. G. Krajenbrink : *ibid*, p. 456.
27) B. A. Kononov and V. K. Struts : Soviet Phys.-Solid State, **11**, 2994 (1970).
28) M. R. Altman, H. B. Dietrich and R. B. Murray : Phys. Letters, **32A**, 423 (1970).
29) H. O. Lutz, S. Datz, C. D. Moak and T. S. Noggle : Phys. Letters, **33A**, 309 (1970).
30) M. R. Altman, L. C. Feldman and W. M. Gibson : Phys. Rev. Letters, **24**, 464 (1970).
31) E. S. Machlin, S. Petralia, A. Desalvo, R. Rosa and F. Zignani : Phil. Mag., **22**, 101 (1970).
32) H. O. Lutz, R. Ambros, C. Mayer-Böricke, K. Reichelt and M. Rogge : Z. Naturforsch., **26a**, 1105 (1971).
33) B. R. Appleton, S. Datz, C. D. Moak and M. T. Robinson : Phys. Rev. B, **4**, 1452 (1971).

34) F. H. Eisen and M. T. Robinson : Phys. Rev. B, 4, 1457 (1971).
35) M. T. Robinson : Phys. Rev. B, 4, 1461 (1971).
36) S. Datz, C. Erginsoy, G. Leibfried and H. O. Lutz : Ann. Rev. nucl. Sci., **17**, 129 (1967).
37) R. S. Nelson : The Observation of Atomic Collisions in Crystalline Solids (North-Holland Publishing Co., Amsterdam, 1968), Chap. 4, p. 32-168.
38) M. T. Robinson : Phys. Rev., **179**, 327 (1969).
39) R. von Jan : Phys. Stat. Sol., **29**, 755 (1968).

Errata: Transmission of Fast Protons through Si Single Crystals, Kazuho Sone and Fumio Fukuzawa (Memoirs of the Fuculty of Engineering, Kyoto Univ., 34, Part 3, 325 (1972))

(i) Photos.: Turn upside down Photos. 1 and 4. And then interchange 1 and 5 labels.

(ii) The expression "$E_A=S_A d=\cdots\cdots$, $E_P=\cdots\cdots$, $E_R=\cdots\cdots$" on page 328 (i. e., the seventh line from the top) should read "$\Delta E_A=\cdots\cdots$, $\Delta E_P=\cdots\cdots$, $\Delta E_R=\cdots\cdots$"