

Radiation Damages in Silicon Surface Barrier Detectors with 0.5-1.5 MeV Electrons

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(Received August 23, 1972)

The radiation damages in surface barrier detectors with 0.5-1.5 MeV electrons were investigated. The detectors were fabricated from phosphorus-doped silicon crystals with a resistivity between 200 and 5000 Ωcm . The changes in the forward and reverse currents, the junction capacitance, the ^{241}Am alpha spectrum, and their annealing behaviors were measured.

The junction capacitance decreases monotonically with fluence and at high fluence is independent of reverse bias. The spectra of ^{241}Am alpha are degraded by the increase of the fluence. The shift of the peak channel to the lower energy side is observed. The detector with the low resistivity substrate is more stable against the irradiation. At high fluence, the particles incident on the rear ohmic contact become to be detected at low reverse bias. The degradation of the detectors begins to occur, when they are subjected to the irradiation of 0.5-1.5 MeV electrons in the range of 1×10^{14} to $1 \times 10^{15}/\text{cm}^2$.

The damage center has an acceptor-type property and acts as a trapping center for the carriers created by incident particles. The formation rate of this acceptor-type center is in the range of 0.3×10^{-3} to $1.5 \times 10^{-3}/\text{cm}$. Annealing behavior of this center is not observed clearly up to 220°C and the center should be considered as the divacancy. By removing the irradiated surface region of the detectors, the detectors were fabricated again and the damage distribution in depth was observed.

1. Introduction

The radiation damages in silicon surface barrier detectors caused by energetic electrons were investigated to determine the life of the detectors under the energetic electron environment, to identify the defects, and to survey the possibility to apply the effect of radiation damages to electronic devices.

The detectors were made from floating-zoned silicon crystals doped with phosphorus having resistivities in the range of 200-5000 Ωcm . The thickness of the sample was 350-950 μm . The Au evaporated sensitive area of 5mm in diameter was uniformly irradiated at room temperature in a vacuum with the 0.5-1.5 MeV electron beam with the incident area of 25mm in diameter. The radiation damages in the

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detectors changed the characteristics of the forward and reverse currents, junction capacitance, and ^{241}Am alpha spectrum.

From these measurements, the effect of the radiation damages in the detectors were observed, which is dependent on the incident electron energy and fluence, and on the resistivity of the sample. The damage rate, or the formation rate of the acceptor-type damage center was calculated from the decrease of the junction capacitance which is dependent on the electron fluence. To investigate the possibility to recover the damaged detectors, the detectors were annealed in air in a temperature range of 100 to 220°C. Some of the damaged detectors were fabricated again by etching out the damaged surface and the damage distribution in depth was observed.

2. Experimental Methods

The detectors were irradiated at room temperature (23°C) with energetic electrons from the Van de Graaff accelerator (VE-20) in Kyoto University. In order to obtain the uniform irradiation on the detector, the beam from the accelerator was scattered by a thin Al foil located over the detector about 30 cm. The scattered beam, passing through a circular slit of 10 mm in diameter, was incident on the Au layer of the detector with the area of 25 mm in diameter. The irradiation rate was 1×10^{12} – $4 \times 10^{12}/\text{cm}^2\cdot\text{s}$ and the total fluence on the detector 7×10^{18} – $4 \times 10^{19}/\text{cm}^2$.

After the irradiation, the detector was taken away from the chamber and annealed at room temperature for about two hours. The forward current-voltage (I_F -V), reverse current-voltage (I_R -V), capacitance-voltage (C-V) characteristics, and ^{241}Am alpha spectrum were measured with the same method as mentioned in a previous work¹⁾. Isochronal annealing effects (10 min) of C-V characteristics and alpha spectra were measured in the temperature range of 100 to 220°C in air. Some of the degraded detectors could be survived by etching away the front Au layer (7 to 380 μm in depth) and evaporating Au again to prepare a new surface barrier.

3. Results and Discussions

The I_F -V characteristics changed by the irradiation as to increase the bulk resistivity of the detector. This is explained from the fact that induced defects introduce electron and/or hole trap-levels in the forbidden gap of silicon²⁾ and serve to convert the *n*-type property to the intrinsic-like one³⁾.

The change of I_R -V characteristics was very complicated as mentioned in the previous work¹⁾. The I_R -V change due to the electron irradiation differs from the one induced by the heavy ion irradiation in which I_R at a constant reverse bias increases monotonically with fluence⁴⁾. This difference may be ascribed to the damage density and its distribution in depth in the detector¹⁾.

The change of C-V characteristics was more drastic than that in the previous work. By use of the uniform irradiation on the sensitive area, the damaged area distribution in the parallel direction to the sensitive surface was almost uniform. So the capacitance value will give the informations from the uniformly depleted depth. The C-V characteristics

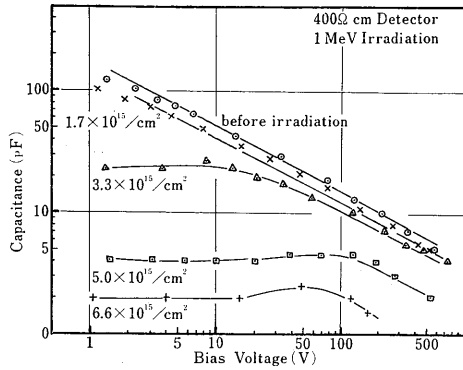


Fig. 1 Capacitance-voltage characteristics of a 400Ωcm detector irradiated with 1 MeV electrons with various fluences.

800 kHz, the capacitance value has almost no dependence on the frequency. This frequency dependence of the junction capacitance is concerned with the relaxation time of the traps induced by the irradiation^{6,7}). At low frequency, the trapped charge can follow the frequency and the capacitance behaves as if the density of the traps was low. At high frequency, the trapped charge cannot move and almost all the traps will contribute to the capacitance value. We chose the frequency of 800 kHz.

The change of the capacitance is closely related to the initial resistivity of the detector as seen in Fig. 2. If the initial resistivity is higher, the change of the capacitance occurs at lower fluence. For example, at the 1 MeV irradiation, the capacitance value begins to decrease below $1 \times 10^{14}/\text{cm}^2$ for 5000Ωcm detectors and above $1 \times 10^{15}/\text{cm}^2$ for 200Ωcm detectors.

The change of the capacitance is also related to the incident electron energy. As seen in Fig. 3, the change of the capacitance begins at lower fluence, when the incident energy is higher. The decrease of the capacitance with 1.5 MeV electrons occurs at a decade lower fluence compared with the one by 0.5 MeV electrons*. From Fig. 1 to Fig. 3, the capacitance value tends to decrease monotonically with fluence, so the induced damages introduce acceptor-type defects which compensate the initial phosphorus donor ions.

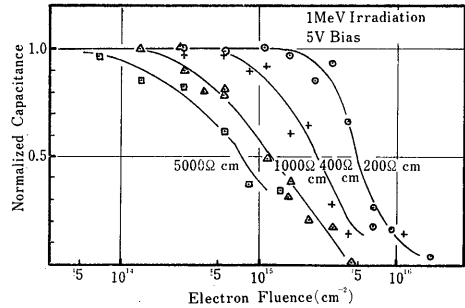


Fig. 2 Normalized capacitance of 200-5000 Ωcm detectors irradiated with 1 MeV electrons against fluence. Normalized capacitance is defined as the ratio of the irradiated capacitance at 5 V bias to the unirradiated one at 5 V bias.

*In the previous work¹⁾, the similar behavior of the capacitance was observed, but the change occurred at higher fluence region. The difference is attributed to *local irradiation* in the previous work and the *uniform irradiation* at present. The slight change of the capacitance in the locally irradiated region could not contribute to separate the capacitance curve from the curve of the unirradiated detector as in Fig. 5 of Ref. 1, and so the change of the normalized capacitance did not occur until the irradiation of higher fluence.

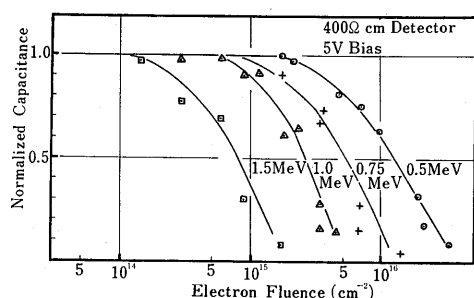


Fig. 3 Normalized capacitance of 400 Ω cm detectors irradiated with 0.5–1.5 MeV electrons against fluence. Normalized capacitance is defined as in Fig. 2.

From the parallel region at high bias of the C-V curves in Fig. 1, we calculated the produced acceptor density as a function of fluence. The formation rate of acceptor type defects per an incident electron was deduced. The values calculated are shown in Tab.1 for 200–1000 Ω cm detectors and for 0.5–1 MeV irradiations. The defect formation rate, or the damage rate, is in the range of $0.3 \times 10^{-3}/\text{cm}$ to $1.5 \times 10^{-3}/\text{cm}$ and 1 MeV electrons have larger damage rate than 0.5 and 0.75 MeV electrons. According to the

table, the damage rate is almost independent of the resistivity. The damage centers introduced by electrons are known as the E center (vacancy-phosphorus), A center (vacancy-oxygen), and divacancy²⁾. If the E center is dominant, the damage rate must have a linear relation with the donor density or must be reciprocally proportional to

Tab. 1 Damage rates calculated from C-V curves as in Fig. 1 for the detector resistivities of 200–1000 Ω cm and for the irradiated electron energies of 0.5–1 MeV.

Energy (MeV)	Resistivity (Ω cm)	Fluence (cm^{-2})	Acceptor Type Damage Rate (cm^{-1})
1.0	200	2.49×10^{15}	1.45×10^{-3}
		4.42×10^{15}	1.40
		8.83×10^{15}	0.93
	400	1.66×10^{15}	0.76
		2.21×10^{15}	0.68
		3.31×10^{15}	0.74
	1000	1.11×10^{15}	1.15
		1.66×10^{15}	0.96
		2.21×10^{15}	1.10
0.75	200	3.32×10^{15}	1.53
		6.64×10^{15}	0.98
		1.32×10^{16}	0.81
	400	1.66×10^{15}	0.43
		3.35×10^{15}	0.82
		6.64×10^{15}	0.59
	1000	1.11×10^{15}	0.54
		1.38×10^{15}	1.35
		1.66×10^{15}	1.35
0.50	200	8.84×10^{15}	0.68
		1.77×10^{16}	0.51
		3.54×10^{16}	0.34
	400	1.11×10^{15}	0.38
		2.21×10^{15}	0.58
		4.42×10^{15}	0.37
	1000	1.11×10^{15}	1.17
		2.21×10^{15}	0.76
		4.42×10^{15}	0.54

the resistivity⁸⁾. For example, the damage rate of 200 Ωcm detectors must be multiplied by the factor of five to the damage rate of 1000 Ωcm detectors. This tendency cannot be seen in the table, so the E center is not dominant. As described later, at the annealing stage of 138°C, considered to be related to the E center, the recovery of the capacitance curve and alpha spectra is small and even at 220°C, the annealing effect is not obvious. So the damage center produced by the irradiation is almost the A center or the divacancy.

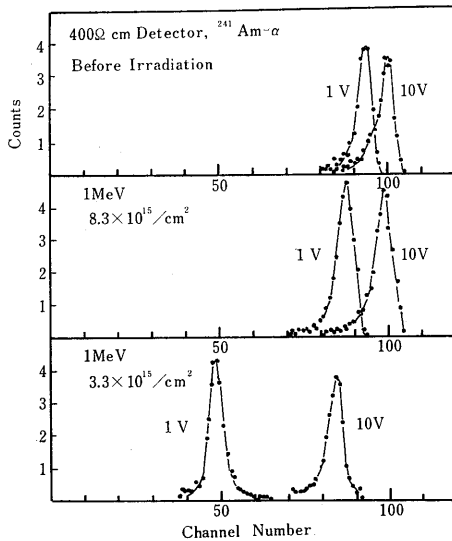


Fig. 4 ^{241}Am alpha spectra of a 400 Ωcm detector at 1 V and 10 V bias irradiated with 1 MeV electrons. The channels below or above the alpha peaks have no appreciable peaks.

The degradation of ^{241}Am alpha spectrum by the irradiation is shown in Fig. 4. The double peaking phenomena observed in the previous work and Liu and Coleman⁹⁾ do not appear in the case of the uniform irradiation. It was concluded that the double peaking effect is composed of two spectra: the defect spectrum from the damaged area and normal spectrum from the undamaged area. At the present experiment, the sensitive area is uniformly damaged, so only the defect spectrum is observed. The peak channel of ^{241}Am alpha shifted to the lower channel by the irradiation as in Fig. 5. The high resistivity detectors are degraded more rapidly and the degradation is faster by the irradiation of higher energy electrons. These tendencies are similar to the phenomena occurred in C-V characteristics. The shift of the peak channel is contributed by two origins: the one is due to that the rise time of the output pulse from the preamplifier becomes long and the other is because the pulse height becomes low. The former means that the field intensity near the surface is lowered or the series resistance near the surface becomes large. The latter means that the trapping effect of the created carriers becomes large.

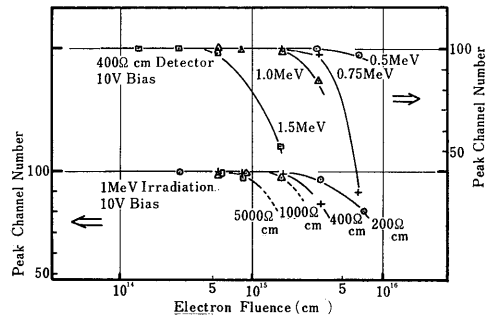


Fig. 5 Alpha peak channel shift against electron fluence. Upper curves show the peak channel shifts of 400 Ωcm detectors at 10V bias irradiated with 0.5–1.5 MeV electrons. Lower curves show the shifts of 200–5000 Ωcm detectors at 10 V bias irradiated with 1 MeV electrons.

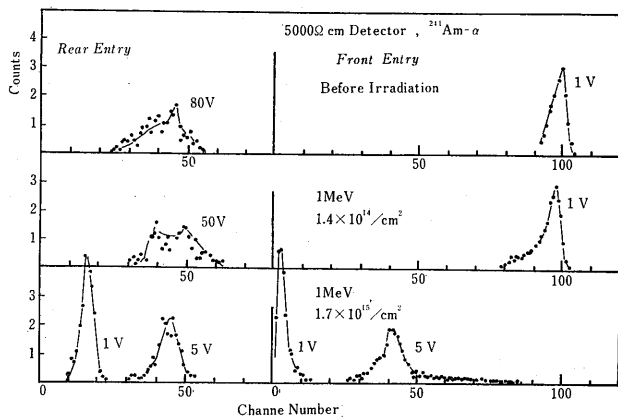


Fig. 6 ^{241}Am alpha spectra resulting from the rear and front entry for a $5000\Omega\text{cm}$ detector irradiated with 1 MeV electrons. Low and broad spectra of the rear entry are resulted from the thick rear ohmic contact fabricated by Ni-plating.

spectrum of the front entry with 1 V bias has the lower peak channel than that of the rear entry with 1 V bias. The similar phenomena had been observed by Liu⁹⁾, i.e., the decrease of the charge collection efficiency occurred for the front entry and only a decrease of energy resolution for the rear entry. Liu explained these phenomena by the preferential trapping of electrons or the field decrease of the front contact. Our results also are explained in the same manner. The depletion depth extends to the rear contact even at low bias, because the *n*-type property is converted to the intrinsic one by the irradiation⁸⁾. So the electric field near the rear contact requires low bias to detect incident particles. Two explanations are possible for the difference between the front and rear entry spectra of the last stage in Fig. 6. The one is that if the field distribution near the front contact does not change by the irradiation or the field distribution becomes constant over the whole region of the detector, the damage centers tend to trap electrons rather than holes on account of the difference of the carrier transit path. Another explanation is as follows: if the field near the front contact is lowered by the irradiation and the field near the rear contact becomes higher, the rear entry particles are more detectable than the front entry particles.

Some of the irradiated detectors were isochronally annealed in air at the temperature range of 100 to 220°C . A typical example is shown in Fig. 7. The annealing effect of the capacitance and alpha peak channel at the constant bias of 1 V is shown. The annealing effect occurs at 138°C annealing stage, i.e., the capacitance increases and the channel number of the alpha peak increases. Below and above 138°C , no significant change occurs. This annealing stage is probably the reordering stage of the E center. After the 220°C annealing, there exists a large unannealed fraction. These annealing phenomena mean that the E center formation by the electron irradiation is small.

The other experiment, in which the alpha particles were incident on the rear ohmic contact of the totally depleted $5000\Omega\text{cm}$ detectors, showed an interesting result. By the irradiation, the alpha particles incident on the rear contact became detectable at lower bias as seen in Fig. 6. Before the irradiation, the detector required about 80 V bias to be depleted totally. After the irradiation of $1.4 \times 10^{14}/\text{cm}^2$ at 1 MeV, the detector is depleted at 50 V bias and finally at $1.7 \times 10^{15}/\text{cm}^2$, 5 V bias is enough to deplete the detector. At this last stage, the

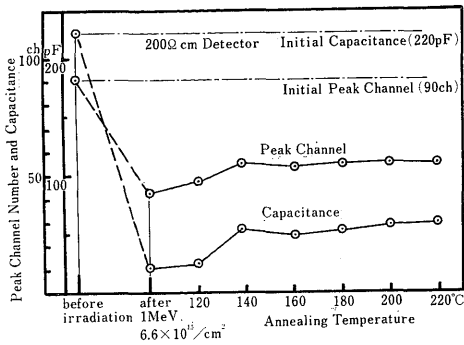


Fig. 7 Annealing effects of the capacitance and ^{241}Am alpha peak channel at 1 V bias for a 200 Ωcm detector irradiated at $6.6 \times 10^{15}/\text{cm}^2$ with 1 MeV electrons.

Above 220°C annealing, the oxidation of silicon must be considered, so we must anneal in inert gas or in a vacuum. We are planning to anneal the irradiated detectors in a vacuum at high temperature in the future.

By etching the irradiated front surface, the detector was fabricated again. The effect of removing the damaged area is shown in Fig. 8. The recovery of the capacitance and alpha peak channel was observed, according as the damaged depth was taken away. The damaged depth in Fig. 8 is larger than 400 μm for the 0.5 MeV irradiation of $3.3 \times 10^{16}/\text{cm}^2$. This recovery curve is slightly different from the Flicker's experiment¹⁰⁾ using the electron voltaic effect, in which the damage rate distribution approached zero at about 400 μm in depth. The detector irradiated with 1 MeV electrons did not recover at all after 500 μm removal.

4. Conclusions Remarks

The detectors fabricated from various resistivity silicon crystals were irradiated with 0.5–1.5 MeV electrons. The radiation damages degraded the detector performance.

The alpha spectrum degradation begins to occur at the fluence of $1 \times 10^{14}/\text{cm}^2$ with 1 MeV electrons for 400 Ωcm detectors, but if we can increase the bias voltage up to 10V apart from noise problem, the degradation is not serious until the irradiation of a decade higher fluence. When the resistivity of the detector is higher, i.e., the donor concentration is lower, the degradation begins at lower fluence. The higher energy electrons also degrade the detector faster. From the C-V characteristics, acceptor-type damage centers are produced, so the high resistivity detector can be depleted widely with lower fluence. The created electrons by the alpha particles near the front contact (about 30 μm in depth from the front contact) must transit a long path in the depletion layer. On the other hand, in the low resistivity detector, the donor concentration is not compensated easily by the irradiation, so the width of the depletion layer does not increase with lower fluence. The high energy electrons produce high concentration of

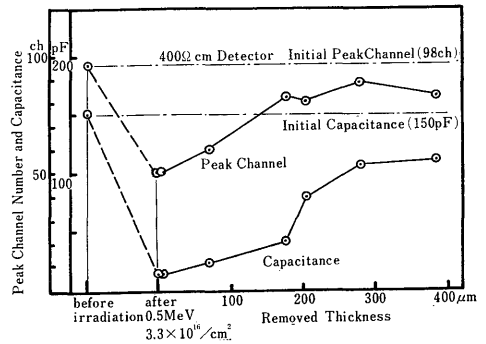


Fig. 8 Recovery curves of the capacitance and ^{241}Am alpha peak channel for a 400 Ωcm detector irradiated at $3.3 \times 10^{16}/\text{cm}^2$ with 0.5 MeV electrons against the removed depth by etching the damaged surface.

damages and large damaged region in the detector, so the detector is degraded faster.

The number of the acceptor-type damages produced by electrons is calculated from the C-V characteristics. The damage rate is almost independent of the resistivity of the detector, so the E center which has an acceptor-type property is not the main damage center. This is consistent with the isochronal annealing data in Fig. 7 where only a small fraction of the damage centers is annealed at 138°C. The formation and annealing process of the E center was studied^{2,11,12,13)} in phosphorus-doped silicon. In these studies, it is shown that the E center has the energy level of $E_c-0.4\text{eV}$ and anneals near 150°C, where E_c is the energy level of the conduction band minimum. However these studies were done in low resistivity silicon with high concentration of phosphorus. The phosphorus concentration of the radiation detector is one or two decade lower. So in our case, the E center formation may not be obvious. The detector fabricated from float-zoned silicon which is considered to contain low oxygen impurity, so the A center is not also the dominant center in our detector. The divacancy has two acceptor levels at $E_c-0.4\text{ eV}$ and $E_v+0.45\text{ eV}$ ²⁾ and does not anneal up to 300°C^{11,13)}, where E_v is the energy level of the valence band maximum. The damage rate studied by Corbett¹⁴⁾ and Bemski¹⁵⁾ for 1 MeV electron irradiation on *n*-type silicon were $4\times 10^{-3}/\text{cm}$ and $1\times 10^{-3}/\text{cm}$. From these values being in the same order with our value of $0.7\text{--}1.5\times 10^{-3}/\text{cm}$ in Tab. 1 and the existence of the large unannealed fraction at 220°C in Fig. 7, the dominant damage center in the detector may be considered as the divacancy.

The rear entry spectra of the alpha particles in Fig. 6 show that the depletion layer extends to the rear contact according to the increase of fluence. Then the field near the front contact is lowered, or the preferential trapping of electrons occurs. Which mechanism is effective is not clear at present.

The recovery of the detector performance by etching the irradiated region is obtained as in Fig. 8. For the 0.5 MeV irradiation, the complete recovery does not occur up to 380 μm etching. The radiation-induced deterioration is the main weak point for radiation semiconductor detectors. The surface barrier detectors irradiated by electrons show the spectrum degradation. The limiting fluence for the detectors allowable to be exposed to energetic electrons is shown in Tab. 2. This table is obtained from the figures similar to Fig. 5 and shows the guide of usable limit of surface barrier detectors when the irradiated detector can be proof against 10 V bias regardless of noise problem. If the surface barrier detectors

Tab. 2 Allowable electron fluences for surface barrier detectors until which the spectra degradation at 10 V bias is not serious.

Energy (MeV)	Detector Resistivity (Ωcm)			
	200	400	1000	5000
0.50	$8\times 10^{15}/\text{cm}^2$	$7\times 10^{15}/\text{cm}^2$	$4\times 10^{15}/\text{cm}^2$	$4\times 10^{15}/\text{cm}^2$
0.75	3×10^{15}	3×10^{15}	2×10^{15}	1×10^{15}
1.0	2×10^{15}	1×10^{15}	1×10^{15}	6×10^{14}
1.5	1×10^{15}	6×10^{14}	4×10^{14}	2×10^{14}

are required to be used for the heavy particle detection in such surroundings exposed to energetic electrons as in the satellite, the lower resistivity silicon is desirable because of its long practical life-time as clearly shown in Fig. 5 and Tab. 2. Of course the value of the resistivity is limited by the possibility of stopping the incident particles in the depletion layer.

The application of the radiation damage to electronic devices is already established in the field of the ion-implantation¹⁶⁾. Germanium compensated by gamma-irradiation is used as a high resistivity germanium detector¹⁷⁾.

The detectors irradiated with electrons have high trap density for electrons and/or holes. These traps are similar to the deep trap levels in silicon and germanium introduced by the doped impurities such as Au or Cu. Then the double injection^{18,19)} is possible in the irradiated detectors. We could observe the negative resistance in the forward-biased characteristics of the irradiated detector. This negative resistance has the possibility to be applied as switching devices.

The spectrum degradation means the pulse-height defect in the damaged region. If we irradiate the detector with various fluences at separate areas, the pulse-height defect has a respective degree according to the irradiated fluence. By shielding some parts of the surface region in a suitable manner, we can obtain three kinds of surface areas (non-irradiated, lightly irradiated, heavily irradiated) in only one detector. When the monoenergetic alpha particles are incident on this detector, the spectrum peak corresponding to the incident position is observed. It is possible to determine the incident position from the respective peaks. This can be used as a position-sensitive detector²⁰⁾.

The author is indebted to T. Aoki and K. Kawabata for the considerable assistance of this work, to Dr. M. Sakisaka and Dr. F. Fukuzawa for the encouragement, and to K. Norisawa for the operation of the accelerator VE-20 in Kyoto University.

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