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Proton irradiation on p-bulk silicon strip detectors using 12 GeV PS at KEK

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Abstract

P-bulk n-strip silicon strip detectors were irradiated with a 12 GeV proton beam at the KEK Proton Synchrotron in order to investigate a radiation damage due to high fluence of high energy protons. Primary 12 GeV protons extracted at the EP1-A beam line was used for the irradiation. The detectors were irradiated with the fluences of 1.1×10^{14} and 4.3×10^{13} protons/cm^2 for the high and low fluence exposures, respectively. Bias voltage for achieving the full depletion of the irradiated p-bulk detectors was observed to be significantly higher than that for the n-bulk detectors. The full depletion voltage did not increase monotonically as the fluence increased; it showed little variation up to about 5×10^{13} p/cm^2 and then started to increase. The behaviour could be explained by assuming a contribution from three processes: effective acceptor creation, persistent acceptor component, and acceptor removal.

1. Introduction

The silicon detector is one of the few candidates for a tracking device usable in a harsh radiation environment near the collision point of a high energy hadron collider such as LHC, considering the tracker should satisfy demanding requirements on spatial resolution of about ten microns and a high speed measurement with a clock cycle of faster than a few ten MHz. The radiation fluence at inner detector region of a LHC experiment is estimated to reach over 10^{14} particles/cm^2 in 10 years operation [1], even at a modest distance from the collision point, for example, at $r = 30$ cm where ATLAS is going to place the inner most layer of a silicon strip detector. Therefore, it is vital for the LHC experiments to develop a silicon detector which can survive up to such a high radiation fluence.

The most serious concern from the point of view of operating the detector is an increase of the depletion voltage with accumulating radiation fluence. This effect can be explained by a change of effective impurity concentration caused by an irradiation of protons and other particles [2]. In fact, the prominent damage on a silicon bulk by high energy protons and other particles is a generation of a defect which behaves like an acceptor. The full depletion voltage for the p-bulk is expected to increase more or less monotonically since effective acceptor concentration increases as a function of fluence. As a result, the p-bulk silicon is expected to require higher voltage, when compared at the same fluence, than the n-bulk silicon for which depletion voltage drops until original donor dopant is effectively removed and compensated by radiation induced acceptors. In order to investigate characteristics of these effects, p-bulk silicon strip detectors were irradiated with a 12 GeV proton beam from the proton synchrotron at KEK.

In this report, we describe briefly the irradiation procedure carried out at the KEK-PS, and discuss the effects of the irradiation on the full depletion voltage for a p-bulk silicon strip detector.

2. Proton beam

A small open space, just upstream of the first quadrupole magnet, of the EP1-A beam line in the north experimental hall at KEK-PS, shown in Fig. 1, was used for the irradiation on silicon detector samples. Typical beam intensity was about 2×10^{12} protons/spill. The beam spill duration was 2 s in a repetition of 4 s. The profile of a beam pulse measured with a MWPC showed a Gaussian shape with the size (σ) of 26 mm in horizontal and 11 mm in vertical. Since the beam was steered during an exposure, integrated beam profile was somewhat distorted as shown in Fig. 2. This was measured with an activation method using aluminum foils. 49 aluminum foils, of size 1 cm $\times$ 1 cm (area) $\times$ 0.05 mm (thickness), were arranged in a 7

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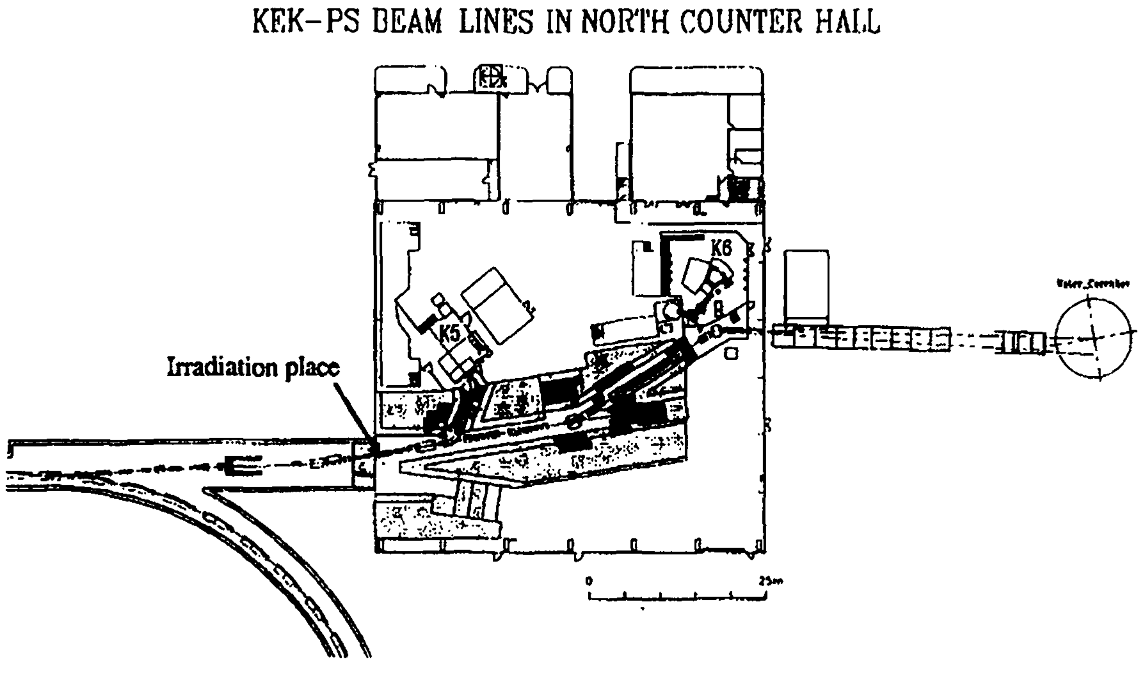


Fig. 1. The place used for the irradiation at the EP-1 A beam line in the north counter hall at KEK-PS.

cm×7 cm matrix. The foils were exposed with the beam for about two hours to measure the beam profile as well as the absolute flux. The beam intensity was also monitored with a secondary emission chamber (SEC) for every beam spill. The aluminum foil measurement gives a reliable calibration for the SEC chamber.

Thermal neutron flux at the exposure area was also measured by using an activation of a gold foil. Pairs of gold foils, the one covered with a cadmium shield and the other without it, were placed at several places near the beam line to measure the thermal neutron flux. The foil was 1 cm×1 cm (area)×0.1 mm (thickness) and the shield was made from a 1 mm thick cadmium plate. The flux measured at about 0.1 m from the beam line at the exposure point was 6×10^6 neutrons/cm^2/s and it decreased to 3×10^6 neutrons/cm^2/s at about 1 m away horizontally from the beam line. The neutron flux is practically small enough to be negligible for this irradiation case.

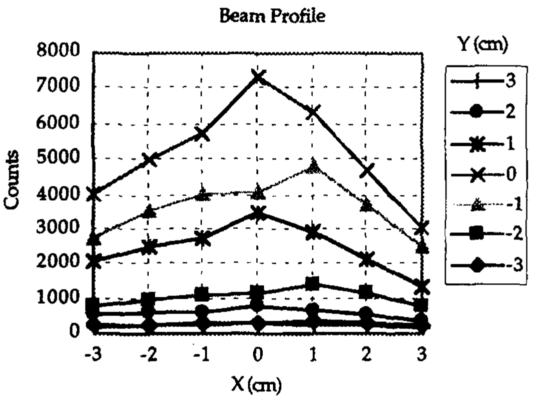


Fig. 2. The beam profile measured with an activation of aluminum foils. The horizontal position is in x [cm] and the vertical in y [cm].

3. Silicon detectors

A p-bulk n-strip-readout single-sided silicon strip detector was fabricated for the proton irradiation study. The n-bulk silicon detector is known to invert the type of bulk from n to p with accumulating fluence. This change of bulk means that the p–n junction moves from the p-side to the n-side, and requires that the detector should have an elaborate lithography on both sides. On the other hand, a p-bulk detector may not experience the type inversion and a simple backside processing is enough for the single-sided detector.

The detector fabricated was 6.0 cm×3.4 cm (area)×300 μm (thickness) with n-readout strips of 50 μm pitch. The

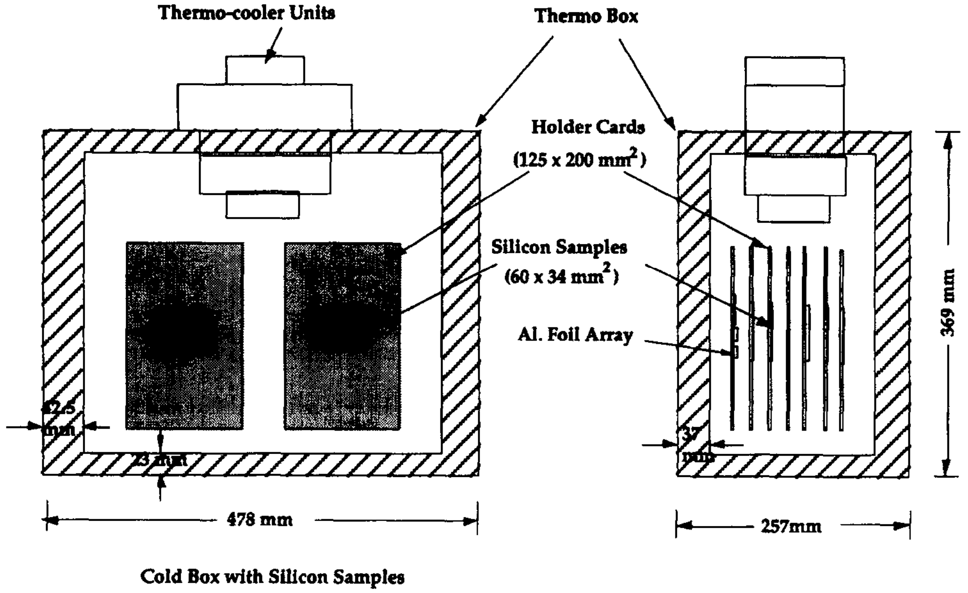


Fig. 3. The arrangement of the silicon detectors in the cold box which has a Peltier thermo-cooler unit.

masks used were the n-side masks of the SDC prototype double-sided silicon strip detector[1] [3]. The detector had p-stop implantation between the n-strips to intercept the accumulation layer due to the interface charge-up positively. Two densities of implantation were made to verify the effect of the interface charge-up. The bias voltage required for the full depletion was measured to be slightly higher than 150 V before the irradiation. The resistivity of the p-bulk was about 6 kΩ cm. The specifications of the detector is summarized in Table 1. Four samples of the p-bulk detectors were irradiated together with other samples: two at a low fluence and two at a high fluence.

Table 1
p-bulk detector specifications

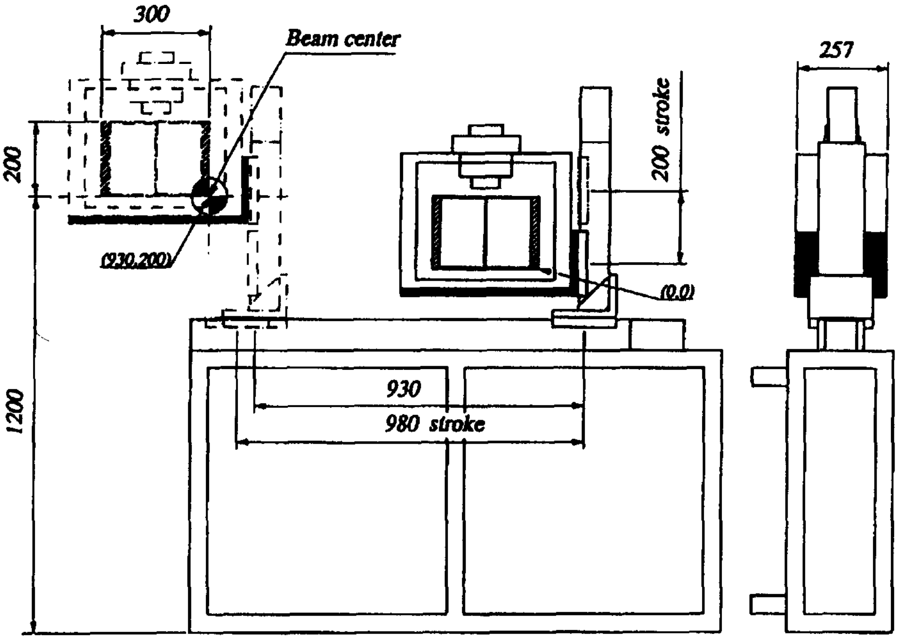
Coupling	AC
Substrate	p-type
Resistivity of substrate	6 kΩ cm
Chip size	60.0 mm × 34.1 mm
Wafer thickness	300 μm
n-side	
Strip pitch	50 μm
Number of strips	640
Implant type	n^+
Implant strip width	12 μm
Al strip width	6 μm
p-stop width	26 μm
p-stop implant	2 samples
High density doping	1×10^{14} ions/cm^2
Low density doping	2×10^{13} ions/cm^2
Bias resistor	250 kΩ
p side	
Planar implant	p^+

4. Irradiation procedure

The silicon detector samples were enclosed in a thermally insulated cold box which was equipped with a Peltier thermo-cooler unit. The temperature of the samples inside the cold box were cooled at 10°C and controlled within 1°C. A bias voltage of typically 60 V was applied to the silicon detectors during the exposure. Those samples were arranged into two rows in the cold box, as shown in Fig. 3, to have a different fluence for each row, high and low fluences respectively. This two row arrangement is also to satisfy the restriction that an amount of materials intersecting the beam must be always thinner than an equivalence of a 1 mm thick steel plate in order to minimize a disturbance to the beam which is used for downstream experiments.

During the exposure, position of the cold box was moved with respect to the beam spot, using a remote controllable stage (Fig. 4), so as to have a uniform fluence over the whole area of the samples, typically 6.0 cm (horizontal)×3.4 cm (vertical), and also to change the rows of the samples to be exposed. Exposure times were 3 hr 23 min and 1 hr 28 min for the high and low fluences respectively. After achieving the expected fluences, the cold box was moved sideways by about 1 m from the beam line and stayed there for 13 days until the end of this

[1] Fabricated by Hamamatsu Photonics Co. ltd., Hamamatsu, Japan.



Proton irradiation X-Z stage

Fig. 4. The movable stage which was operated outside the beam area to control the fluence on the detectors.

PS operation cycle. The temperature of the cold box was kept at 10°C for this period. An actual history of the detector temperature is summarized in the Table 2. The detectors have always been kept at 0°C after they were brought to a measurement room, even during measurements.

Integrated fluences on the detectors were estimated by an activation of an aluminum foil. The aluminum foil of size 1 cm×1 cm (area) x 0.05 mm (thickness) was positioned at the centre of the silicon samples of each row. Radioactive species of ^{7}Be converted from aluminum were measured by detecting 411 keV gamma rays with a liquid nitrogen cooled Ge-SSD detector. The integrated fluence at the centre of the detectors was measured to be:
1.2×10^{14} protons/cm^2 for high fluence, and
4.2×10^{13} protons/cm^2 for low fluence.

Uniformity of the fluence over the detector area was also measured using an array of aluminum foils. The foil was 1 cm×1 cm in area and 0.05 mm in thickness. The 25 pieces of aluminum foils were arranged, with a 1 cm horizontal gap between each other, into a 5×5 matrix which covered the area of 9 cm (horizontal)×5 cm (vertical). The relative activation of those foils were counted with a GM-counter equipped with an automatic sample changer. The measured fluence distribution is shown in Fig. 5. The distribution has a broad peak at the centre of the detector and is uniform within 11 (7)% over the detector area of 6.0 cm (horizontal)×3.4 cm (vertical) for the high (low) fluence. An averaged fluence over the detector area was estimated, with a correction of this fluence distribution, to be:
1.1×10^{14} protons/cm^2 for high fluence, and
4.3×10^{13} protons/cm^2 for low fluence.

5. Depletion voltages

The radiation damage on a silicon bulk should be seen as a change of a depletion voltage and also as an increase of a leakage current. In order to estimate the full depletion voltage, a bias dependence of a body capacitance, i.e., the

Table 2
Temperature history of the irradiated detectors

Date [yr/mon/day]	Time [hr:min]	Temperature [°C]	Comments
95/7/19	16:30	10	Start of irradiaton
95/7/19	21:21	10	End of irradiation, moved to off-beam position
95/7/31	15:15	25	Open the cold box to remove from the beamline
95/7/31	16:50	−20	In a refrigirator in the radiation control building
95/8/21	13:30	0	Stored in a refrigirator in the measurement room

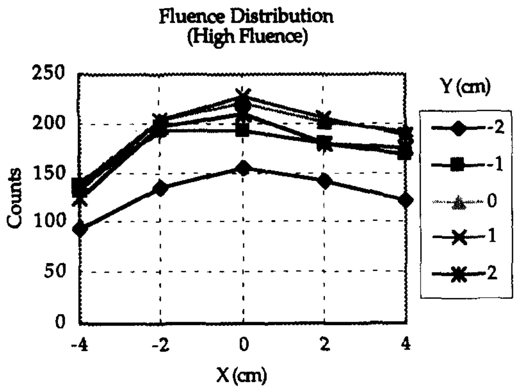


Fig. 5. The distribution of the fluence over the detector area. The area of 9 cm × 5 cm was measured with an activation of aluminum foils.

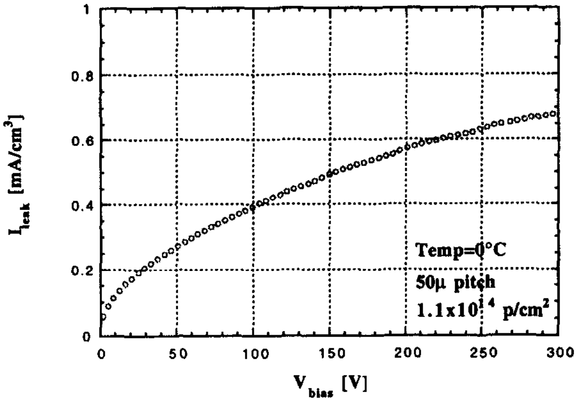


Fig. 7. The leak current of the irradiated p-bulk detector as a function of a bias voltage. The detector was exposed with high fluence of 1.1×10^{14} protons/cm^2, measured at 0°C.

capacitance between the front and back surfaces of the detectors was measured. Fig. 6 shows the body capacitance of the irradiated detector at the fluence of 1.1×10^{14} p/cm^2 as a function of a bias voltage. It is clearly seen that the curve has a knee at over 200 V. The full depletion voltage was fitted to be 226 V by defining the knee as the intersection of the characteristic curve of the semiconductor material and a constant line after the full thickness is depleted. The measurement was performed at 90 days after the irradiation. In these 90 days the samples were kept at 0°C most of the time and the depletion voltage was kept nearly constant. It showed only a small amount of annealing from the values at 40 days after the irradiation by several to 10 V. The leakage current, shown in Fig. 7, was also measured at the same time. The temperature of the detectors was kept at 0°C during the measurements.

The fluence dependence of the full depletion voltage of the p-bulk detectors is shown in Fig. 8. Two samples were irradiated at each fluence. The lower fluence samples showed good coincidence of the depletion voltage. The highest fluence samples showed a slight discrepancy. The only difference known to us in these samples was the density difference of the common p-stop lithography. One group of samples (shown in circle) had a common p-stop lithography with a high density doping of 1×10^{14} ions/cm^2; the others (shown in cross) had a low density of 2×10^{13} ions/cm^2 (see Table 1). Although the n^+-strips of the n-side were the p–n junctions, the p-stop lithography was required to isolate the n^+ strips after heavy irradiation. The data shows that the higher density doping had the higher depletion voltage. The effect of this difference to the depletion voltage is yet to be investigated.

6. Discussions

Basically the depletion voltage of the silicon bulk is controlled by the impurity concentration in the bulk. When the donor and acceptor concentrations are given at N_d and

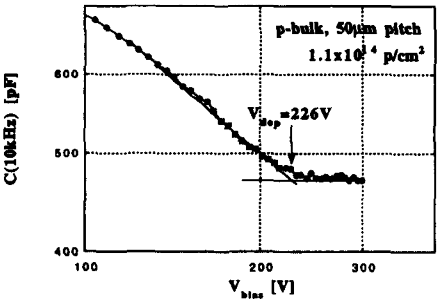


Fig. 6. The measurement of the body capacitance of the irradiated p-bulk silicon detector as a function of a bias voltage. This detector was exposed with high fluence of 1.1×10^{14} protons/cm^2. The full depletion voltage is estimated at the knee point of the curve.

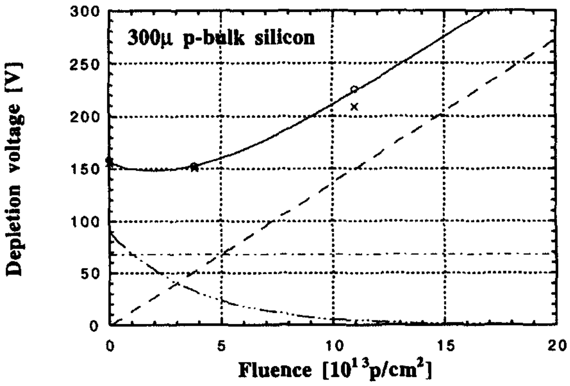


Fig. 8. Variation of the full depletion voltage of the p-bulk silicon strip detectors: data points (circle: high density p-stop, cross: low density p-stop), the curve (solid) combining the three hypotheses (acceptor creation (dashes), persistent acceptor component (dot–dash), and acceptor removal (double-dot–dash).

N_a, respectively, the depletion voltage, for the large area parallel electrode geometry such as PIN diodes, is given by

$$V_{dep} = qN_{eff}t^2/2\epsilon, \tag{1}$$

where $N_{eff} = N_d - N_a$ is the effective impurity concentration, q is the unit charge, t is the thickness of the bulk, and ϵ is the dielectric constant of the bulk. In the Eq. (1) the depletion voltage of the n bulk is expressed in positive values and the p-bulk in negative, for convenience.

The resistivity of the bulk is given by the charge carrier densities, n for electrons and p for holes, and their mobilities, μ_n and μ_p as

$$\rho = 1/q(\mu_n n + \mu_p p). \tag{2}$$

The charge carrier densities can be derived, with the impurity concentrations and the intrinsic carrier density, n_i, from the two relations:

$$np = n_i^2, \tag{3}$$

and

$$n + N_a = p + N_d. \tag{4}$$

Eq. (3) is called "Equilibrium carrier concentration" and Eq. (4) "Charge neutrality relationship". The carrier densities are, then

$$n = \tfrac{1}{2}\left[(N_d - N_a) + \sqrt{(N_d - N_a)^2 + 4n_i^2}\right], \tag{5}$$

$$p = \tfrac{1}{2}\left[-(N_d - N_a) + \sqrt{(N_d - N_a)^2 + 4n_i^2}\right]. \tag{6}$$

As seen in the above equations, the depletion voltage and the resistivity are controlled only by the difference of the impurity concentrations, N_{eff}. From the initial depletion voltage of about 150 V, the effective impurity concentration is estimated to be $N_{eff} = 2.2 \times 10^{12}$ ions/cm^3 with the values of $t = 300$ μm, and $\epsilon = 11.9 \times 8.85$ pF/m, and the resistivity of the bulk to be $\rho = 6.3$ kΩ cm with the values of $n_i = 1 \times 10^{10}$/cm^3, $\mu_n = 1350$ cm^2/(V s), $\mu_p = 450$ cm^2/(V s).

Although there are only three fluence points in Fig. 8, the tendency of the fluence dependence of the depletion voltage is evident: little variation up to about 5×10^{13} p/cm^2 and then steady increase. It may be difficult to give a quantitative explanation but we can propose the following practical hypotheses to, at least qualitatively, describe this behaviour of the depletion voltage of the p-bulk silicon.

i) *Effective acceptor creation* – In the n-bulk silicon, defects by an irradiation are known to produce effective acceptor states. Since the defect creation occurs in a crystal and the impurity concentration of 2×10^{12} ions/cm^3 is minute compared with the Si lattice of 5×10^{22} atoms/cm^3, the effect can be assumed to be similar in the n-bulk and p-bulk. After tracing the temperature effects, the damage slope factor at the time of measurement is estimated about $\beta = 0.020 \times 10^{13}$ ions/cm^3 using the formulae given by Ziock et al. for the annealing and anti-annealing of the n-bulk silicon [2]. The effective acceptor creation can be thought to occur from the null state. The expected line (dashes) is shown in Fig. 8. This curve is essentially the expected depletion voltage of the n-bulk silicon at high fluences [2,4]. The measured p-bulk detectors had about 70 V higher depletion voltage than the n-bulk silicon.

ii) *Persistent acceptor component* – With the hypothesis i) alone, this high depletion voltage of the p-bulk silicon at the high fluence can not be fully counted. We may need to assume, therefore, there is a persistent component, which is a fluence independent component, in the effective impurity concentration to account for the difference between the data and the effective acceptor creation due to the radiation damage. In order to account for the 70 V excess at the high fluence point, the amount of the persistent component is estimated to be slightly more than 40% of the initial impurity concentration, $N_a^p = 0.9 \times 10^{12}$ ions/cm^3 as shown (dot–dash) in Fig. 8.

iii) *Acceptor removal* – The little variation of the depletion voltage at low fluence can be explained by a removal of the initial impurity concentration. A concept of a donor removal is well known in the n-bulk silicon with its fluence constant of about 0.9×10^{13} p/cm^2 [2]. However, the effect of the donor removal for the p-bulk works as to enhance the increase of the depletion voltage. We may need, therefore, to assume also an acceptor removal which can prevent the increase of the depletion voltage at low fluence.

The initial concentrations of the donor and acceptor in the present p-bulk silicon are not known individually; only their difference is known. However, simplifying the situation by assuming that the initial impurity concentration is acceptor only and combining the hypotheses i), ii), and iii), we can derive an equation for the effective impurity concentration as a function of fluence:

$$N_{eff} = (N_a - N_a^p)e^{-\phi/\phi_a} + N_a^p + \beta\phi. \tag{7}$$

The data (Fig. 8) can be fitted with a fluence constant of the acceptor removal of about $\phi_a = 3.8 \times 10^{13}$ p/cm^2. The acceptor removal curve (double-dot–dash) is overlaid in Fig. 8. This removal constant of the p-bulk is four times larger than the donor removal constant.

To verify these hypotheses we clearly need more measurements, especially i) at high fluences, e.g., at 2 and 3×10^{14} p/cm^2, to determine the slope of the effective acceptor creation and to confirm the fluence independent persistent component, and ii) at low fluences to map out the acceptor removal. We also need to understand the mechanism to explain these phenomena as the persistent acceptor component and acceptor removal.

Although these hypotheses are only practical at the moment, we can make a prediction of the effect of the acceptor removal in the n-bulk silicon: since the acceptor removal is significantly slower than the donor removal, the n-bulk silicons with higher acceptor concentration would show the type inversion from n-bulk to p-bulk at the lower fluence even if they have the same initial effective impurity.

7. Summary

The proton irradiation on the silicon detectors was carried out successfully using the 12 GeV PS at KEK. The place used for the irradiation at EP1-A beam line in the north counter hall is suitable for our purpose, although an amount of materials to be exposed at a time is strictly limited. The beam is intense enough to have a high fluence of over 10^{14} protons/cm^2 within a reasonable exposure time. The beam profile is relatively broad, which is helpful to have a uniform exposure over the detector area, although a remote controlled movable stage is necessary to manipulate the position of the detectors in order to control the fluences. A thermal neutron flux is practically negligible at this place. The temperature of the samples was carefully controlled during and after the irradiation.

The full depletion voltage of the p-bulk detector was more than 200 V at a fluence of 1×10^{14} p/cm^2, which is significantly higher than the expected depletion voltage of about 130 V for the n-bulk silicon. The p-bulk silicon did not show the expected monotonic increase of the depletion voltage; it showed little variation up to a fluence of about 5×10^{13} p/cm^2 and then started to increase. This behaviour of the depletion voltage may be explained with three hypotheses: acceptor creation, persistent acceptor component, and acceptor removal. Based on these practical hypotheses we found that the fluence constant of the acceptor removal would be about four time larger than that of the donor removal, although we need further study to confirm the hypotheses.

Acknowledgments

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