Evaluation of Radiation Damaged P-in-n and N-in-n Silicon Microstrip Detectors

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Abstract

Two p-in-n and one n-in-n silicon microstrip detectors were radiation-damaged and tested in a beam. A comparison was made between the p-in-n and the n-in-n in high resistivity wafers, and the p-in-n in a low and a high resistivity wafer. The charge collection showed a clear difference in the n-in-n and the p-in-n detectors, which suggested that the signals were shared between strips more in the irradiated p-in-n detectors. Although a difference of the low and the high resistivity wafers was observed in the body capacitance measurement, little difference was observed in the beamtest results.

I. INTRODUCTION

In high energy hadron colliders, such as LHC, the number of particles generated at the interaction point is so large that the detectors installed near the interaction point need to be radiation-tolerant. The silicon microstrip detectors in the ATLAS detector will experience a fluence of 3 x 10^{14} particles/cm^2 over the 10 years of operation [1]. A radiation-tolerant design has been developed including the development of structures sustaining higher bias voltages and improvement in reducing the high electric field at the edges of implantation [2]. The radiation-tolerant silicon strip detectors developed have been evaluated, starting from the double-sided detector [3], and then the single-sided detectors with n-strip readout [4].

One of the major consequences of radiation damage to the silicon detectors is the mutation of the bulk type from the initial n-type to p-type due to the creation of effective acceptor states in the bulk. Single-sided detectors with n-strip readout are efficient below full-depletion because the p-n junction is in the n-strip side after type-inversion. The detector, however, requires several lithograph steps in fabricating the backside to make the p-n junction and guard structures initially in the backside.

The p-readout was not considered first for two reasons: (1) it may require full-depletion to be efficient after the mutation of the bulk, and (2) it may not sustain high bias voltages. The second point needs an explanation. The p-readout single-sided silicon strip detector sustains the bias voltage in the p-n junction in the p-strip side, in the initial state. The backside of the p-readout detector is fabricated by a simple diffusion process to make a planar densely doped n-layer, forming an ohmic contact to the bulk. When the detector is sawed out, the edge of the interface of the planar n-layer and the silicon bulk is on the surface of the cutting edge. When the bulk type is inverted, the interface becomes the p-n junction and the edge of this p-n junction is on the cutting edge. In the unirradiated detectors, the p-n junction on the cutting edge is known to break down even with a small bias voltage.

Recent experience in the study of radiation tolerant silicon strip detectors has shown that the edge of the p-n junction on the cutting edge of the inverted detectors did not break down at a low bias voltage, not even as high as several hundred volts. With the development of sustaining high bias voltages and the accumulation of knowledge of the charge collection in the p-strips in the radiation-damaged detectors, e.g., the p-side of the double-sided detector, it was becoming likely that the improved p-readout single-sided detector would work sufficiently for the application in the ATLAS experiment. The p-readout in the n-bulk silicon detectors had cost-advantage because of the simpler backside processing.

Another interesting issue in the bulk damage was the increase of the depletion voltage in different resistivity wafers. The common resistivity of wafers of the silicon microstrip detectors had been 4 to 8 kΩcm, so-called “high resistivity” wafers. The low resistivity wafers, e.g., 1 kΩcm, had more donors. The radiation damage would create effective acceptors, and, if the donors were to remain, the donors would help to reduce the depletion voltage after type inversion. There was a report that the donors were removed at low fluences [5], which suggests that the full depletion voltages would become similar after heavy irradiation.

In this report, three silicon microstrip detectors were tested: one with p-readout in a high resistivity n-bulk wafer (p-in-n high), one with p-readout in a low resistivity n-bulk wafer (p-in-n low), and one with n-readout in a high resistivity n-bulk wafer (n-in-n high). These detectors were irradiated with protons and then subsequently put in a beamtest to evaluate the charge collection in the detectors.

II. DETECTOR SAMPLES

The p-in-n and n-in-n silicon microstrip detectors were fabricated according to the ATLAS silicon microstrip detector specification [1]. One p-in-n detector (Sintef p-in-n: SinP10) [6] and one n-in-n detector (Ham n-in-n: HamN) [7] were made on high resistivity n-bulk wafers, 5 kΩcm and 4 kΩcm, respectively. One p-in-n detector was made on a low resistivity wafer, 1 kΩcm (Ham p-in-n: HamP) [7].

The detectors had a strip pitch of 80 µm and an outer dimension of 63.6 mm (width) x 64.0 mm (strip direction). The detector's parameters are summarized in Table 1. The nominal thickness of the detectors was 300 µm. The measured thicknesses were 293 µm, 300 µm, and 300 µm, for the Sintef p-in-n, the Ham p-in-n, and the Ham n-in-n detector, respectively, with a measurement error of about 1 µm.

Table 1.
Parameters of the p-in-n and n-in-n silicon strip detectors

Detector type:	AC-coupled, Single-sided	
Bulk:	N-bulk, nominal 300 µm thickness	
Resistivity:	High (4 or 5 kΩcm) and Low (1kΩcm)	
Size (Outer):	6.36 cm × 6.4cm (width × length)	
Strips:	80 µm pitch × 770 strips	
Backside:	Uniformly doped n^+ layer	
Strip parameters:		
Length:		62 mm
Readout pitch:		80 µm
Implant width:		16 µm
Resistance of implant:		≤100kΩ/cm
AC coupling:		SiO2 + SiN
Width of Al. readout:		16 µm
Resistance of Al. readout:		≤20 Ω/cm
Bias resistance:		1.5±0.5 MΩ

III. PROTON IRRADIATION

A. Irradiation at KEK

The detectors were irradiated with 12 GeV protons in the EP1A beamline of the 12 GeV Proton Synchrotron at KEK [8]. The irradiation used the setup being developed for irradiations in the past [9]. The thermo-box stored the detectors and kept the temperature inside at -5 °C on average.

The nominal beam size was 61 mm full-width-half-maximum (FWHM) in the horizontal and 26 mm FWHM in the vertical. In order to cover the 6 cm x 6 cm detector area uniformly, the thermo-box was moved. The total intensity was counted with a secondary emission chamber (SEC) and triggered the stage movement. The absolute fluence was estimated from the activation of 1 cm x 1 cm Aluminium foils in a 5 x 5 matrix attached at the detector position.

In the run, there was a change of beam size which invalidated our calculation of the uniformity. With a correction to the movement, we could only achieve a fluence uniformity of ±16% at the maximum and minimum relative to the average in the readout region. The fluence variation with positions is shown in Figure 1. At the centre of the detector, the fluence was 4.2 x 10^{14} protons/cm^2, with an error of 10% which was dominated by the error in the cross section. In the subsequent beamtest, the readout region was set in the middle of the detector with an area of 2 cm x 2 cm horizontally and vertically. The detectors were kept cold, at -5 °C on average in the beamline, and stored at 0 °C after extraction.

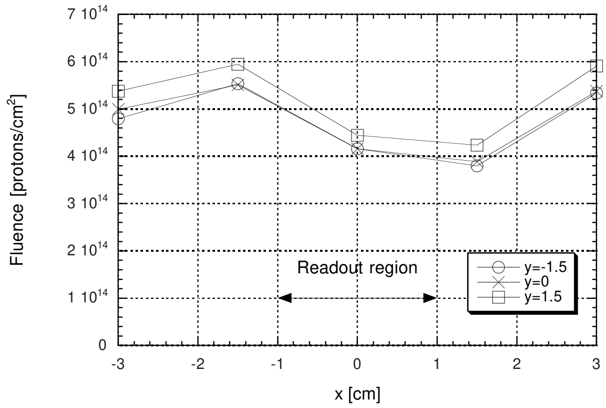

Figure 1: Proton fluence in the detector. The horizontal axis, x, is the position perpendicular to the strips and the parameter, y, is the position along the strip, in units of cm.

Before the beamtest, the irradiated detectors were warmed up for 5 days at room temperature, because of the beamtest preparation, and for 7 days at 28 °C, in order to anneal the damage and to simulate the effects of the warm-up in the maintenance of the real experiment. We calculated that the full-depletion voltage had increased by about 20% above the minimum in the warm-up before the beamtest.

The annealing and the anti-annealing of the full-depletion voltage was experimentally parameterized by H. Ziock [10]. Because of the different time dependence of the annealing and the anti-annealing effects, the full-depletion voltage first decreases and then increases. The change of the full-depletion voltage in time can be expressed by scaling the time with the characteristic time to reach the minimum, the time of minima. The temperature dependence of this time is shown in the bottom figure of Figure 2 and the full-depletion voltage at a fluence of 1x10^{14} p/cm^2 is shown in the top figure of Figure 2. The full-depletion voltage is being parameterized to be linear with the fluence.

B. Capacitance measurement

After the warm-up, the body capacitance, i.e., the capacitance between the top and the bottom surface, was measured as a function of bias voltage. This is a common method to estimate

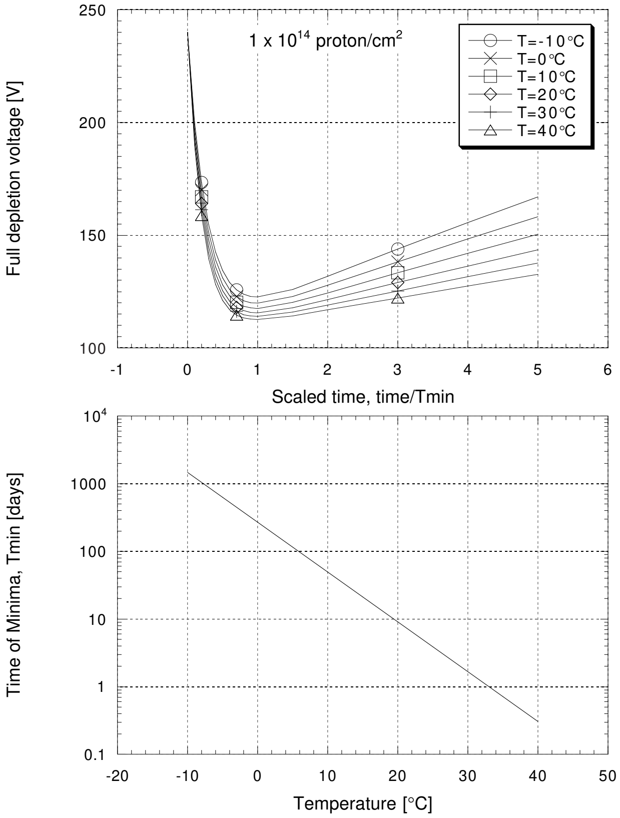

Figure 2: Expected full-depletion voltage as parameterized by H. Ziock as a function of time scaled by the characteristic time to the minimum (top figure), and the temperature dependence of this time (bottom figure)

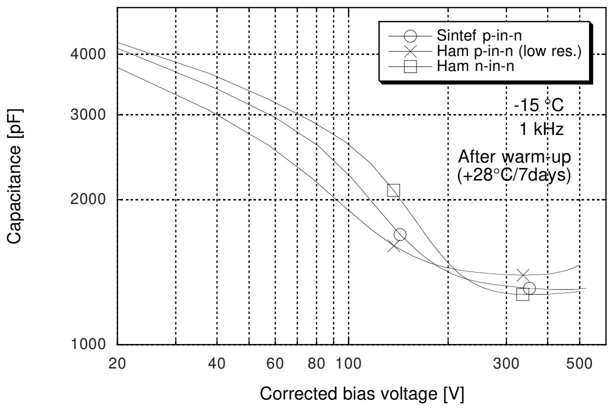

Figure 3: Body capacitances of the irradiated detectors as a function of the bias voltage after the warm-up. Sintef p-in-n (circle), and Hamamatsu n-in-n (square) were in the high resistivity bulk, and Hamamatsu p-in-n (cross) was in the low resistivity bulk wafer.

the full-depletion voltage, using the corner between the theoretical $\sqrt{V}$ decrease and the saturation value, where V is the bias voltage. The environment temperature in the measurement was set at -15 °C in order to limit the leakage current. The measured capacitances are shown in Figure 3.

The first impression was that the detector in the low resistivity wafer, HamP, had the lowest corner voltage, the p-in-n detector in the high resistivity wafer, SinP, the second, and the n-in-n in the high resistivity, HamN, the highest. This may suggest: the low resistivity wafer would develop lower full depletion voltage than the high resistivity ones; the p-n junction in strip geometry (radiation-damaged n-in-n detector) would require a higher voltages to deplete the bulk than the p-n junction in a planar one (radiation-damaged p-in-n).

However, as evident from the data, (1) the decrease of the capacitance was not monotonic and did not follow the theoretical expectation of $\sqrt{V}$, (2) the corner of the decreasing part and the saturation was very mild, and (3) the order of the saturated capacitances was opposite to the order of the capacitances in the decrease. Because of these observations, it was difficult to extract the corner voltage and, in turn, the full-depletion voltage.

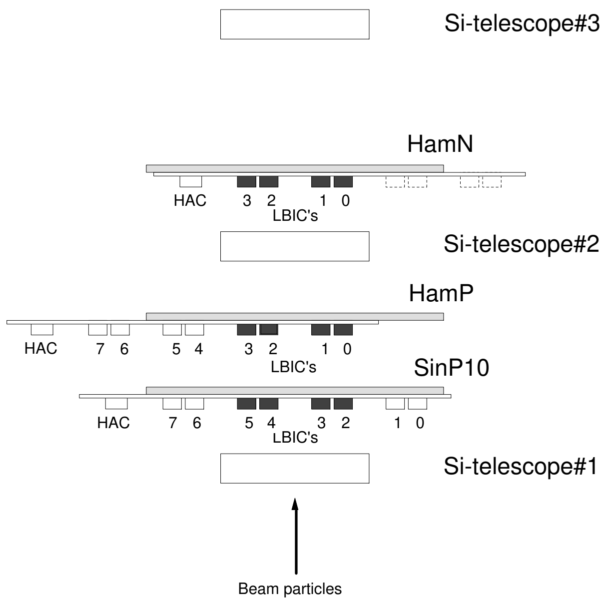

Figure 4: Beamtest setup of the irradiated detectors with the silicon strip detector telescopes which define the beam particle positions. The distance between each detector was about 30 mm.

IV. BEAMTEST

A. Setup

The irradiated detectors were tested in a beam at the π2 beamline of the 12 GeV proton synchrotron at KEK [11]. Negatively charged pi-mesons of 3 GeV/c were selected. The detectors were positioned in a thermo-box in the beamline as shown in Figure 4, together with the “Si-telescopes”.

Each detector was connected to a readout hybrid which carried an electronics with on-off readout (one threshold, binary readout) with the 64 channel bipolar amp-shaper-discriminator LSI chips (LBIC) and the 128 channel CMOS digital buffer LSI chips (CDP) [12]. The electronics was fast, the peaking time of the shaper being about 22 ns. The readout was interfaced via a communication chip, HAC, on the hybrid to the backend electronics and the data acquisition system. Because of limited available chips, only 4 LBIC's areas were readout in the middle of the detectors.

The irradiated detectors were sandwiched with silicon strip detectors instrumented with a Viking chips [13], "Si-telescopes", which provided a position resolution of 5 μm on the incident particles. The detectors were separated by about 30 mm. The smearing by multiple scattering [14] was less than 10 μm when the incident particle positions at the detectors were interpolated with the Si-telescopes.

B. Leakage currents

The leakage current was monitored during the beamtest. The environment of the thermo-box was kept at -17 °C in order to keep the leakage current small and prevent thermal runaway in the detector at higher bias voltages. A typical bias voltage dependence of the leakage currents is shown in Figure 5.

All three detectors drew the same level of leakage current up to 500 V. The bias voltage of the leakage currents being saturated seemed to be about 300 V for all three detectors.

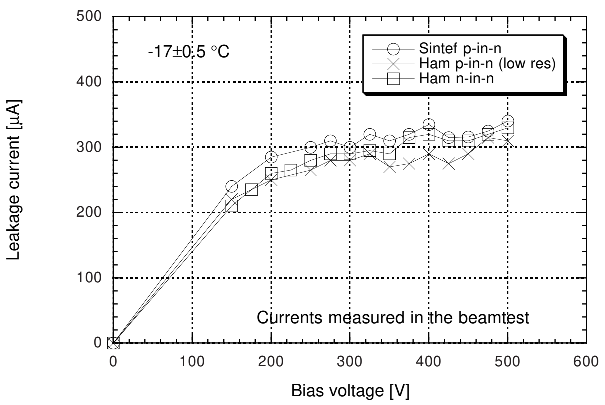

Figure 5: Leakage currents of the irradiated detectors during the beamtest. Environment temperature was set at -17 °C.

C. Charge collection

With one threshold in the electronics, only the efficiency of detecting signals above the threshold in a single strip can be obtained at a time. By scanning the thresholds, the pulse height (Landau) distribution was obtained in its integral form, convoluted with a Gaussian with a width characteristic of the system. An example of the threshold scan is shown in Figure 6.

The median of the Landau distribution was the threshold of 50% efficiency. In order to get the threshold, a modified error

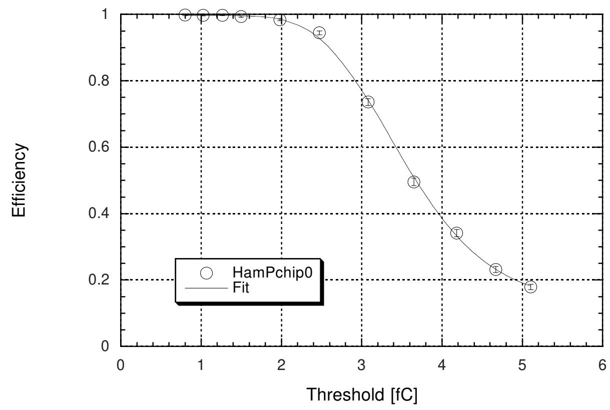

Figure 6: An example of a threshold scan for a channel in the Hamamatsu p-in-n detector. The efficiency curve was fit to a function described in the text and the median charge was defined as the threshold of 50% efficiency.

function, eq. (1), was fitted to the efficiency data,

$$eff(q) = p_3\left(1 - erf\left(\frac{q - p_1}{p_2} f(q)\right)\right) \tag{1}$$

where

$$f(q) = max\left(0.6,\ 1 - p_4\left(\frac{q - p_1}{p_2}\right)\right). \tag{2}$$

The function, *erf*, was the integral of the Gaussian distribution. The function, *f(q)*, is a phenomenological correction function to modify the Gaussian to the Landau distribution. The fitting parameters expressed the median (*p1*), the width (*p2*), the saturation (*p3*), and the skew (*p4*).

The median charges are shown as a function of bias voltages in Figure 7. A number of corrections were involved to reach this figure: (1) The median charges of each LBIC chips were scaled so that the average of the medians in the "strip region" at the bias voltages of 450, 475, and 500 V to be 3.5 fC. This was to correct the non-uniform radiation damage within a detector, and also correct the imperfect calibration of the amplifier responses. The definition of the "strip region" will be given in the section D; (2) The bias voltages were corrected for the leakage current to give the bias voltages applied to the silicon bulk. There was a resistance of 11 kΩ in the bias voltage supply line externally; and (3) The bias voltages of the Sintef p-in-n detector were increased, to correct the thickness, by a simple theoretical expectation of $(300\ \mu m/293\ \mu m)^2$ which was to increase the bias voltages by 4.8%. The data showed: (1) the irradiated p-in-n detectors required higher voltages to reach the same median charges as the irradiated n-in-n detector, and (2) two irradiated p-in-n detectors collected charges very similarly.

The first observation would be a reflection of the location of p-n junction after bulk type inversion:

The irradiated n-in-n detector:-- In the case of an n-in-n detector, the median charges decreased rapidly below the bias voltage around 300 V. In the irradiated n-in-n detector, after bulk type inversion, the p-n junction was located on the n-strip side. Below the full-depltion voltage, an undepleted neutral bulk region separated the depleted region from the p-backside. The rapid decrease of the median charges indicated that the charges from the undepleted region did not generate the signals in the n-strips. The signals are generated by the real charges moving in the electric field in the bulk [15]. Since the electronics was fast, only signals generated by fast moving charges in the high electric field were sensitive. The charges in the undepleted region, whether lost by recombination or not, would be insensitive to the electronics.

The charge collection can be compared with the ideal diode, where the collected charges scales as the depletion depth, $\sqrt{V}$ where V is the reverse bias voltage, and saturates once fully depleted. This ideal charge collection is plotted on Figure 7 with the full depletion voltage being set at 300 V. The charge collection of the n-in-n detector was close to that of the ideal diode but slightly different, which could be attributed to the strip structure of electrodes, the sensitivity of electronics, and the sharing of charges in neighbour strips.

The irradiated p-in-n detector:-- The charge collection in the irradiated p-in-n detector was smaller than that of the irradiated n-in-n detector. The full-depletion voltage of the irradiated silicon bulk was estimated to be about 300 V, from the capacitance, the leakage current, and the median charge of the n-in-n detector measurements. The charge collection of the irradiated p-in-n detector at 300 V was about 85% of that of the irradiated n-in-n detector. Since the bulk was thought depleted fully, there would be no significant loss of charges by recombination; the smaller median charges could be attributed to a sharing of charges in neighbour strips. A circumstantial evidence for the sharing was also obtained in the median charges in the inter-strip region in the section D.

The charges observed in the strips were the images of the real charges moved fast, in high electric field, since the electronics was fast. In the irradiated p-in-n detector, the high electric field was near the backside which was several times the strip pitch away from the strips. The image charges would thus have split between several strips. The diffusion of the swath of charges in drift along the electric field would contribute to the charge sharing when the swath was near the boundary of the strips. The charges would also be shared more in the irradiated p-in-n detector because of the larger inter-strip capacitance in the irradiated p-in-n detectors where the p-strip side was non-junction.

The median charges in the bias voltages below 300 V was less than 85% of that of the irradiated n-in-n detector, being about 67% to 85% between 200 V and 300 V. In the irradiated p-in-n detector, when the detector is biased below the full-depletion voltage, the p-strips and the depleted region are separated by an undepleted region. Since the charges were observed with the undepleted region in between, the undepleted region transmitted electric field, but partially. This partial shielding of the field might be another source of the smaller median charges, in addition to the charge sharing. The diffusion and recombination in the undepleted region would have not contributed to the smaller median charges because of the sensitivity of the electronics.

The second observation was that there was little difference in the charge collection between the low and the high resistivity wafers after radiation damaged at the fluence in this test. Provided that the charge collection were reflecting the depletion depth and that the fundamental property of the p-in-n detectors from two vendors were equal, the full depletion voltages of the two wafers would be similar. The result would confirm that the initial donors were removed and the acceptor states created by irradiation dominated the effective doping concentration.

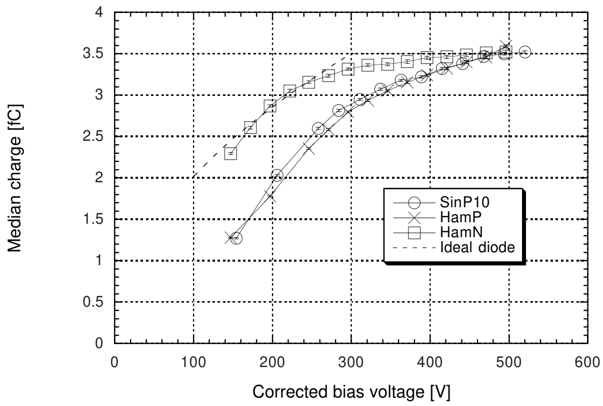

Figure 7: Median charges of the irradiated detectors as a function of bias voltages. The “ideal diode” is the theoretical expectation of the collected charges which scales as $\sqrt{V}$ and saturates at 300 V.

D. Charge collection in the inter-strip region

In order to investigate the charge sharing, the median charges were calculated according to the beam particle position. The positions midway between the strips, with a width of 20 µm, were defined as the inter-strip region. The positions around the strips, with a width of 40 µm, were defined as the strip region. The ratios of the median charges in the inter-strip over the strip regions were calculated and are shown in Figure 8. The uncertainties associated with the non-uniform damage, imperfect calibration of chips, absolute amount of charges collected, etc., were largely eliminated by taking ratios.

The ratios of the irradiated n-in-n detector were insensitive to the bias voltage. The ratios of the irradiated p-in-n detectors were much lower at lower bias voltages than those of the n-in-detector. These could be understood as a reflection of the location of the p-n junction and could be an indication of larger charge sharing in the irradiated p-in-n detectors.

E. Efficiency at 1 fC

In a real experiment, the data taking will be made by setting the threshold at one point. From the efficiency and electronics noise argument, the threshold is to be set around 1 fC. The bias voltage dependence of the efficiency at a threshold of 1 fC is shown in Figure 9. The p-in-n detectors, although requiring larger bias voltages than the n-in-n detector, became efficient (>99%) above a bias voltage of 250 V.

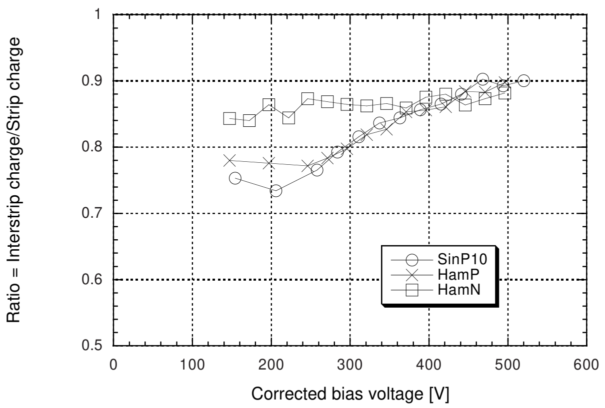

Figure 8: Ratios of the median charges in the inter-strip and the strip regions as a function of the bias voltage, of the irradiated p-in-n (circle and cross) and the irradiated n-in-n detectors (square). The inter-strip region was defined as an area midway between the strips with a width of 20 µm, and the strip region as being around the strips with a width of 40 µm.

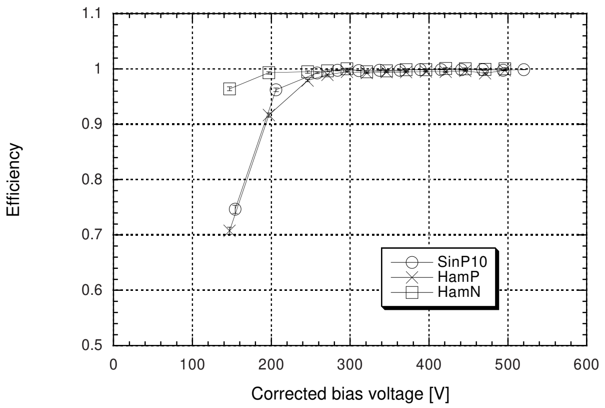

Figure 9: Bias voltage dependence of the efficiency at the threshold of 1 fC of the irradiated p-in-n (circle and cross) and the irradiated n-in-n detectors (square).

V. SUMMARY

Two p-in-n and one n-in-n silicon microstrip detectors of the ATLAS silicon microstrip detector specification were irradiated and tested in a beam. Two comparisons motivated the study: a comparison of p-in-n and n-in-n detectors, and a comparison of low and high resistivity wafers. The resistivities of the wafers were 1 kΩcm for the low resistivity and 4 or 5 kΩcm for the high resistivity wafers. The proton fluence was 4 x 10^{14} p/cm^2. The detectors were kept cold during the irradiation and stored cold. The irradiated detectors were warmed up before the subsequent beamtest to anneal and to simulate the warm-up in the maintenance in the real experiment.

The full depletion voltages of the detectors were estimated. The body capacitance measurement implied that the low resistivity wafer had a lower corner voltage. However, the corner voltage would not be an evidence of a lower full-depletion voltage. The charge collection information was obtained from the beamtest data. The median charges showed that the full-depletion voltage would be around 300 V in the irradiated n-in-n detector. The leakage currents of the detectors suggested all three detectors had a similar full-depletion voltage at around 300 V.

Compared to the irradiated n-in-n detector, there was no clear saturation in the median charges in the irradiated p-in-n detectors. The median charges of the p-in-n detectors increased slowly even above 300 V. The p-in-n detectors required larger bias voltages, by 70~100 V, to reach the same median charges as of the n-in-n detector. The ratios of the median charge in the inter-strip over the strip regions showed smaller charge collection in the inter-strip region in the p-in-n detectors at low bias voltages. The smaller median charges and the smaller ratios would suggest that the charges were shared between strips more in the irradiated p-in-n detectors.

The two p-in-n detectors on low and high resistivity wafers behaved very similarly. Although the full-depletion voltages of the two detectors were not evident in the charge collection, the similarity suggested that there was little difference in the full-depletion voltages of the different resistivity wafers at the proton fluence of 4 x 10^{14} p/cm^2, provided that the fundamental character of the detectors from the two manufacturers were the same.

The irradiated p-in-n detectors required a higher bias voltage for full charge collection, however, the efficiency at 1 fC showed that the detectors were efficient once the bias voltage was over 300 V.

VI. ACKNOWLEDGEMENT

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