Characterization of an Irradiated Double-sided Silicon Strip Detector with Fast Binary Readout Electronics in a Pion Beam

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Abstract

We report on the characterization of an AC-coupled, double-sided silicon strip detector, with fast binary readout electronics, in a pion beam before and after proton irradiation. The proton irradiation was non-uniform and to increase the damage the detector was heated to accelerate the anti-annealing. The effective radiation level was about 1×10^{14} p/cm^2.

Both the bias voltage of the detector and the threshold of the discriminator of the binary readout electronics were varied, and the efficiencies were determined. The irradiated detector clearly shows the effect of bulk inversion. The binary system proved to be efficient well below the full depletion voltage on the p-n junction side. Due to the highly non-uniform irradiation, the depletion voltage changes from close to zero to about 120V along a single strip, but the detector appears to work without any noticeable failures.

I. INTRODUCTION

Silicon strip detectors will play a central role in vertexing and tracking of the charged particles in TeV-energy proton-proton colliders such as the LHC. One of the main concerns for their use is the large predicted radiation doses. In the LHC detector ATLAS, the silicon strip detector (ATLAS SCT-strip) [1] expects a cumulative fluence of more than 10^{14} charged particles/cm^2 over the life of the detector. An n-bulk AC-coupled double-sided silicon strip detector (DSSD) has been designed to have high radiation tolerance [2]. The structures of the strips have been improved to allow high bias voltage operation of more than 150 volts for the 300 micron thick detector. Along with developing a radiation-tolerant silicon strip detector, understanding of the detector performance after radiation damage is an urgent task.

A simple, fast, and low-power electronics has been developed to read out the strip detectors. High speed is required to match the 40 MHz bunch crossing of the collider to tag the bunch crossing of the event, and to keep the occupancy low. Low power is required because the number of channels of a future silicon strip tracking detector would easily reach over several millions of channels, and cooling is a major engineering problem. The readout scheme is the "Binary-readout" that registers only one bit for a hit channel with pulse height above a fixed threshold and stores the bits in a digital pipeline until a trigger arrives [3].

A combination of the DSSD and the binary readout has been beam-tested before at KEK for proof of principle, and, subsequently, for characterization of improved versions of the DSSD and the read-out system [4, 5]. To characterize an irradiated detector, the DSSD used in ref.4 was irradiated with protons at TRIUMF and at LBNL, and, then, beam-tested at KEK. Although the binary readout has a fixed threshold during data taking, it is possible to determine the pulse height by varying the threshold. In this report, we will describe the proton irradiation and a characterization of the non-irradiated and the irradiated DSSD using 4 GeV pions from the 12 GeV proton synchrotron at KEK.

II. PROTON IRRADIATION

The detector assembly ("module") consisted of a PC board that carried one DSSD and two chip pairs of readout electronics as shown in Fig. 1. One pair of chips could readout 64 channels, and the two pairs of chips were bonded to the detector side-by-side. Using three of these detector-boards a beam test was carried out and the results on signal-to-noise ratios were reported in ref.5.

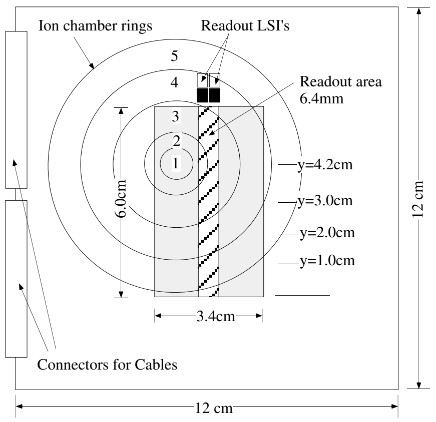

Fig. 1 Schematic drawing of the detector-board. Two chip pairs were mounted to readout an area of 6.4mm width of 6cm strips. Overlaid are the rings of the ion chambers that reflect the fluence profile in the irradiation.

After the beam test of the non-irradiated detectors, one detector-board was irradiated with protons at TRIUMF and at LBNL. At TRIUMF, a fluence of 0.6~0.7×10^{13} p/cm^2 of 500 MeV protons was delivered to the detector uniformly. The samples were cooled at -1 to 0 °C during and after the irradiation at TRIUMF. The fluence was measured with Al foil activation. The calculated fluence from the leakage currents was consistent with the foil measurement. To obtain a fluence near to 1×10^{14} p/cm^2, an additional irradiation was carried out at the LBNL 88" cyclotron using 50 MeV protons at the room temperature. The beam spot at LBNL was much smaller than the detector, and was slightly off-set from the readout area. The profile of the fluence was monitored with an ion chamber setup, whose ring structure is overlaid on the detector-board in the Fig. 1. The fluence fractions are summarized in Table 1. The detectors were kept at below 0 °C immediately after irradiation.

Table 1
Ion chamber area and relative fluence, *Fr.*

Ring#	Radius [cm]	Area [cm2]	*Fr.*
1	0.5	0.78	1.0
2	1.0	2.36	0.97
3	2.0	9.42	0.42
4*	3.0	~14	0.11
5*	4.0	~13	0.03

(*) The rings 4 and 5 were shadowed by the beam aperture. Active areas were ~90% for the ring 4 and ~60% for 5.

After the irradiation the leakage currents for a number of individual strips were measured across the DSSD and the fluence delivered was calculated to be about 6×10^{13} p/cm^2 in 1 MeV neutron equivalent damage at the peak. Because the fluence was still too low for the required 1×10^{14} p/cm^2, we increased the damage level by heating the detector up to 35 °C for 3.3 days to expedite the anti-annealing [6]. It was also heated up to 28 °C for more than 10 days with the heat of electronics while being tested. After tracing the temperature history, the depletion voltage was calculated along the strip at the time of the KEK beam test as shown in Fig. 2.

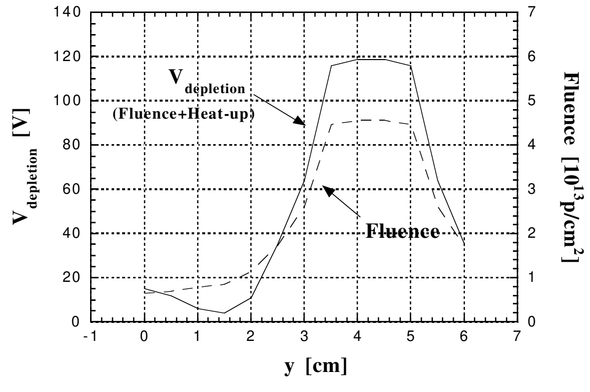

Fig. 2 1 MeV neutron equivalent fluence (dashed line) and calculated depletion voltage (solid line) of the irradiated DSSD at the time of beam test.

The depletion voltage varied widely along the strip: at one end (y=0cm) the depletion voltage was to be less than 20V (non-inverted), at y=1cm the depletion voltage was closer to intrinsic, and at y=4.2cm, which is the most irradiated region in the readout area, the depletion voltage was about 120V. This depletion voltage at the peak is close to the expected voltage when the detector is operated at -10 °C and accumulated a fluence of 1×10^{14} p/cm^2 over 10 years. The initial depletion voltage of the detector was about 70V, essentially uniform over the detector.

The beam test was carried out at a temperature of 20 °C, in which a leakage current of about 550μA was drawn over the whole detector. The leakage current was about 1.6μA per strip in the readout area. Although the radiation damage was non-uniform, the total leakage current per strip at the room temperature was corresponding to the expected leakage current at a fluence of >1×10^{14} p/cm^2 at -10 °C operation. Subsequent to this beam test, the detector was allowed to continue to anti-anneal and its performance was re-measured using a ^{106}Ru telescope [7].

III. Beam Test Setup

The beam test setup was the same as the one used for the non-irradiated detector [5]. The 4 GeV π^- beam was defined by a set of three scintillation counters: one of 2cm×2cm, a pair of 2cm×2cm displaced diagonally to have 1cm ×1cm overlap, and a pair of 7mm(width) × 60mm(height) sandwiching the four planes of detector-boards. The coincidence of area ≤7mm ×10mm supplied a trigger initiating the readout. The two outside silicon detectors were used as anchors having identical bonding arrangements. One inner detector plane, the device under test (DUT), was the detector being irradiated. It had varying strip pitch as explained below.

The detectors were n-bulk double-sided AC-coupled with 50μm strip pitch, having narrow implant strips to minimize the interstrip capacitance, developed to have higher tolerance to radiation [2], and fabricated by Hamamatsu Photonics. They were 6cm long, 3.4cm wide, and 300μ thick, with axial strips on the n-side and the stereo strips on the p-side with a 10mrad stereo angle. The detectors were instrumented only in the central part of both sides (6.4mm width) with two pairs of 64channel, fast, low-power, low-noise front-end electronics (FEE). A schematic drawing of the detector-electronics chain is presented in Fig. 3.

The detector is symbolized by the diode. The FEE consists of two chips: the bipolar amplifier-shaper-comparator ASIC (LBIC) [3] and the CMOS 40MHz digital pipeline (CDP64) [8]. The bipolar amplifier-shaper-comparator has an unipolar shaping with a peaking time of 22ns. In the binary readout scheme, two parameters control the performance of the detector: the detector bias voltage to deplete the detector, and the threshold of the discriminator to suppress noise hits and to count events that have signals exceeding the threshold.

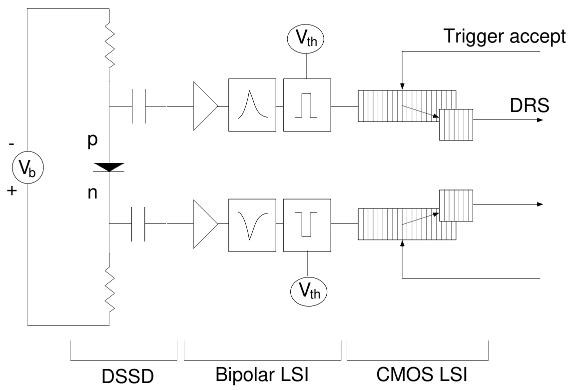

Fig. 3 Binary readout concept of the DSSD. Two controls in the system: Bias voltage of the detector and threshold of the discriminator.

To characterize the performance of the detector as a function of its pitch, we employed different bonding schemes between the detector strips and FEE channels. On one chip set of both sides of the detectors, each strip was bonded to a corresponding FEE channel with 50μ pitch. On the other chip set, two strips were ganged and bonded into one FEE channel to give 100μ pitch, thus simulating larger detector pitch. On the n-side of the DUT, the chip set was bonded into four configurations: alternating bonding with one intermediate floating (100μ-float), the ganging of two (100μ), the ganging of three (150μ), and the ganging of four (200μ).

IV. Results

Here we report the result on the charge collection of the irradiated detector, in conjunction with the non-irradiated detector. Though the binary system has only one threshold, it is possible to extract pulse height information by varying the thresholds. With one threshold the system accumulates the events where the signal pulse height exceeds the threshold, thus giving efficiency. The efficiency is the integral of the pulse height distribution. By scanning the threshold, one can map out the integral distribution and recover the pulse height spectrum by differentiation. The median pulse height is the point where the efficiency is 50%.

Beam data were collected by changing the bias voltages (40 ~ 160V), the threshold (0 ~ 6fC), the *y* positions for the different damage regions (1 ~ 4.2cm), and incident angles perpendicular to the strips (ϕ angles: 0° ~ 45°). In the previous beam test, the non-irradiated detector in ref. 5, the scanned ranges were slightly narrower than the irradiated detector: bias voltage (60 ~ 120V), threshold (0 ~ 2fC; 0 ~ 8 fC for 100V), and incident angles (0° ~ 54°). In most of the beam data, 20k events were accumulated and, at major points, 50k events were collected. The trigger rate was limited by the DAQ speed and was about 150 events in the beam spill of 2 sec out of the repetition cycle of 4 sec.

The data reduction method is similar to that described in ref. 5. Because the pulse width of the LBIC was of the order of 60ns, typical events give hits in two or three time-slices of the digital pipeline. For the present analysis, since we are not interested in the time-walk of the events, we have OR'ed the time-slices. Essentially the analysis is done for the n-side and the p-side separately.

A. *Efficiency*

In this analysis we present the efficiency for normally incident particles. To measure the efficiency the hits in the outer anchor planes were used to predict the position of the expected hit in DUT. Only one hit (or one cluster where consecutive hits were defined as a cluster) was allowed in each anchor plane. A search for a matching hit was made in the DUT within a region of ±three 50μ-strips. If none was found the event was considered as inefficient.

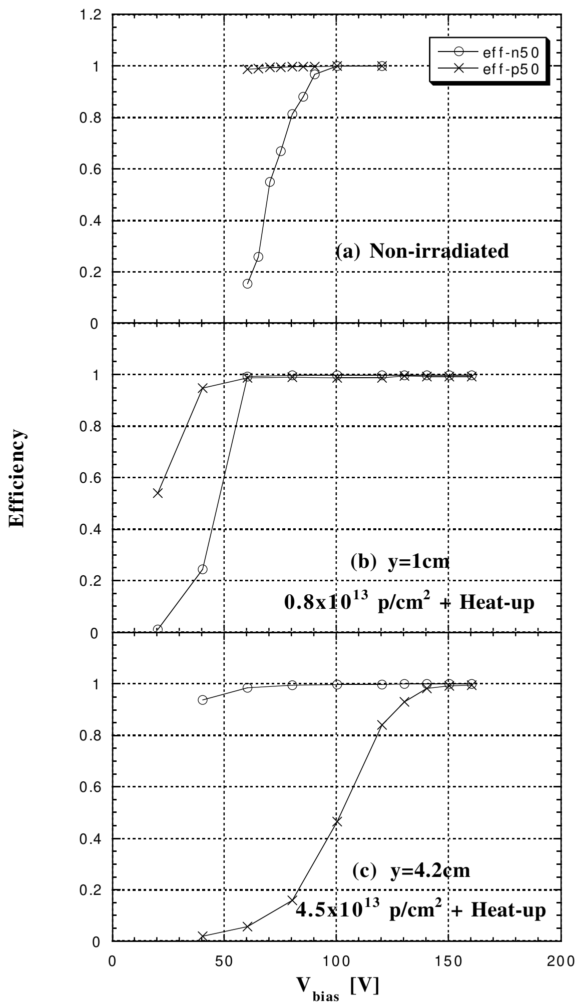

Fig. 4 Efficiencies of 50μ-pitch single strips as a function of bias voltages in the n-side (circle) and the p-side (cross) at a threshold at 1fC: (a) non-irradiated, (b) nearly intrinsic region, and (c) the most irradiated region where the depletion voltage is estimated to be 120V.

Efficiencies measured with single strips of 50μ pitch are shown in Fig. 4 for the non-irradiated, the nearly intrinsic region (y=1cm) and the most irradiated region (y=4.2cm) of the irradiated detector. The data are chosen for a threshold close to 1fC: 0.94 fC and 1.03 fC in the n-side and the p-side respectively for the non-irradiated detector, 0.92 fC and 1.00 fC for the irradiated detector. The difference of the n-side and the p-side was due to the difference of amplifier response to the positive and negative swing of signals. The difference of the non-irradiated and the irradiated detectors was simply the difference of threshold voltage setting.

Clearly seen in the figure is the inversion of the side of high efficiency. In the non-irradiated detector, the p-side has high efficiency at low bias voltage, while in the most irradiated region, the n-side has high efficiency. The high efficiency side is the p-n junction side where the strips are kept in isolation even for bias voltages below the full depletion of the silicon bulk. The binary readout is highly efficient well below the full depletion voltage on the p-n junction side.

When the incident tracks are inclined, the chances are to increase that the charges are split into adjacent strips. We have measured the efficiency as a function of incident angles and have found good efficiency even at incident angles of 14° [9].

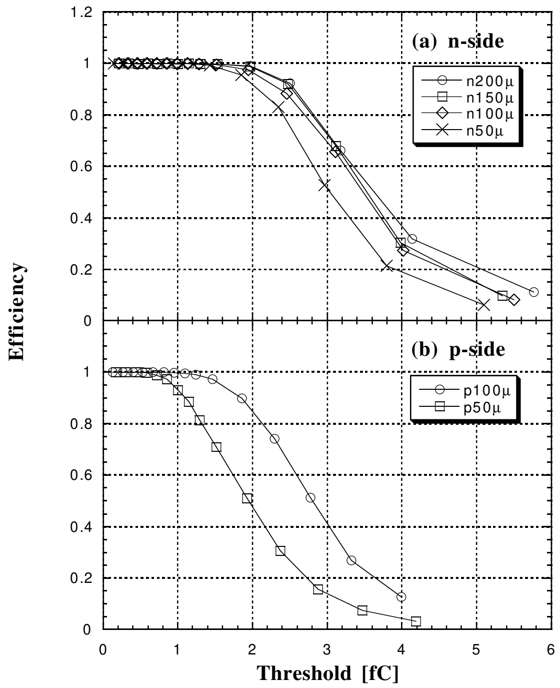

Fig. 5 Efficiencies of various pitches as a function of threshold at a bias voltage of 130V at the most irradiated region (y=4.2cm): (a) n-side with strip pitches of 50μ (cross), 100μ (diamond), 150μ (square), and 200μ (circle), and (b) p -side of 50μ (square) and 100μ (circle).

B. Median pulse height distribution

In threshold scans, the Landau distribution is calculated from the change in efficiency. A typical measurement is shown in Fig. 5 where the threshold scan was carried out for charges up to 6 fC. In order to estimate the peak of the Landau distribution, we have fitted the Error function to the efficiency curves. Since the Landau distribution has a long tail toward larger values, the fit tends to give a higher peak value than the peak of the Landau distribution. The fitted Error function has shown to give a 3% higher peak value using a Monte Carlo simulation of the Landau distribution [10], which we ignore in this analysis.

From the Error function fit, we have obtained the median pulse height distribution as a function of the bias voltage as shown in Fig. 6. This is the charge collected on single strips. At a bias where the pulse height is saturated, the median charge collected on the p-n junction side is, for the 50μ-pitch strips, about 3fC and, for 100μ-pitch (i.e., ganging of two 50μ strips), about 3.5fC. No charge loss was observed between before and after the irradiation (within a precision of 10%). Although the binary electronics had been calibrated by injecting known charges, the uncertainty of the absolute value of the charge collected was estimated to be 10% around 4fC, much smaller for smaller charges, due to the non-linearity of the amplifier that was designed for low-power. A major factor of charge-loss is the ballistic deficit that is more pronounced when the depletion voltage is low, and on the p-side where the slowly drifting holes are collected.

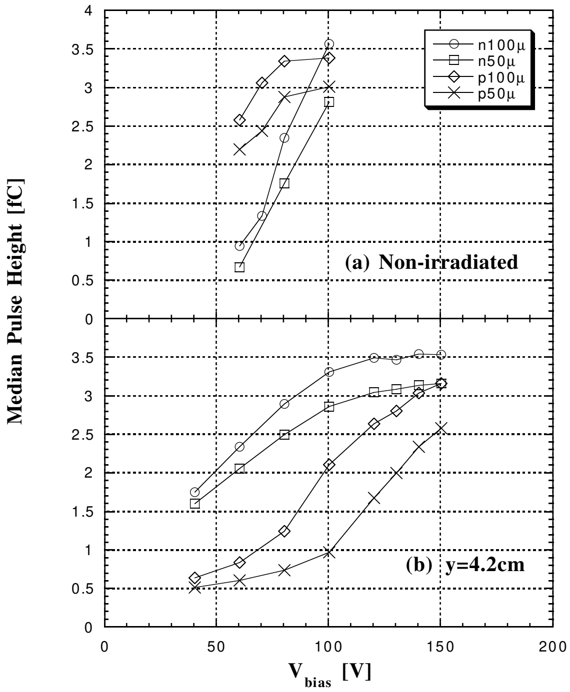

Fig. 6 Median pulse height distribution as a function of the bias voltage: (a) non-irradiated detector, and (b) most irradiated region (y=4.2cm). The n-side strips are 50μ (square) and 100μ (circle), and the p-side strips 50μ (cross) and 100μ (diamond).

The collected charge and thus the pulse height depends on the depletion depth, which varies with the square root of the bias voltage below depletion. Before irradiation the pulse height shows this $\sqrt{V_{bias}}$ behavior on the p-side (Fig. 6(a)) while after irradiation (at y=4.2cm) the n-side shows this behavior (Fig. 6(b)). This is another proof that the n-side, after irradiation, has become the p-n junction and the bulk has inverted.

V. SUMMARY

An n-bulk AC-coupling double-sided silicon strip detector, designed to have a high tolerance to radiation, was characterized with fast binary readout electronics in a pion beam. The detector was tested in the beam before and after proton irradiation. The spot of the irradiation was much smaller than the size of the detector and the irradiation was very non-uniform. To increase the damage, the detector was heated to accelerate the anti-annealing and the effective radiation level was about 1×10^{14} p/cm^2, which is the expected ultimate fluence level of the ATLAS SCT-strip detectors in the LHC.

The detector was characterized by varying two parameters: bias voltage of the detector and the threshold of the compactor of the binary readout electronics. By scanning the threshold we could obtain the integral of the Landau distribution in the form of efficiency curves, which we differentiated to get the pulse height distribution of the charges collected on single strips.

The irradiated detector has clearly shown the effect of bulk inversion, the move of p-n junction from the p-side to the n-side, both in the efficiency variation with a fixed threshold and in the median pulse height distribution, as a function of bias voltage. In the irradiated region, collected charge in the n-side has shown the characteristic $\sqrt{V}$ dependence of the depletion depth, while the charge collection on the p-side suffered losses below depletion due to the sharing of charges on many strips and the ballistic deficit of slowly drifting holes.

The efficiency measurements both on irradiated and unirradiated detectors show that the binary system is efficient when read out on the junction side even if operated well below full depletion voltage. We have clear evidence that the n-side is highly efficient if the bulk is inverted. Finally, we have shown that detectors are to work without failures even when irradiated non-uniformly. In one case the bulk under strips changed from essentially non-irradiated to intrinsic, and to heavily inverted with the effective fluence of about 1×10^{14} p/cm^2 at the maximum.

VI. ACKNOWLEDGMENT

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