Proton Irradiation on AC-coupled Silicon Microstrip Detectors

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Abstract

To test the radiation tolerance of full-size detectors, four large-area AC-coupled single-sided silicon microstrip detectors were fabricated. The detectors had a size of 6 cm×3.4 cm and were made out of a 300 μm thick, high-resistivity, n-type silicon, simulating the p-side of the double-sided silicon microstrip detectors being developed. The AC coupling layer had either a single layer of SiO_2 or double layers of SiO_2 and Si_3N_4, in combination with the surface passivation of SiO_2 or Si_3N_4. The detectors were irradiated at room temperature by 500 MeV protons at TRIUMF to a fluence of 5.7×10^{13} protons/cm^2, promptly stored at 0 °C after irradiation, and periodically measured over the following year. The full depletion voltages showed a substantial annealing and a gradual anti-annealing. The result was compared with the predictions of existing damage parameterization. Time variation of other characteristics, such as leakage current, inter-strip and coupling capacitances, and strip-edge micro-discharges was also followed.

I. INTRODUCTION

In future proton-proton super-colliders, one of the major challenges to the use of silicon strip detectors is the tolerance to radiation damage. The large intensity of the proton beams, which are required to produce a meaningful quantity of heavy objects in the collisions, produces a very large particle flow from the ordinary processes at the interaction point[1]. The particle fluence at a radius of 30cm at the LHC is predicted to be 1.0×10^{14} particles/cm^2 over the 10 years of the detector lifetime [2].

In response to the challenge, extensive investigations on the effect of the radiation (charged particles and photons) have been carried out. The damage effects have been characterized. In the bulk, acceptor-like states are generated increasing the bias voltage required to deplete the bulk after large fluences of a few times 10^{13} particles/cm^2. Recently, the temperature dependence of the annealing and the anti-annealing of the bulk damage has been determined [3,4].

In proportion to the bulk damage, the bulk leakage current also increases. To prevent the flow of the leakage current into the amplifier and to realize a low mass silicon strip detector system, a double-sided silicon strip detector (DSSD), with two dimensional readout and with integrated AC coupling capacitors, has been developed and rigorously investigated [5]. The breakdown of the AC coupling insulator becomes an issue due to the increase of the depletion voltage. An additional problem is the noise generation due to the micro-avalanche breakdown along the strip edge [6]. Taking into account these effects, a radiation-hard design of the silicon strip detector has emerged.

We have produced single-sided detectors with varying AC electrode width, insulator materials, and passivation materials [7] and irradiated these detectors with protons to investigate the damage to the full-size detectors.

II. EXPERIMENTAL SETUP

Detector

To simulate the p-side of the double-sided detector, AC-coupled detectors with p implant strips were fabricated from a high-resistivity, n-type silicon substrate of 300 μm thickness (TABLE I). The strip pitch was 50 μm. To study the strip-edge breakdown phenomenon, the width of the p-implant was fixed at 12 μm and the width of the aluminum AC electrodes was varied systematically. The detectors were subdivided into four zones, with each zone having a different width for the aluminum electrodes. The electrode widths were 4, 6, 8, and 16 μm for zone1, zone2, zone3, and zone4, respectively (Fig. 1). In practice, due to the limited number of pads on the carrier PC board, only three zones were selectively connected to the measuring equipment (TABLE II).

Adding a Si_3N_4 layer to the SiO_2 insulator layer of the AC coupling is known to improve the voltage breakdown characteristics of the AC coupling insulator. However, Si_3N_4 is also known to charge up more than SiO_2. To study the radiation damage on the insulator, two types of the AC coupling insulator were made: single layer of SiO_2 or double layers of SiO_2 and Si_3N_4. In combination, surface passivation was made out of SiO_2 or Si_3N_4. Four detectors were irradiated, one from each combination of the coupling insulators and the passivation as given in (TABLE II).

The ohmic contact was made by implanting n^+ over the whole backplane. When the detector was cut out of a wafer, the ohmic contact was exposed at the cut edges.

TABLE I
SPECIFICATIONS OF THE IRRADIATED SILICON MICROSTRIP DETECTORS

Substrate	
Type	n-type
Resistivity	4~8 kΩ·cm
Thickness	300±10 μm
Size	
Overall dimension	60 mm×34.1 mm
Active strip area	58.8 mm×32.6 mm
Strip	
Single-sided	p^+ strips
Pitch	50 μm
Implant width[a]	12 μm
AC electrode width[a]	4, 6, 8, 16 μm
Bias resistor	
Polycrystalline silicon	250±50 kΩ
AC coupling insulator	SiO_2(0.22μm) or SiO_2(0.22μm)+Si_3N_4(0.05μm)
Passivation	SiO_2(0.7μm) or Si_3N_4(0.7μm)

[a]Measured values

TABLE II
COMBINATION OF COUPLING AND PASSIVATION INSULATORS AND THE ZONES CONNECTED

	Passivation	
AC coupling	SiO_2	Si_3N_4
SiO_2	#1(a-3-2)[a] (4,6,16μm)	#3(a-23-2) (4,6,16μm)
SiO_2+Si_3N_4	#2(b-2-2) (4,8,16μm)	#4(b-10-1) (4,8,16μm)

[a]Detector # (Specific designation)

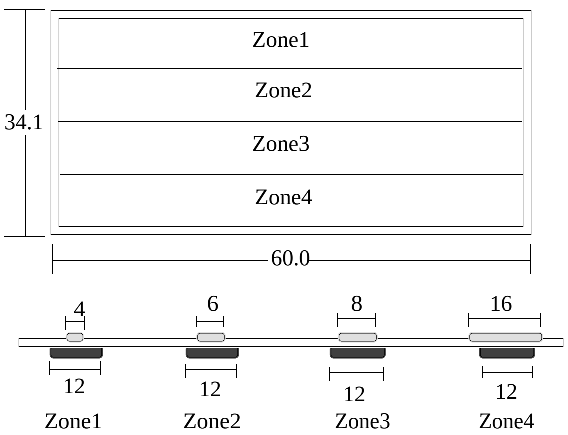

Fig. 1 Single-sided silicon microstrip detector under test. It has four zones of AC electrode widths (#1: 4μm, #2: 6μm, #3: 8μm, #4: 16μm) with a constant p-implant width of 12 μm . Four type of detectors were prepared with the AC coupling layers of SiO_2 or SiO_2+Si_3N_4, and the passivation layer of SiO_2 or Si_3N_4.

Proton Irradiation

The four detectors were irradiated at TRIUMF [8] by polarized protons with a kinetic energy of 500 MeV. The beam was diffused through a lead sheet (approximately 3mm thick) and then passed through 2 sets of lead collimators to make it roughly uniform (to 40%) over a 6cm×6cm area. Several aluminum foils were placed on each detector for the fluence measurements. The room temperature was 22±3 °C during the irradiation. The detectors were irradiated for 3.5 days while being biased at ±40 V. The bias voltage was supplied through protection resistors of 1 kΩ in the positive and the negative bias lines of each detector. The leakage current was monitored during the run (Fig. 2). After irradiation the detectors were left at the room temperature to cool the radiation (1.3 days), then transferred to a refrigerator and kept at -18 °C until shipment (20 days). The temperature during the transportation was also kept below 0 °C with dry ice (5 days).

The fluence measurements on the foil were done at Los Alamos Nat. Lab. The average fluence was 5.7×10^{13} protons/cm^2 with a spatial uniformity within 10%. The statistical errors of the fluence were typically under 3%, whereas the total error was nearly 10% and dominated by the uncertainty in the reaction cross section

$$^{27}Al + p \rightarrow {}^{22}Na + X.$$

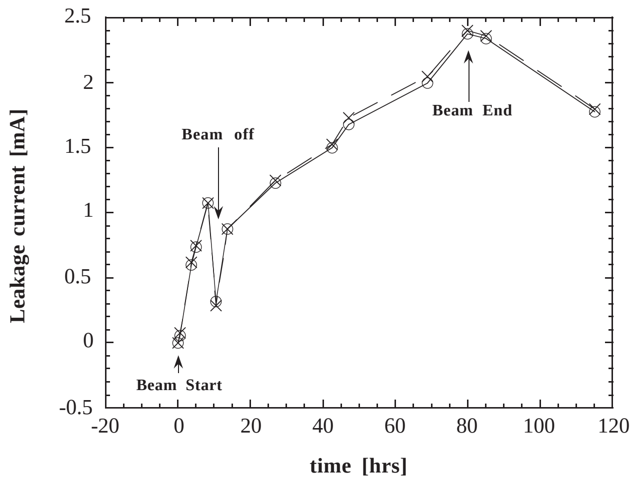

Fig. 2 Leakage current of a detector under irradiation. The bias voltage of ±40V is supplied during the irradiation (circle: n^+ back plane, cross: p^+ strip side). AC electrodes were grounded.

Measurement

Characterization of the detectors was done at 0 °C before irradiation, and then approximately once every month after the irradiation. Measured were the bias voltage dependence of the leakage current, the capacitances between the p-strips and the backplane (body capacitance), between the p-strips (inter-strip capacitance), between the p-implants and the AC electrodes (coupling capacitance), and the noise generation at the strip edges.

While being measured, the detectors remained in the refrigerator at 0 °C. Bias and measurement lines were passed out of the refrigerator to the measuring equipment. Current through the bias line was measured by a current meter (Keithley 196). Capacitances were measured by an impedance meter (HP4192A). Noise was measured using a chain consisting of a charge preamplifier, a bipolar shaper (Canberra 2021: shaping time constant of 250 ns, which was the fastest of the module), and a digital oscilloscope (Tektronix 2440) providing an RMS value for the noises over a 20 μs interval. All the equipment was controlled by a personal computer (NEC PC98) through a GPIB interface.

III. RESULTS

Full Depletion Voltage

The full depletion voltages were extracted from the body capacitances. The body capacitance was measured between the bias ring and the backplane. The bias ring had connections to p-implant strips via bias resistors. To isolate the capacitor in the power supply from the detector, a pair of resistors of 100 kΩ was put in the positive and negative supply lines. The capacitance was measured at a frequency of 10 kHz. The body capacitances were fitted to a characteristic depletion curve, $C \propto 1/\sqrt{V}$ in the depleting region (in addition to an extra capacitance effect in the power supply module). After the full depletion was achieved, the body capacitance stayed constant. The full depletion voltage was obtained from the intersection point of the two curves (Fig. 3).

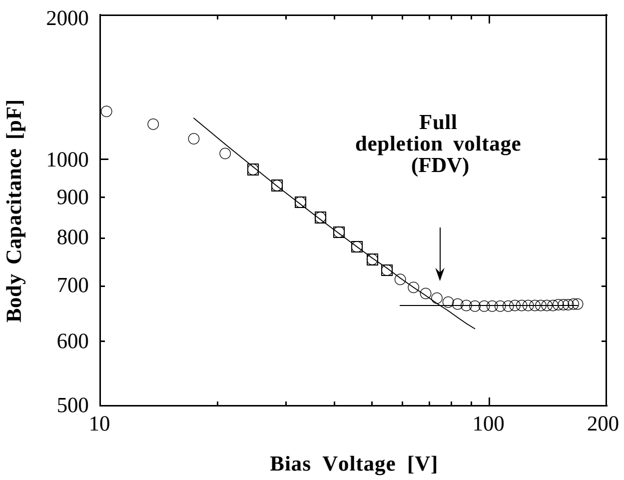

Fig. 3 Calculation of the full depletion voltage from the body capacitance measurement at the frequency of 10 kHz. The full depletion point is defined as the intersection point of the two fitted curves: $y=a+b/\sqrt{x}$ to the under-depleted region, y=c to the over-depleted region. The data shown are for the detector #1, 185 days after irradiation.

The full depletion voltages of the four detectors were plotted as a function of time after irradiation (Fig. 4). The full depletion voltages decreased for nearly 150 days and then started to increase. Because of the low temperature (0 °C) the annealing was substantially slowed, and the anti-annealing was greatly delayed, but still became observable at later times.

Plotted in the same figure is the prediction of the parameterization for the full depletion voltages by Ziock (solid curve [3]). The Ziock parameterization has both annealing and anti-annealing terms and reproduces the time variation very well. The parameterization was obtained for PIN photodiodes. Due to the finite strip pitch and width, the microstrip detectors require a larger depletion voltage than the planar geometry. A 10% increase is expected for the 50 μm pitch and the 12 μm strip width (dashed curve [9]). The Ziock parameterization is accurate within 5 %.

The LHC is anticipated to operate at a luminosity of 10^{33} $cm^{-2}s^{-1}$ in the first 3 years and 10^{34} $cm^{-2}s^{-1}$ afterwards. The fluence of the 1×10^{14} p/cm^2 will be delivered in the last 7 years over the 10 years of operation. Assuming a uniform yearly fluence and no warming-up, the Ziock parameterization predicts the full depletion voltage of 157 V at 0 °C operation and a minimum full depletion voltage of 136 V at -7 °C operation.

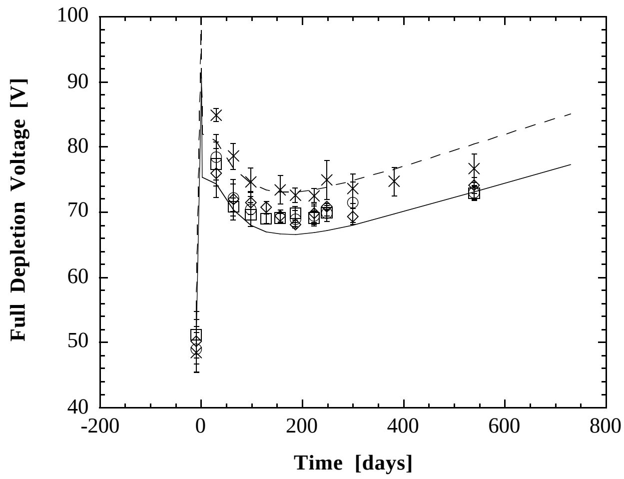

Fig. 4 Time variation of the full depletion voltage of the four detectors (cross: #1, diamond: #2, square: #3, circle: #4). Detectors were kept and measured at 0 °C after irradiation. The prediction of the Ziock's parameterization (solid curve) and a 10% increase for the strip detectors with a finite strip pitch and width (dashed).

Leakage current

The leakage current is known to increase as the bulk damage increases. The increase we observed was several orders of magnitude. Although the increase was large, it had very little bias voltage dependence (Fig. 5).

The leakage current values of the four detectors (Fig. 6) were the values at a bias voltage of 30V above the full depletion voltage. The current annealed but leveled off slightly above the Fretwurst predictions (dashed curve [4]).

The excess might be attributed to the effect of the exposed p-n junction after the bulk type inversion.

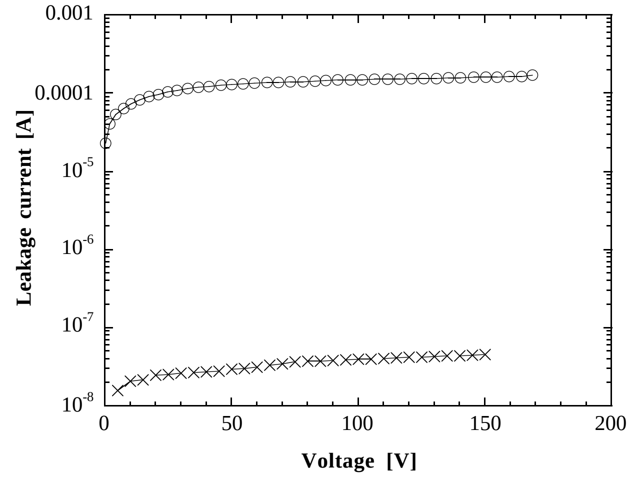

Fig. 5 Leakage current of a detector (#1) before irradiation (cross) and 185 days after irradiation (circle). Both currents were measured at 0 °C.

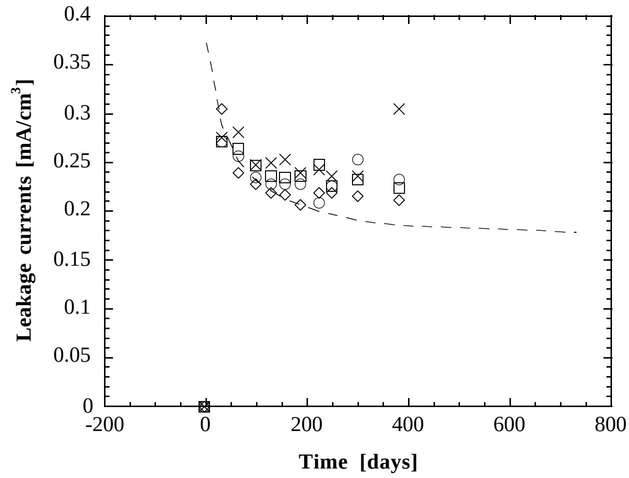

Fig. 6 Time variation of the leakage currents per unit volume for the four detectors at 0 °C. The dashed curve is the prediction of Fretwurst parameterization.

Interstrip Capacitance

Interstrip capacitance was measured between a strip and its adjacent neighbors on both sides at 1 MHz. The detectors had four zones of different widths (4, 6, 8, and 16 μm) for the AC electrodes. The p-implant had a constant width of 12 μm. The inter-strip capacitances before irradiation were more clustered around 1 pF/cm than the previous measurement [9]. A possible explanation is the constant width of the p-implant strips. After irradiation the inter-strip capacitances increased and also showed a slight variation in time (Fig. 7). The increase was worse for the wider strips. Also noticeable was the effect of the different passivation material for the wider strips. For the 16 μm electrode width, the Si_3N_4 showed a larger increase than the SiO_2 passivation.

The fundamental source of the increase is thought to be the inversion of the bulk type. After inversion, the p strips and the bulk form the ohmic contact instead of being the p-n junction as they were before the irradiation. Another source would be the trapped charge in the (interfaces) of the insulators and the bulk.

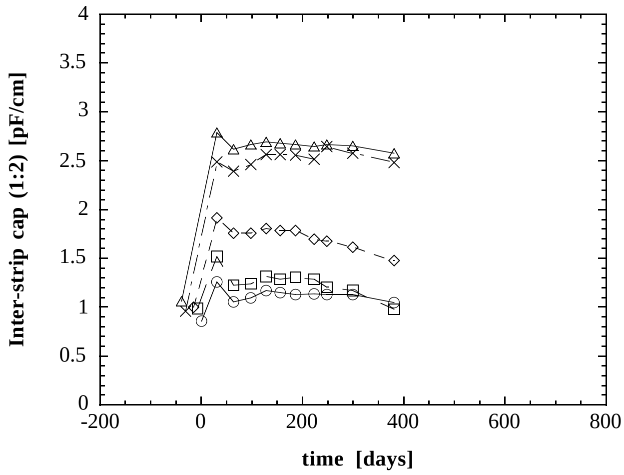

Fig. 7 Time variation of the inter-strip capacitances to the adjacent neighbors on both sides, averaged per zones (circle: 4μm, square: 6μm, diamond: 8μm, cross: 16μm-SiO2 passivation, triangle: 16μm-Si_3N_4 passivation). The data before irradiation are displaced for readability.

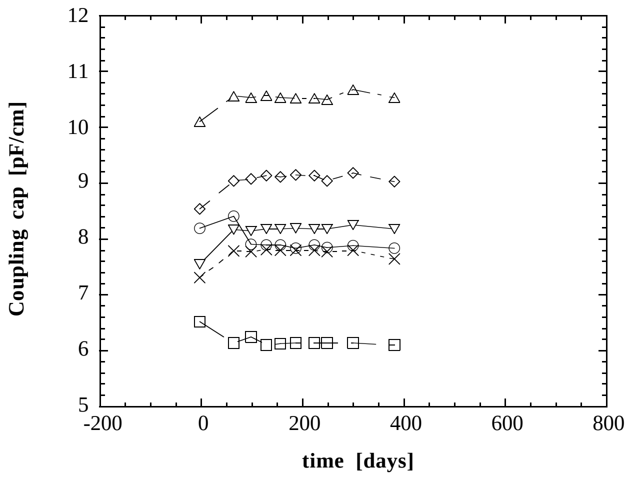

Fig. 8 Time variation of the AC coupling capacitances averaged per the zones and the insulators (O: SiO_2, ON: SiO_2+Si_3N_4) (circle: 4μm-O, square: 4μm-ON, diamond: 6μm-O, cross: 8μm-ON, up-triangle: 16μm-O, down-triangle: 16μm-ON).

Coupling Capacitance

The AC coupling capacitor works to decouple the bias voltage and the leakage current from the amplifier. The coupling capacitances, measured at 10 kHz, showed a slight increase after irradiation but very little variation in time (Fig. 8). The coupling capacitances were lower for the insulator combination of SiO_2 and Si_3N_4 than for that of SiO_2, mainly due to the thickness. Since there is strong frequency dependence in the measurement of the coupling capacitance, the values at 10 kHz are not reflecting the intrinsic capacitance but only relevant for relative comparison.

Edge-breakdown Onset Voltage

In strip detectors, the electric field near the p-n junction strip is high. The field strength increases when a ground plane is nearby. When the field strength is higher than the critical strength required to generate an electron-hole pair in the silicon, an avalanche occurs, generating additional electrical noise. This had been observed and we used narrower AC electrodes to help reduce the field strength [6]. The noise generation of the four detectors was measured by keeping the backplane and the AC electrodes grounded and applying the negative potential to the p-implant strips.

The bias voltages where the edge-breakdown noise was larger than the thermal noise were plotted as a function of the strip widths before and after the irradiation (Fig. 9). Before irradiation there was a clear trend that the narrower width helped. After irradiation, no excess noise was observed up to the bias voltage of 150 V, even for the 16 μm width. This was an additional evidence that the bulk had inverted from n-type to p-type. After inversion, the p-implant strip was the ohmic contact, instead of being the p-n junction, and the field strength would be much lower than when the p-n junction existed there.

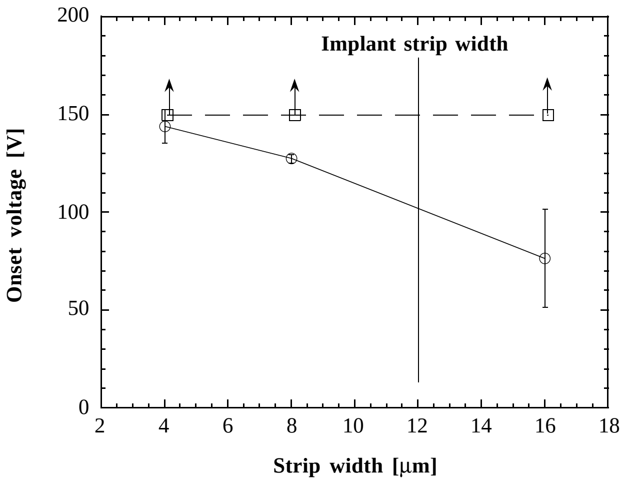

Fig. 9 Onset voltage of the edge-breakdown before (circle) and after (square) the irradiation. Before irradiation there was a clear trend as a function of the AC electrode width. After irradiation, no breakdown onset was observed up to the bias voltage of 150 V.

IV. CONCLUSION

Four single-sided n-substrate/p-implant silicon strip detectors were irradiated with 500 MeV protons at TRIUMF to a fluence of 5.7×10^{13} protons/cm^2. The irradiation was done at room temperature and the detectors were subsequently kept and measured at 0 °C to suppress the anti-annealing effect. Time variations of the detector characteristics were followed for nearly one year.

The full depletion voltage, which reflects the effective dopant concentration in the bulk, was obtained from the body capacitance measurement. The full depletion voltages have shown an annealing and an anti-annealing effect. Ziock's parameterization has reproduced the time variation and the values well.

Leakage currents have also shown an annealing effect. Fretwurst's parameterization reproduces the result reasonably well. In detail, the leakage current levels off at a somewhat larger value; possibly due to effects following type inversion at the exposed p-n junction along the edges of the detector.

Inter-strip capacitances increased after irradiation, but showed some slight annealing over time. The wider strips (i.e. narrower inter-strip gap) showed more significant capacitance increase. The Si_3N_4 passivated detectors also showed a larger increase in capacitance than the SiO_2 ones. The AC coupling capacitances have shown almost no time variation.

As expected, generation of noise at the strip-edges was observed before the irradiation. The noise appeared at lower bias voltages for the wider AC electrode widths. After irradiation, the noise was not observed up to the bias voltage applied. This can be explained as a result of type-inversion. The p-n junction moved to the backside of the detector and the electric field was greatly reduced around the p-implant strips where there was now an ohmic contact.

V. ACKNOWLEDGMENTS

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