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Efficiency of Non-uniformly Irradiated Double-sided Silicon Strip Detectors

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ABSTRACT

We have investigated the efficiency and the noise occupancy of double-sided silicon strip detectors, which were subjected to non-uniform proton irradiation of fluences up to a maximum of equivalent $5*10^{13}$protons/cm^2. The depletion voltages, varying over time due to controlled annealing, were close to zero on one end of the 6cm strips and 190V at the high radiation end. We determined the efficiency and noise occupancy on both n-side and p-side in a ^{106}Ru telescope, using a binary read-out system with 22ns shaping time. The n-side exhibits superior performance after type inversion.

I. INTRODUCTION

Silicon strip detectors have been proposed as tracking devices for both detectors[1-2] at the Large Hadron Collider (LHC), the high luminosity hadron collider approved at CERN. Due to the large flux of both ionizing and displacing particles, the radiation tolerance of the silicon detectors have to be evaluated carefully. In the past we have evaluated the post radiation performance of static parameters, like the leakage current, depletion voltage and the interstrip capacitance. Ultimately, these parameters are important only in their consequence for the operation and performance of the detectors. We have now made measurements of the efficiency and noise occupancy of irradiated detectors, using realistic front-end electronics (FEE) with short shaping times. Due to the fact that the bulk in n-type detectors inverts during operation at LHC [3], the relative performance of the p-side and n-side has to be monitored.

II. IRRADIATION HISTORY OF THE DETECTOR

As detector we used an AC coupled n-bulk double-sided silicon detector (DSSD), developed for the SDC detector by Hamamatsu Photonics [4]. It is 6cm long, 300µm thick, has 50µm pitch, 12µm implants, and 6µm metal; the n-side has 30µm p-blocking implants to minimize the interstrip capacitance. On both sides, 128 of the 640 strips were connected to a fast, low noise binary read-out system to measure the pulse height and noise characteristics. The bipolar amplifier-comparator chips LBIC [5] with 22ns shaping time are followed by a CMOS digital pipeline CDP [6]. In channels were the pulse height exceeds the threshold, a bit is kept in the pipeline until a trigger from the scintillator causes readout into the computer.

Two irradiations were performed: first, in March 1994, the detectors were irradiated with $8*10^{12}$ p/cm^2 450 MeV protons at TRIUMF. In December 1994, it was followed by irradiation with 55MeV protons in the 88” Cyclotron at LBNL. Due to the small beam spot, the later irradiation was extremely non-uniform, with the equivalent high energy proton fluence along a strip varying from $4*10^{13}$ at the maximum to less than 10^{13}p/cm^2 at the minimum. In January and February 1995, we started annealing of the detectors at room and elevated (35^{o}C) temperature to raise the depletion voltage by the anti-anneal process, described by the approximate formula:

$$V_{dep}(t,T) = v_c*F+v_a*F*(1-e^{-t/\tau_L}) \qquad (1)$$

For the fluence applied, eq. (1) is close to

$$V_{dep}(t,T) = 50+200*(1-e^{-t/\tau_L}) \qquad (2)$$

In previous experiments [7], we have measured the anti-anneal time to be τ_L = 180 days for 23^{o}C, τ_L = 38days for 35^{o}C. Table 1 shows the depletion voltage history of the most irradiated spot.

Table 1: Depletion Voltage History at most irradiated Location

Date	Depletion Voltage [V]	Comment
pre-rad:	77	
Feb 1995, post-rad	120	inverted, elevated temp anneal
Mar 1995 KEK beam test:	130	inverted, room temp anneal
Aug 1995	190	inverted, room temp anneal

Pre-rad., the depletion voltage was measured with C-V measurements, and post-rad, it was predicted from our radiation damage data and the p-side behavior, because C-V measurements were not usable due to the non-uniformity of the irradiation along the strips. In February 1995, the efficiency and position resolution of the irradiated detector was measured in a beam test at KEK [8].

The actual depletion voltages in Table 1 should be compared with a depletion voltage of 135V after 10 years of LHC operation at -10^{o}C [1]: our detector exhibits already more severe radiation damage than expected from the LHC radiation both in depletion voltage and in leakage current, due to room temperature operation.

III. THE RUTHENIUM TELESCOPE

The efficiency was measured with a ^{106}Ru telescope. Details can be found in Ref. [9]. The electrons were collimated to a beam spot of 1mmx3mm, traversed the silicon detector after a distance of 3mm and were measured in a scintillation counter 2mm wide, 6mm long and 6mm thick after a total distance of 6mm after the collimator. The threshold of the scintillation counter was set relatively high in order to accept only the upper 10% of the spectrum, to insure that only high energy tracks were recorded. This geometrical arrangement provided a beam of minimum ionizing particles with an angular divergence of 8 degrees, similar to high momentum tracks in the silicon tracking detector of the LHC detector ATLAS.

The efficiency is defined as the ratio of triggers with hits in the detector to all triggers, after noise subtraction, which is very small except for small thresholds. An advantage of determining the efficiency with the Ru telescope instead of using light signals like IR lasers or LED's is the fact that the electrons are penetrating the whole detector, including the metal, independent of varying reflection coefficients of oxides and implants, and give an absolute signal height. We have compared the pulse height distributions with the ones obtained in the KEK beam test for the same detector [8,10] and found the median pulse to be about 15% lower in the Ru telescope, which can be attributed to the finite crossing angles of the tracks mentioned above.

IV. EFFICIENCY FOR DIFFERENT DEPLETION VOLTAGES

The efficiency of the detector depends on the bias voltage, and is expected to be a function of the depletion voltage, which changes both as a function of time due to the annealing and as a function of location due to the non-uniform irradiation. The efficiencies at 1fC threshold as function of bias voltage are shown for the most irradiated spot with a fluence of $5{*}10^{13}$p/cm^2 in Fig. 1 for the p-side and in Fig. 2 for the n-side.

The difference between the n-and p-side both pre- and post-rad. are striking, as is the difference between the behavior pre- and post-rad. for either side. On the p-side, the efficiency before radiation is only a weak function of the bias voltage, and we find good efficiency even for bias voltages below the depletion voltage of 77V. The situation is very different after inversion. For both depletion voltages 120V and 190V, the efficiency falls below unity immediately below the depletion voltage, as expected from the fact, that the p-side is the ohmic side after inversion and thus looses isolation below depletion. On the other hand, the n-side (Fig. 2) is loosing efficiency immediately below depletion before irradiation, because it shorts out, but exhibits large efficiencies even at bias voltages far below depletion after irradiation, which is typical for the junction side.

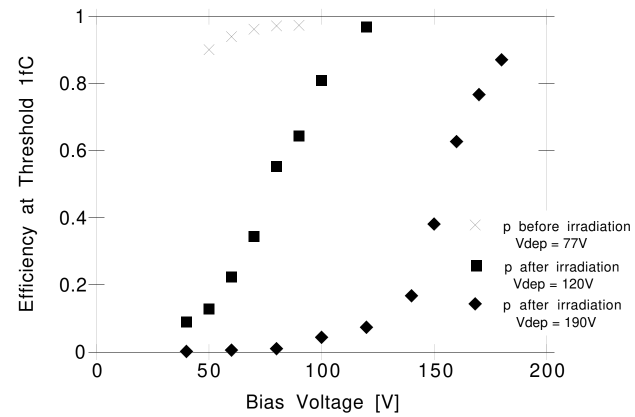

Fig. 1: Efficiency of the p-side at 1fC threshold for the most irradiated spot ($5{*}10^{13}$ p/cm^2) as a function of bias voltage for three different times in the irradiation history.

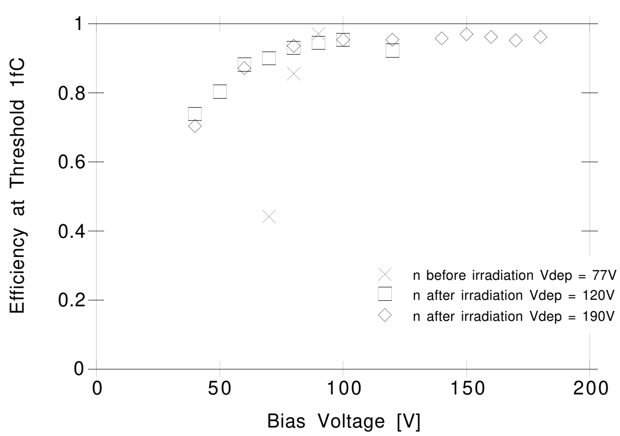

Fig. 2: Efficiency of the n-side at 1fC threshold for the most irradiated spot ($5{*}10^{13}$ p/cm^2) as a function of bias voltage for three different times in the irradiation history.

V. EFFICIENCY ALONG THE DETECTOR STRIPS

The detector has extremely non-uniform depletion characteristics along the strips: at the end where the fluence was low, the depletion voltage is below 50V; at the other end the depletion voltage is close to 190V. The efficiency as a function of bias voltage for three location and pre-rad is shown in Fig. 3 for the p-side, and in Fig. 4 for the n-side, both for the most annealed case. The bias voltage to achieve high efficiency varies along the strip for the p-side, while it is much more uniform for the n-side. We have no indication of any dead regions when we scan along the strips, but we are doing now a systematic study in fine steps with a LED. The area with low fluence showed little change in efficiency over the anneal time at constant bias, while on the highly irradiated end, the depletion voltage rose from 120 to 190V.

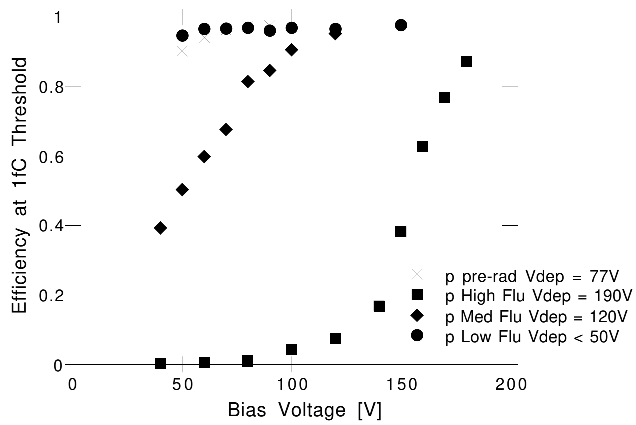

Fig. 3: Efficiency of the p-side at 1fC threshold for three different location along the detector after anneal and pre-rad as a function of bias voltage.

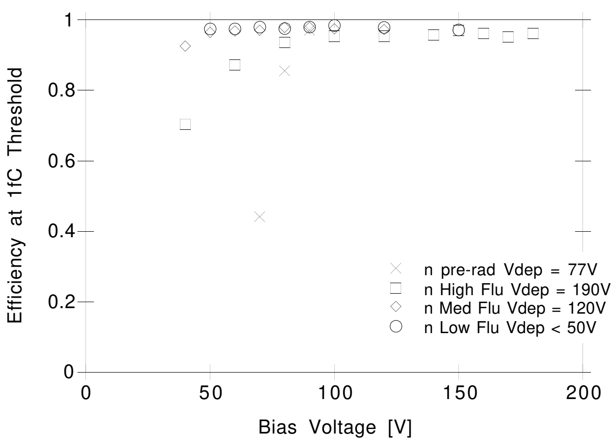

Fig. 4: Efficiency of the n-side at 1fC threshold for three different location along the detector after anneal and pre-rad as a function of bias voltage.

VI. NOISE OCCUPANCY

The noise occupancy can be determined taking data out of time with the trigger, or with off-beam data. The noise sigma can be extracted from the noise occupancy vs threshold voltage curves [11], and agrees with the noise determined with the calibration procedure. The noise depends on the interstrip capacitance. We have observed before that the interstrip capacitance changes dramatically due to inversion [12]. The n-side interstrip capacitance, which is strongly bias dependent before inversion, becomes bias independent after inversion and shows a strong decrease. The p-side interstrip capacitance increases slightly after inversion.

As expected, the same trend is seen in the measured noise, as seen in Fig 5. The n-side noise after inversion is much smaller than the noise before, and even smaller than the p-side noise, either before or after irradiation. At 1fC threshold, the noise occupancies are below the 10^{-6} level for 6cm long detectors. It will be interesting to measure 12cm irradiated detectors, although it seems probable that we will reach a noise occupancy of less than 10^{-3} with inverted n-side detectors, the performance target for the ATLAS silicon system.

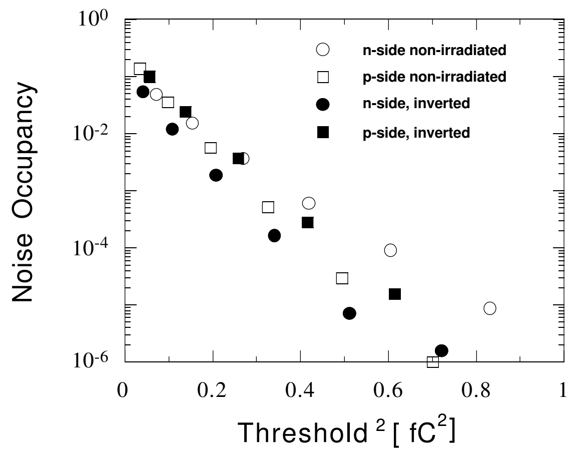

Fig. 5 Noise occupancy as function of threshold for 6cm long detectors before and after proton irradiations. The large decrease of the n-side noise after inversion is evident.

VII. OPERATION OF HIGHLY IRRADIATED DETECTORS

As shown in Fig. 2, the n-side looses efficiency after inversion only very slowly below depletion voltage. Larger inefficiency occurs when the bias voltage reaches about half the depletion voltage, where 70% of the detector is depleted. Our simulations [13] have shown that due to the finite drift time, the charges collected from the detector region beyond 70% of the thickness do not contribute to the signal in a fast shaping amplifier. This so-called ballistic deficit [14] degrades the signal even above the depletion voltage, and is a constant effect as long as the bias voltage is above half the depletion voltage. Only after the bias voltages drops below half the depletion voltages, the loss in collection region decreases the signal.

VIII. ULTIMATE FLUENCE FOR THE ATLAS SILICON TRACKER

We observed that the efficiency on the n-side is still above 95%, when the inverted detector is biased at half the depletion voltage. This is in contrast to the p-side, which is efficient only after the detector is fully depleted. We are now routinely operating detectors at 200V bias, and take this as a conservative upper operating point. We can anticipate that we will be able to operate detectors with a depletion voltage of 400V at this voltage and still be efficient. For ATLAS [1], we expect (for operation at -10^{o}C) a depletion voltage of about 135V after a fluence of 10^{14}particles/cm^2. Thus, it looks very plausible that one can operate n-side detector safely with high efficiency after at least three times that fluence, i.e. $3{*}10^{14}$particles/cm^2.

For our next beam test at KEK in February, we plan to irradiate detectors to fluences of (1 to 3)$*10^{14}$p/cm^2 to prove this point. This will require continuous cooling of the detectors to about $0\,^{o}$C .

IX. CONCLUSIONS

We determined the efficiency of highly irradiated double-sided silicon detectors on both the n- and p-side with a fast read-out chip. The fluence changed continuously along the strips: part of the detector was inverted with a depletion voltage of close to 200V, the other end had a depletion voltage of less than 50V. In the inverted part, the p-side efficiency is close to unity only when the bias voltage is above the depletion voltage, while the n-side is efficient already at half the depletion voltage.

Because we operate single-sided detectors now routinely at 200V, and based on our observation that inverted n-side detectors are efficient at half the depletion voltage, we predict that we will be able to operate efficiently detectors which deplete at 400V. Under continuous operation at a lowered temperature of $-10\,^{o}$C , we expect that this depletion voltage is reached for the ATLAS silicon tracker at an ultimate fluence of $3*10^{14}$particles/cm^2.

The reduced n-side noise, together with the robust signal performance, points to stable operations of n-side detectors after inversion. Use of n-side detectors allows a large safety margin in signal-to-noise with respect to the expected radiation levels in ATLAS.

X. REFERENCES

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