Pulse Height of MIP's in an n-side Silicon Microstrip Detector after Proton Irradiation with a Fluence of $1 \times 10^{15}\ \mathrm{p\,cm^{-2}}$

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Abstract

We have irradiated a n-side silicon microstrip detector with 55 MeV protons up to an equivalent fluence of $1 \times 10^{15}\ \mathrm{p\,cm^{-2}}$ high energy protons. We determine the median pulse height to be 0.7 fC at 180 V bias and deduce a depletion region of about 80 μm.

I. Introduction

Plans for a pixel detector in ATLAS at the LHC [1] anticipate a total fluence of about $10^{15}\ \mathrm{p\,cm^{-2}}$. This is about a factor 10 higher than for the silicon strip detectors. The advantage of pixels is the potentially low noise and thus the possibility to achieve satisfactory signal/noise levels with under depleted detectors. The depletion voltage of a 300 μm thick detector after those fluences is projected to be in excess of 1000 V at an operating temperature of $-50°$C. We have irradiated an n- on-n strip detector with initial depletion voltage of 70 V through inversion up to an equivalent high energy fluence of $10^{15}\ \mathrm{p\,cm^{-2}}$ and have measured the median pulse height with a ^{106}Ruthenium source at bias voltages varying from 90 to 250 V.

II. Detector and Beam

The detector was a double-sided, AC-coupled, silicon strip detector with $50\mu\mathrm{m}$ pitch and narrow implant, fabricated by Hamamatsu Photonics and used in the 1995 KEK beam test [2]. The thickness was $300\mu\mathrm{m}$ and the depletion voltage was 70 V before irradiation. We connected 128 strips on the n-side to the channels of a low-power, fast amplifier comparator chip LBIC [3] followed by a digital pipeline CDP64 [4], and providing the bias to the p-side. The readout was done via a local level shifter board located about 10 cm from the detector and 20 m cable through the VME based readout sequencer DRS at 40 MHz into a Mac PC. The beam of 55 MeV protons was produced by the 88" Cyclotron at LBNL. At 55 MeV, we expect about twice the displacement damage of high energy pions or protons [5]. Thus we will later double the fluences to convert to damage due to high energy protons, which we will call "MIP's". The beam was collimated with a carbon block to a diameter of 1 cm and had an intensity of about $10^{14}\ \mathrm{p\,cm^{-2}\,hr^{-1}}$ of 55 MeV protons. After predetermined fluences were reached ($2.5 \times 10^{12},\ 1 \times 10^{13},\ 5 \times 10^{13},\ 2.5 \times 10^{14},\ 5 \times 10^{14}\ \mathrm{p\,cm^{-2}}$), the beam shut off automatically and, after a waiting period of about 20 min to 1hr to allow the latent activity to die down, the response of the detector at the irradiated spot was measured with a ^{106}Ruthenium source and scintillator telescope, with a beam spot of minimum ionizing particles of 3 μm [6]. To shield the non-rad hard part of the front end electronics, we covered both faces of the detector with lead sheets of 1/2" thickness, leaving only 1 cm x 1 cm beam holes. The program of measuring the response after each irradiation step was followed until the step at $2.5 \times 10^{14}\ \mathrm{p\,cm^{-2}}$, after which the increased activation of the lead shield released such a large flux of gamma's that a charged particle trigger from the source was swamped with gamma ray hits. At that point, we performed threshold scans during irradiation, using a random trigger. The intensity was so high that we could expect about 6 particles in each strip in each 25 ns time slice, allowing for a large signal. We were able to monitor the proper working of the DAQ chain on-line. The response of the detector to the final fluence of $5 \times 10^{14}\ \mathrm{p\,cm^{-2}}$ equivalent to $1 \times 10^{15}\ \frac{\mathrm{MIP}}{\mathrm{cm^2}}$ was measured in the laboratory after the detector had been stored for about two weeks at $-20°\mathrm{C}$ to loose enough activity to be transported. The geometrical arrangements were very different for the on-line and laboratory measurements, which resulted in different geometric corrections.

III. Temperature Control

The detector was biased to about 100 V during the irradiation, with current monitoring to prevent thermal run-away. In addition, the detector was kept at a constant temperature of $47 \pm 3°$C with the help of heater tapes. The reason for the strict temperature control is that the observed depletion voltage is a function of both the applied fluence and the operating temperature during irradiation and annealing. For intense irradiation as performed here, the initial depletion voltage right after beam shut-off is up to a factor 4 higher than at the minimum, which is reached after a short-term annealing time τ_s. With increasing time, the depletion voltage increases again, the so-called anti-annealing, with a characteristic long-term anti-anneal time τ_l. The lowest depletion is reached at a time long with respect to τ_s and short with respect to τ_l.

Thus, during irradiation with constant flux F, the depletion voltage V_D is given approximately by [7]:

$$V_D = v_z F \times t + v_s F \tau_s (1 - e^{-\frac{t}{\tau_s}}) + v_a F (t + \tau_l(-1 + e^{-\frac{t}{\tau_l}})) \quad (1)$$

and after an instantaneous fluence ϕ, and elapsed time dt, the depletion voltage is:

$$V_D(dt) = \phi(v_z + v_s e^{-\frac{dt}{\tau_s}} + v_a(1 - e^{-\frac{dt}{\tau_l}})) \quad (2)$$

To first order, the constants v are independent of fluence and temperature and have been measured to be:

constant minimum : $v_z = 1.06 \times 10^{-12} \mathrm{V\ cm^{-2}}$
short-term : $v_s = 3 \times 10^{-12} \mathrm{V\ cm^{-2}}$ [8]
long-term : $v_a = 3.8 \times 10^{-12} \mathrm{V\ cm^{-2}}$.

As pointed out before, the lowest depletion voltage is reached when: $\tau_s \ll t \ll \tau_l$. Both anneal times are independent of fluence and are a function of the operating temperature alone:

$\tau_s = 70 \times e^{-0.175t}$ days
$\tau_l = 9140 \times e^{-0.152T}$ days, T in °C.

Table 1 shows the anneal times as a function of temperature. It should be noted, that for the LHC where the duration of irradiation is several years, we plan to operate at -10°C. Here, where the times are of the order hours, an elevated temperature gives the minimum depletion. From table 1, we found an optimal operating temperature of $+45$°C. Because we have ensured that the initial damage is annealed out, the uncertainty in the exact size of this part which anneals out on the short time scale is irrelevant.

Table 1
Temperature dependance of annealing constants

T [$°C$]	τ_s [days]	τ_s [hrs]	τ_l [days]
-10	403	9670	4.18×10^4
-5	168	4030	1.95×10^4
0	70	1680	9140
5	29.2	700	4270
10	12.2	292	1999
15	5.07	122	935
20	2.11	50.7	437
25	0.881	21.1	20
30	0.367	8.82	95.6
35	0.153	3.67	44.7
40	0.0638	1.53	20.9
45	0.0266	0.639	9.78
50	0.0111	0.266	4.57

Fig. 1 shows the depletion voltage vs. time assuming a constant flux of $10^{14}\ \mathrm{p\,cm^{-2}\,hr^{-1}}$ and one hour measuring times without beam; the depletion voltage is smaller for higher temperatures. In this scenario, for an operating temperature of 45°C and a fluence of $10^{15}\ \mathrm{cm^{-2}}$ of high energy protons ("MIP's"), we can expect a depletion voltage of about 1400 V for the 300 μm thick detector. This is about a factor 10 higher than that for the ATLAS silicon strips in 10 years of LHC operation.

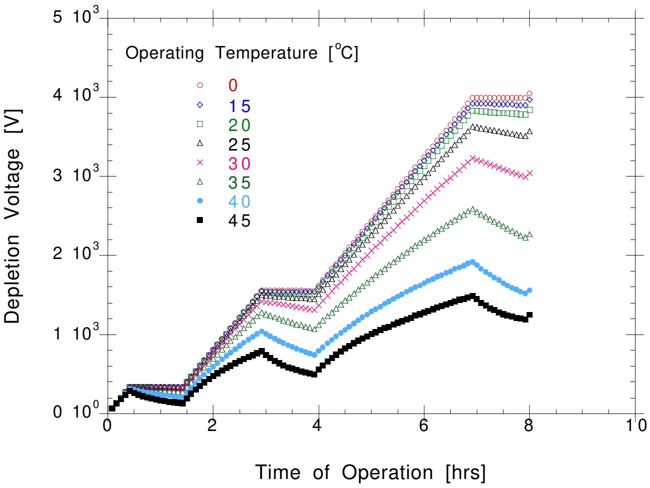

Fig. 1 Predicted depletion voltage as a function of time for a constant flux of $10^{14}\ \mathrm{cm^{-2}\,hr^{-1}}$ and one hour measuring time after 1/2, 3, 7 hours, as a function of operating temperature.

IV. Results

The pulse height is extracted from threshold scans, where the counting rate as a function of threshold setting is determined. They are shown in Fig. 2 for the different fluence points. The pulse height spectrum is the derivative of this integral spectrum, and the median is simply the threshold point where the counting rate reaches 50 %. One has to understand possible geometrical inefficiencies and trigger biases to determine the 50 % point. For example, during on-line measurements, the distances between detector and source and defining scintillator were very large and the source particles were not contained; as mentioned above, the photon rate in the scintillator increased during the run due to activation. The geometrical efficiency was thus about 50 %. (see Fig.2). During the final laboratory measurement, the geometric efficiency was close to 100 %.

To prove that the detector was still working after $10^{15}\ \mathrm{p\,cm^{-2}}$, we show in Fig. 3 the channel maps of the ^{106}Ru tests at a constant threshold of 1.4 fC for different bias voltages: the source profile is clearly seen in the first 50 channels, and otherwise there is little noise, up to a bias of 220 V.

At the highest fluence, $10^{15}\ \mathrm{p\,cm^{-2}}$ of high energy protons, the pulse height is 0.7 fC and the noise becomes an issue. The detector showed leakage currents of a few mA, all concentrated in a small area of about 50 strips. Thus strip currents of 10-100 μA were encountered - given the high operating temperature -, with corresponding noise of 1000's of electrons. The counting rate has been corrected for the noise with the help of source-off scans. Fig. 4 shows the median pulse height as a function of fluence for the runs where the "on-line" threshold scans were possible and for the final fluence.

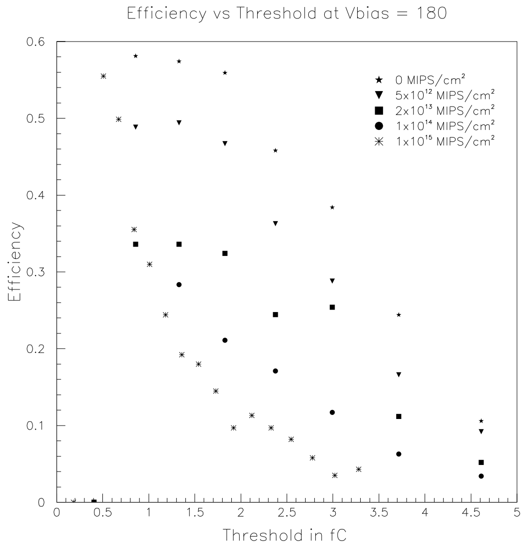

Fig. 2 Threshold scans with ^{106}Ru source after different fluence levels. The pulse height is the threshold at which the distributions reach 50 % of their maximum occupancy.

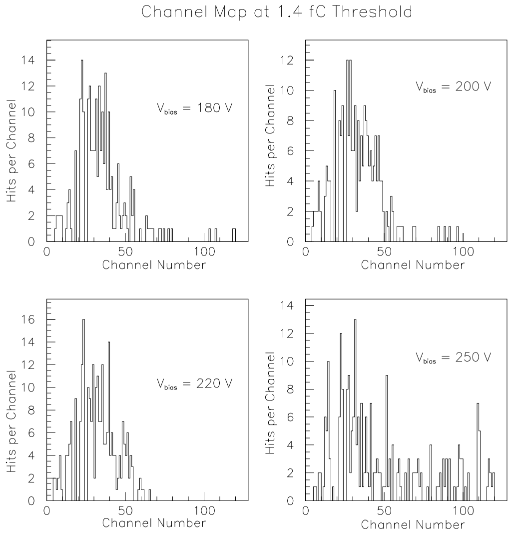

Fig. 3 Channel maps at 1.4 fC threshold for different bias voltages at the highest fluence.

Fig.5 shows the relative pulse height for the 300 μm thick detector as a function of fluence, normalized to the pre-rad value, at a bias voltage of 180 V. After a fluence of 10^{15} $\mathrm{MIP\,cm^{-2}}$, the pulse height is about 20 % of its initial value. For comparison, we also show the pulse height data from [9], where we have averaged the values for the peak and mean for comparison with our median data. Given that the data were taken at different bias voltages and temperatures, the data agree well.

For collider application, the dependence of the pulse height on both the fluence and bias voltage is of interest. In the absence of charge loss due to trapping [10], the pulse height is directly proportional to the depleted region, and thus depends on the ratio of bias voltage to depletion voltage. With the bias voltage $\mathrm{V_B}$ limited to about 200 V, and the depletion voltage reaching about 2000 V, the detector will be under-depleted and

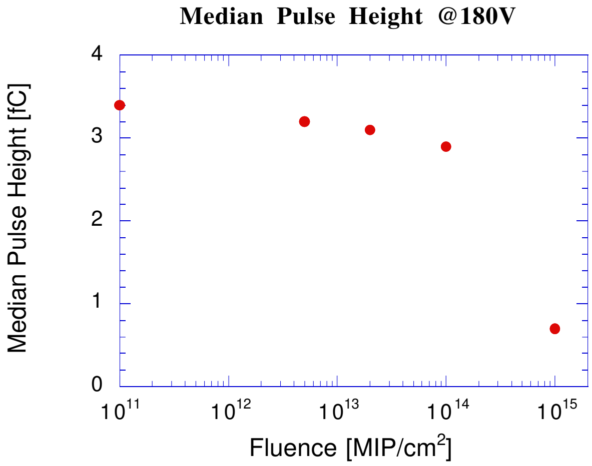

Fig. 4 Median Pulse height of the ^{106}Ru scans as a function of fluence, taken at 180 V bias. The pre-rad value is shown at 10^{11} $\mathrm{MIP\,cm^{-2}}$.

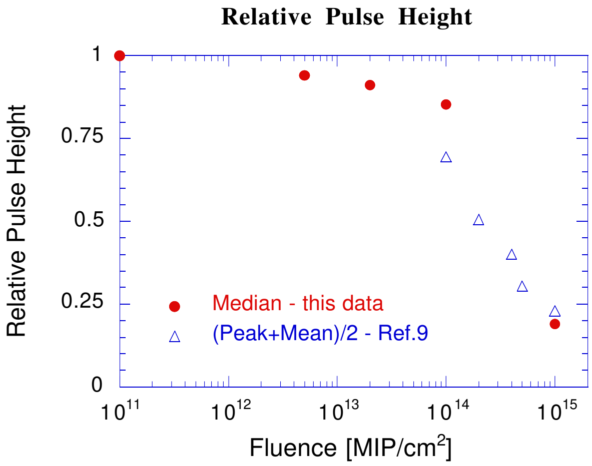

Fig. 5 Median pulse height of the ^{106}Ru scans, normalized to the pre-rad value (shown at 10^{11} $\mathrm{MIP\,cm^{-2}}$), as a function of fluence, taken at 180 V bias. In addition, the average of peak and mean pulse height of Ref. 9 are shown.

thus the pulse height will be less than the initial 3.4 fC. The depletion voltage is proportional to the square of thickness of the depleted region, and thus the pulse height PH has two different dependences on the depletion voltage $\mathrm{V_D}$:

$$\mathrm{PH} \simeq \mathrm{const} \qquad \mathrm{for V_D < V_B}, \tag{3}$$

$$\mathrm{PH} = 3.4 \times \sqrt{\frac{\mathrm{V_B}}{\mathrm{V_D}}}\ \mathrm{fC} \qquad \mathrm{for V_D > V_B}. \tag{4}$$

At a depletion voltage of about 2000 V, one predicts a pulse height PH of about 1fC, when biased with 180V. Trapping would reduce this value to about 0.7 fC, the number we are observing. In order to check the consistency of the data, we plot in Fig.6 the pulse height vs $\frac{1}{\sqrt{\mathrm{fluence}}}$: as we see, the pulse height is essentially constant up to a fluence of 10^{14}, and should reach zero at infinite fluence. A straight line between the origin and the point at 10^{14} passes close to the point at the highest fluence. We find that the observed pulse height agrees with the our expectations.

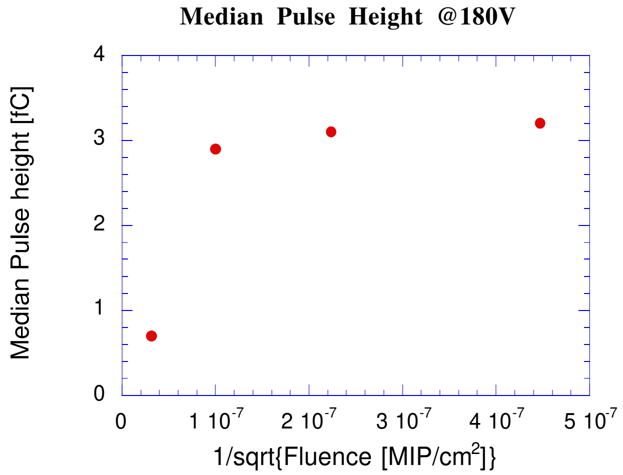

Fig. 6 Median pulse height of the $^{106}\mathrm{Ru}$ scans,taken at 180 V bias as a function of the inverse of the square root of the fluence.

V. Bias Voltage Dependence

We find that at the ultimate fluence the median pulse height is only weakly dependent on the bias voltage: between 180 V and 220 V the median increases by about 10 % , which is consistent with both a depletion voltage close to 2000 V and a square root dependence of the pulse height on the bias voltage, as explained above. Taking into account trapping, the 0.7 fC median corresponds to a depletion thickness of about 80μm at 180 V bias. Assuming, as the data indicate, that the depletion voltage is close to 2000 V at a fluence of $10^{15}\ \frac{\mathrm{MIP}}{\mathrm{cm}^2}$, we can determine the pulse height for different bias voltages. Fig. 7 shows the pulse height for the fluence of $10^{15}\ \frac{\mathrm{MIP}}{\mathrm{cm}^2}$ as a function of the bias voltage. The fact that the pulse height varies only slowly with the bias voltage in the realistic range below 500 V is one of the characteristics of n-on-n detectors which allows their use in the cases where the depletion voltages are very high.

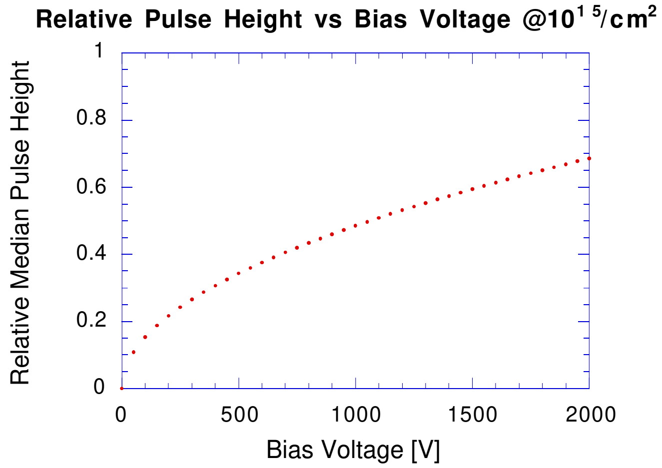

Fig. 7 Predicted median pulse height at a fluence of $10^{15}\ \frac{\mathrm{MIP}}{\mathrm{cm}^2}$ as a function of the bias voltage.

VI. Conclusions

We have tested the response of a n-on-n silicon strip detector after irradiations to fluences up to equivalent $10^{15}\ \frac{\mathrm{P}}{\mathrm{cm}^2}$ of high energy protons. Using a $^{106}\mathrm{Ru}$ telescope, we find a median pulse height of about 0.7 fC at a bias of 180 V, in reasonable agreement with expectations based on the measured fluence and temperature dependence of the depletion voltage.

VII. References

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[8] The value vs= 1.34*10-12 in Ref. 7 is a likely underestimate

[9] R. Horisberger et al, *presented at the 3rd International Workshop on Pixel Detectors for Particles and X-Rays, Bari, Italy, March 1996*

[10] Extrapolating the data of C. Leroy et al, *CERN-ECP/96-08*, trapping is expected to reduce the pulse height by about 30 % at the highest fluence