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High Voltage Performance of Silicon Detectors Irradiated under Bias

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Abstract

The CMS Preshower detector contains $16m^2$ of silicon. The silicon sensors' design is being finalized by taking into account their performance after five years of operation at high luminosity. Three detectors from different manufacturers were irradiated by neutrons and photons under bias and at low temperature. Their electrical parameters and their response to α and β particles were measured. The charge collection efficiency attains a plateau at around 300 V. The irradiation set-up and the results of the measurements are presented in this paper.

1 Introduction

The CMS experiment contains two end-cap preshower detectors whose main function is to provide $\pi^\circ - \gamma$ separation. The preshower detectors consist of two thin lead converters, 2 and 1 $X_\circ$, each followed by silicon strip detector planes. The choice of solid state detectors has been dictated by the requirement to have compact, segmented detectors with good linearity in their energy response.
The total area covered by silicon sensors is $16m^2$. For the detectors located at the highest rapidity covered by the preshower, η=2.6, the integrated fluence will reach $1.6 \times 10^{14} n/cm^2$ and the dose $7 \times\ 10^4$ Gy after 10 years of LHC operation. The preshower project requires therefore the development of low cost but robust and radiation hard silicon detectors.

2 Irradiations

Full size Preshower detectors from two manufacturers were available for this study [1]. They were made on n-type, floating zone (FZ), high resistivity ($> 4.5k\Omega cm$) silicon. The active area was 60x60 mm^2, with 32 DC coupled strips at a pitch of 1.8 mm.

The neutron fluences and doses each detector received and the irradiation conditions are shown in table 1. The thickness of the detectors was estimated from the full depletion layer capacitance of the complete detector before irradiation.

Detector	A	B1	B2	B3
Thickness [μm]	353	302	277	313
Fluence [$\times 10^{14} n/cm^2$]	1.22	1.35	1.82	-
Dose [kGy]	75	75		
Bias [V]	100	100	off	
Irradiation temperature ^oC	-5	-5	20	

Table 1: Parameters of the irradiated detectors.

Two detectors, A and B1, were irradiated in the Ulysse reactor in Saclay [1] at -5^oC under a bias of 100 V. Detector B2 was irradiated at the Dubna reactor [2] at room temperature for 3 hours and without the bias voltage. All detectors were kept at low temperature, always below 0^oC, after irradiation.

3 Neutron flux calibration

The neutron flux calibration is an important issue of the irradiation procedure. Since we are only interested in the damage process in the detectors, we used silicon diodes to calibrate the *1 MeV equivalent* flux of the Ulysse reactor and to cross check the calibration of the Dubna reactor.

The leakage current of Si diodes increases proportionally with the fluence, which can be calculated from the relation: $\Delta I/\Delta v = \alpha \times \Phi$, where ΔI is the increase of the leakage current, Δv is the sample's volume, Φ is the neutron fluence and α is the damage constant.

3.1 The Ulysse reactor

The goal of this calibration was to measure the neutron flux per unit area, time and reactor's power and also the neutron flux as a function of the position along the canal in the reactor. The irradiation canal has a cross section of $11 \times 11 cm^2$ and a length of 40 cm and is located inside the graphite reflector and extends up to the Uranium plates. The detectors are placed in the canal parallel to its axis and we expected a small non-uniformity of the the netron flux over the detectors area.

Nineteen silicon diodes [2], $2 \times 2 \times 0.04 cm^3$, were used for the study. They were made on n-type, FZ silicon from Wacker [3] of an initial resistivity of $\rho > 6k\Omega cm$. They were placed at different locations on the support structure

[1] detectors A were produced by ELMA, Zelenograd, Russia, detectors B by Hamamatsu, Japan

[2] Produced by ELMA, Zelenograd, Russia

[3] Wacker AG, Burghausen, Germany

and inserted in the reactor's canal. Location at 0 cm corresponds to the end of the canal, the position closest to the Uranium plate.

The diodes were irradiated without bias and at room temperature. They were then stored at room temperature for about 35 hours and at -10^0C for a further 19 days, before measurements begun.

The attenuation of the neutron flux along the canal is shown in figure 1, where the leakage current at full depletion voltage is plotted as a function of the diode's distance from the end of the canal. One sees from the plot that the neutron flux decreases by approximately a factor of two every 8 cm.

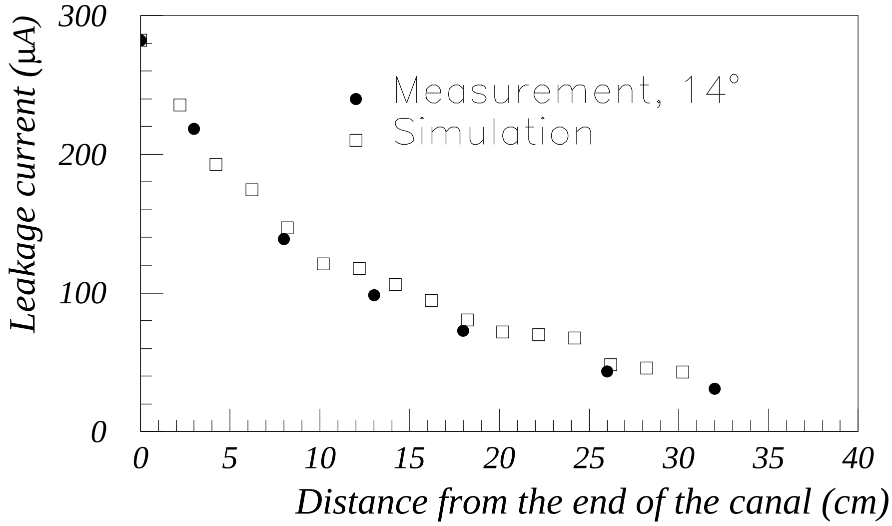

Figure 1: Leakage current of silicon diode $2 \times 2 \times 0.04\ cm^3$ as a function of the sensor's position in the canal of Ulysse reactor.

To confirm these results a simple model of the reactor has been developed. The geometry of the shielding and of the graphite reflectors has been introduced in the simulation. Only the three Uranium plates, 6.5 cm wide and 60 cm high, closest to the canal are taken into account. The distance between the neighbouring plates is 15 cm. Neutrons emitted by the U plates scatter elastically and isotropically in the graphite with a mean free path of 7 cm, while those hitting the shielding are absorbed. In the simulation sixteen sensors are placed along the canal. The number of neutrons, N, and the neutron path, l, in each of them is calculated. The damage of the Si crystal lattice is proportional to the number of neutrons and to their path length in the silicon, so $N \times l$ is proportional to the expected leakage current. The results are shown in figure 1, where the result of the simulation is normalized to the measured leakage current at position 0 cm. The simulation agrees very well with the measured dependence of the flux on the distance from the U plates.

A consequence of this dependence is the fact that the fluence uniformity on a $6 \times 6cm^2$ detector is about $\pm 15\%$.

The absolute neutron flux can be derived from the increase of the volume leakage current. Several values of the damage constant, α, have been reported [3]-[16]. They were measured at different times after the irradiation and at different temperatures. An average of a couple of independent measurements made after several days of room temperature annealing is about $3 \times 10^{-17}A/cm$ and this is the value we used for our computation. In order to be sure that our detectors were annealed we took out of the fridge 7 out of 19 diodes and stored them at approximately 22^oC, measuring frequently the leakage current and the full depletion voltage. The measurements were always done at 14^oC. Figure 2 shows the dependence of the leakage current on time for these diodes. The values of the leakage current measured on the seventieth day after irradiation were taken for the absolute neutron measurements.

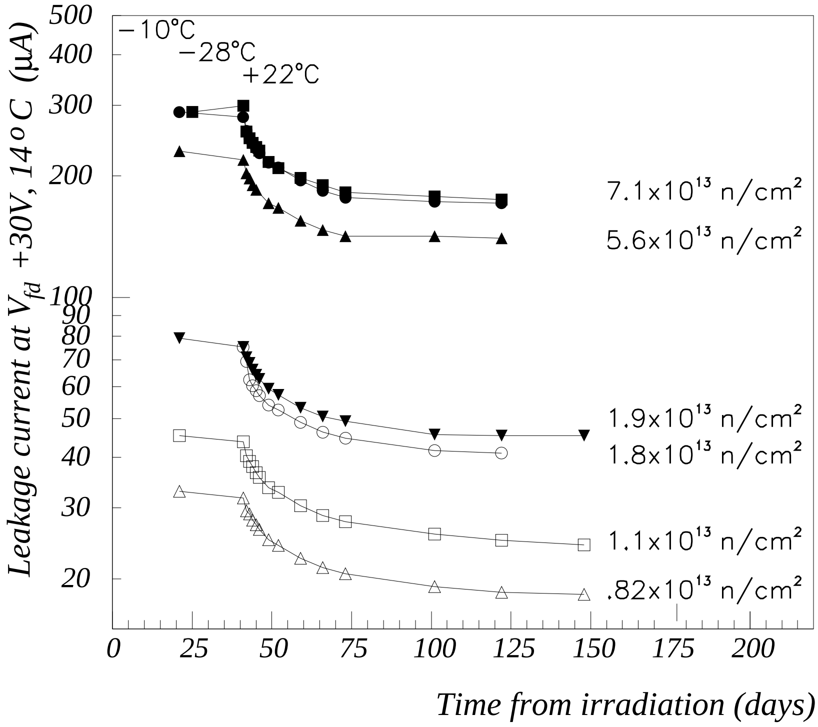

Figure 2: Leakage current of 7 Silicon diodes $2 \times 2 \times 0.04$ cm^3 as a function of time for different storge temperatures. Measurements are always done at 14^oC. The neutron fluences shown were calculated from the leakage current after 70 days.

3.2 The Dubna reactor

In the Dubna reactor the detectors are placed parallel to the reactor's axis and the radiation is homogeneous over the whole surface. The neutron flux in this reactor was calibrated using the threshold detector activation method for several reactions with thresholds between 0.4 MeV and 6 MeV [2]. The precision of this method is estimated to be around 20 %.

To cross check the relative calibration of the two reactors, three diodes of the type previously described were irradiated in Dubna and the leakage current measured in exactly the same conditions as for the Ulysse reactor calibration. The agreement between the fluence estimated from leakage current and the fluence derived from the activation method was better than 15 %.

4 Electrical measurements

Figure 3 shows the total leakage current of detectors A, B1 and B2 as a function of bias voltage at about -3^oC. All detectors can stand high values of the bias voltage values without breakdown. The ratio of the leakage current for B1 (irradiated with bias) and B2 (irradiated without bias), 0.76, is in good agreement, given the flux uncertainties, with the expected value, 0.81, due to the different fluences and thicknesses of the two detectors.

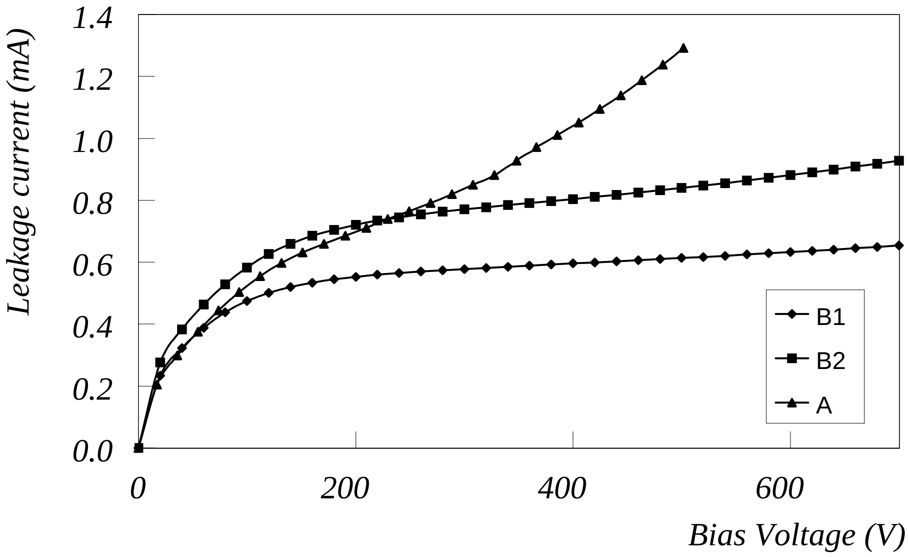

Figure 3: Total leakage current of detectors A, B1 and B2 measured at -3^oC.

Figure 4 shows the inverse square of the depletion layer capacitance of detectors A, B1 and B2 measured at 100 kHz. The estimated full depletion voltages are 93 V and 105 V for B1 and B2 respectively. Because of its larger thickness detector A has a slightly higher full depletion voltage (114 V).

In conclusion, the electrical measurements do not show sizeable differences between the detectors irradiated with or without bias.

5 Response to particles

5.1 α particles

Two strips of detector B1 were bonded to a charge amplifier with an integration time of about $1\mu s$ and the detector was exposed to an ^{241}Am source producing α particles of about 5 MeV. Figure 5 shows the recorded pulse height as a function of the bias voltage for the source illuminating the p-side and the n-side. As expected a small signal is visible at low voltages when the α particles are injected on the n-side proving that the silicon is inverted to p-type and that the junction is on the n^+ side. Placing the source on the p^+ side requires a much higher voltage in order to see the signal. In both cases the efficiency plateau is reached at about 300 V.

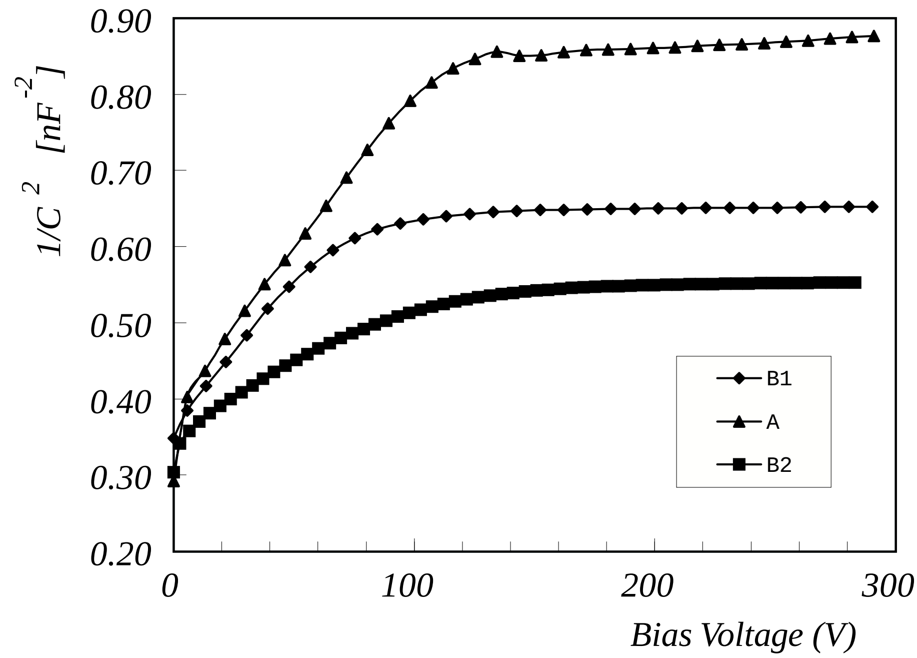

Figure 4: Inverse of the square of depletion layer capacitance (for the whole detector) of detectors A, B1 and B2 measured at 100 kHz.

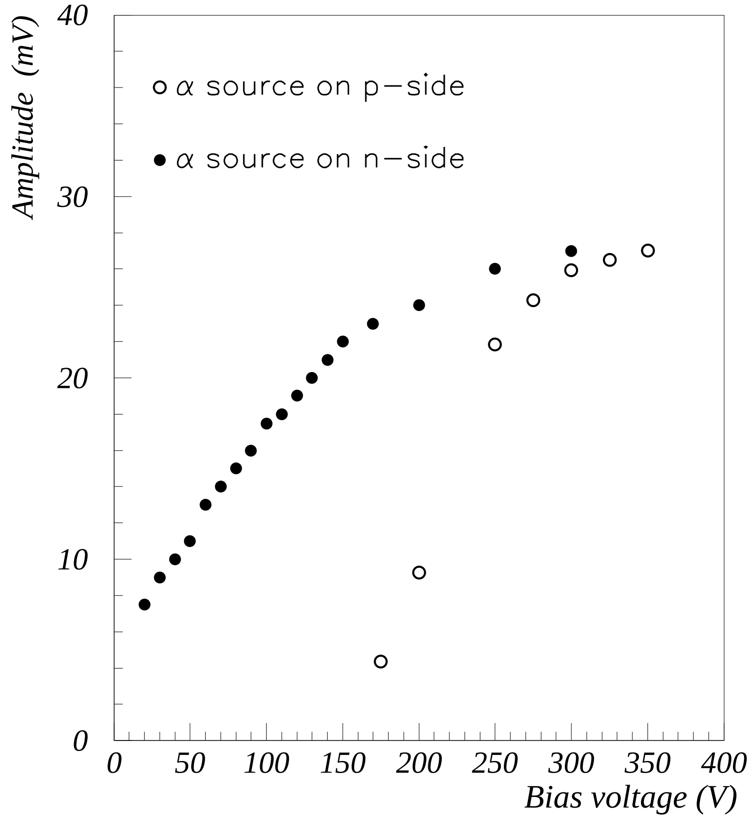

Figure 5: Signal from an α source measured on detector B1 as a function of bias voltage.

5.2 β particles

All detectors were bonded to SCT32 [17] chips and signals from a ^{106}Ru source were recorded. The chip contains 32 channels of preamplifiers and shapers with a peaking time of 25 ns, followed by an analog pipeline and a multiplexer. Setting a relatively high current of the preamplifier we measured an equivalent noise charge of $ENC = 1190e^- + 38e^-/pF \times C_{det}$. The detector capacitance, dominated by the capacitance to the backplane, is about 37 pF. The measurement was done at -14^oC at which the leakage current per strip was about $10\mu A$ giving a contribution of about $1700e^-$ to the noise. The total noise measured was about $3200e^-$ and the signal to noise ratio was of the order of 7:1. The size of the source spot was typically 1cm FWHM, in the centre of the detector. To normalize the measurements on the different detectors for which we used different readout cards, the non irradiated detector B3 was, in a first set of measurements, bonded to each card in turn. An electronic test pulse was later used to follow possible changes of the gain with time.

Figure 6 shows the pulse height as a function of voltage recorded from detectors A, B1, B2 and from detector B3 (not irradiated). One can see that it is necessary to apply ≈300 V bias to the irradiated detectors to reach the charge collection efficiency plateau. Despite the higher fluence and higher full depletion voltage, we see a small shift (40V), towards lower bias, of the efficiency curve for B2, the detector irradiated without bias.

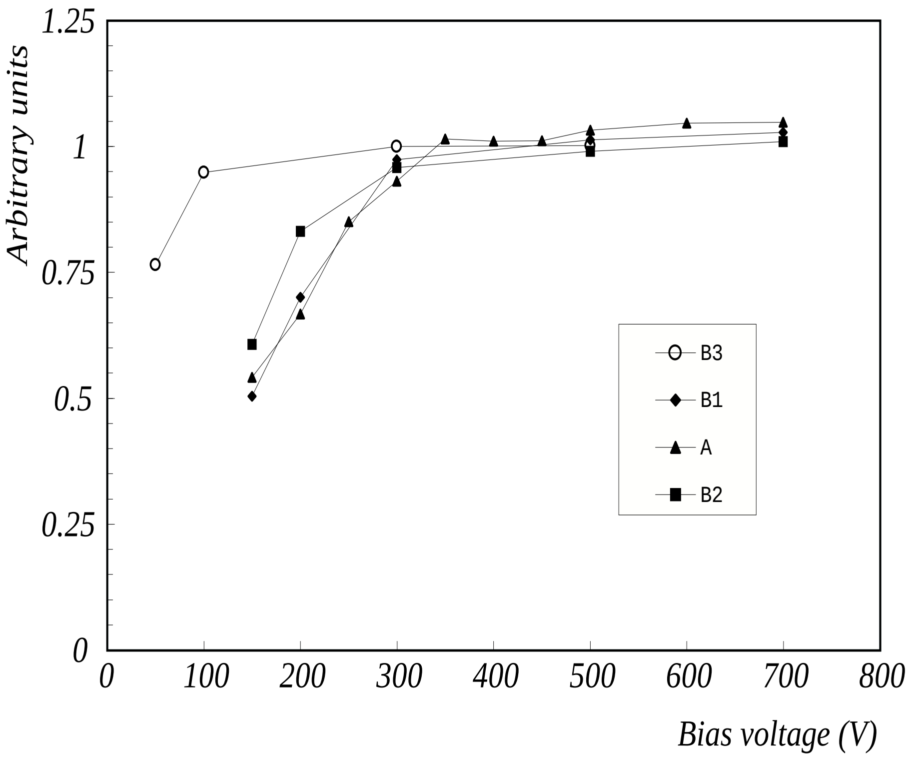

Figure 6: Signal from a β source measured on detectors A, B1 B2 and B3 as a function of bias voltage.

On the efficiency plateau, we do not observe a significant charge loss with respect to the non-irradiated detector.

6 Conclusions

Three Preshower full size detectors from different manufacturers were irradiated with neutrons with and without the bias voltage to fluences above $1 \times 10^{14} n/cm^2$. The full depletion voltage derived from the capacitance measurements at 100 kHz is about 100V. Measurements of the signals generated by α and β particles show however that an efficiency plateau is only attained at 300 V. Finally, we have not observed large differences between detectors irradiated with and without bias.

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