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Signal height in silicon pixel detectors irradiated with pions and protons

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ABSTRACT

Pixel detectors are used in the innermost part of multi-purpose experiments at the Large Hadron Collider (LHC) and are therefore exposed to the highest fluences of ionising radiation, which in this part of the detectors consists mainly of charged pions. The radiation hardness of the detectors has been tested thoroughly up to the fluences expected at the LHC. In case of an LHC upgrade the fluence will be much higher and it is not yet clear up to which radii the present pixel technology can be used. To establish such a limit, pixel sensors of the size of one CMS pixel readout chip (PSI46V2.1) have been bump bonded and irradiated with positive pions up to $6 \times 10^{14}\,n_{eq}/cm^2$ at PSI and with protons up to $5 \times 10^{15}\,n_{eq}/cm^2$. The sensors were taken from production wafers of the CMS barrel pixel detector. They use n-type DOFZ material with a resistance of about $3.7\,k\Omega\,cm$ and an n-side read out. As the performance of silicon sensors is limited by trapping, the response to a Sr-90 source was investigated. The highly energetic beta-particles represent a good approximation to minimum ionising particles. The bias dependence of the signal for a wide range of fluences will be presented.

1. Introduction

The tracker of the CMS experiment consists of only silicon detectors [1]. The region with a distance to the beam pipe between 22 and 115 cm is equipped with 10 layers of single sided silicon strip detectors covering an area of almost $200\,m^2$ with about 10^7 readout channels. The smaller radii are equipped with a pixel detector which was inserted into CMS in August 2008. It consists of three barrel layers and two end discs at each side. The barrels are 53 cm long and placed at radii of 4.4, 7.3, and 10.2 cm. They cover an area of about $0.8\,m^2$ with roughly 800 modules. The end discs are located at a mean distance from the interaction point of 34.5 and 46.5 cm. The area of the 96 turbine blade shaped modules in the disks sums up to about $0.28\,m^2$. The pixel detector contains about 6×10^7 readout channels providing three precision space points up to a pseudo-rapidity of 2.1. These unambiguous space points allow an effective pattern recognition in the dense track environment close to the LHC interaction point. A precise measurement enables the identification of displaced vertices for the tagging of b-jets and τ-leptons.

The two main challenges for the design of the pixel detector are the high track rate and the high level of radiation. The former concerns the architecture of the readout electronics while the high radiation level mainly affects the charge collection properties of the sensor, which degrades steadily.

A possible luminosity upgrade of the LHC is currently being discussed. With a minor hardware upgrade, a luminosity above $10^{34}\,cm^{-2}\,s^{-1}$ might be reached. Later, major investments will aim for a luminosity of $10^{35}\,cm^{-2}\,s^{-1}$ [2]. The inner regions of the tracker will have to face an unprecedented track rate and radiation level. The detectors placed at a radius of 4 cm have to withstand the presently unreached particle fluence of $\Phi \approx 10^{16}\,n_{eq}/cm^2$ or must be replaced frequently. However, the operation limit of the present type hybrid pixel system using "standard" n-in-n pixel sensors is not yet seriously tested. The aim of the study presented is to test the charge collection of the CMS barrel pixel system at fluences exceeding the specified $6 \times 10^{14}\,n_{eq}/cm^2$ [3].

2. Sensor samples

The sensors for the CMS pixel barrel follow the so-called "n-in-n" approach. The collection of electrons is advantageous in a high radiation environment as they have a higher mobility than holes and therefore suffer less from trapping. After irradiation induced type inversion, the highest electric field in the sensor is located close to the n-electrodes used to collect the charge. Double sided sensors are more expensive to produce than single sided p-in-n

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sensors. However, the double sided sensors have a guard ring scheme where all sensor edges are at a ground potential and this greatly simplified the design of detector modules. The n-side isolation was implemented through the so-called moderated p-spray technique [4] with a punch through biasing grid.

The sensor samples were taken from wafers of the main production run for the CMS pixel barrel which were processed on n-doped DOFZ silicon according to the recommendation of the ROSE-collaboration [5]. The resistance of the material prior to irradiation was 3.7 kΩ cm.

The approximately 285 μm thick sensors have the size of a single readout chip and contain 52×80 pixels with a size of $150 \times 100\,\mu m^2$ each.

This study applied the same bump bond and flip chip procedure as used for the production of the CMS pixel barrel [6] which simplified the assembly considerably and resulted in a very good bump yield. As this procedure includes processing steps at elevated temperature, this was done before irradiation. This means that the readout chips were also irradiated. In previous studies [7] only the sensors were irradiated and then were attached to non-radiation hard readout electronics using a special flip-chip procedure without heat application. Although the operation of irradiated readout circuits poses a major challenge and source of measurement errors, it gives a realistic picture of the situation in CMS after a few years of running.

The sandwiches of sensor and readout chip were irradiated at the PSI-PiE1-beam line with positive pions of momentum 280 MeV/c to fluences up to $6 \times 10^{14}\,n_{eq}/cm^2$ and with 26 GeV/c protons at CERN-PS up to $5 \times 10^{15}\,n_{eq}/cm^2$.

All irradiated samples were kept in a commercial freezer at $-18\,^\circ C$ after irradiation. However, the pion irradiated ones were accidentally warmed up to room temperature for a period of a few weeks (due to an undetected power failure).

3. Measurement procedure

The aim of the study was to determine the signal caused by minimum ionising particles (m.i.p.) as a function of sensor bias and irradiation fluence. For this, the response of the samples to a Sr-90 source was investigated. The endpoint energy of the beta particles is about 2.3 MeV which approximates a minimum ionising particle.

The samples were mounted on a water cooled Peltier element and kept at $-10\,^\circ C$. The source was placed inside the box about 10 mm above the sensor. As the compact setup did not allow the implementation of a scintillator trigger, a so-called random trigger was used. In this operation mode the FPGA generating all control signals for the readout chip stretches an arbitrary cycle of the clock sent to the readout chip by a large factor, and, after the latency, sends a trigger to read out the data from this stretched clock cycle. The stretching factor was adjusted such that about 80% of the triggers showed hit pixels.

The testing and calibration procedure was similar to what is used to test and calibrate the modules installed in the CMS experiment [8]. The threshold of the pixels was adjusted to about 4000 electrons. This procedure was perfectly adequate for all samples up to a fluence of $1 \times 10^{15}\,n_{eq}/cm^2$.

For the samples irradiated to $2.8 \times 10^{15}\,n_{eq}/cm^2$ the feedback resistor of the preamplifier and shaper had to be adjusted manually to compensate for the radiation induced change of the transistor's transconductance. The DACs which control these settings are not implemented in the testing software. Then, the standard calibration procedure was used with the exception that the pixel threshold was lowered to about 2000 electrons. An additional feature of the readout chip, the leakage current compensation, which might be useful for such highly irradiated samples, was not used.

The readout chips of the samples irradiated to $5 \times 10^{15}\,n_{eq}/cm^2$ showed some functionality, however, a calibration and quantitative analysis of the data was not yet possible and will be the subject of further investigations.

After the calibration, data were taken using the Sr-90 source. The sensor bias was varied over a wide range. The maximum voltage applied was 250 V for the unirradiated samples, 600 V for the samples irradiated up to $1 \times 10^{15}\,n_{eq}/cm^2$, and 1100 V for the samples which received a fluence of $2.8 \times 10^{15}\,n_{eq}/cm^2$. The change of the sensor bias has no effect on the calibration performed before. The temperature was kept stable during the bias scan within $0.2\,^\circ C$. The effect of such small temperature variations has been shown to be negligible.

The data were analysed off line. First, all analogue pulse height information was converted into an absolute charge value. Then, a pixel mask was generated which excluded faulty pixels. A pixel was masked if it showed much less ("dead") or more ("noisy") hits than its neighbours, or if the pulse height calibration failed. In addition a manually generated list of pixels was excluded. Due to the low threshold of only 2000 electrons, the highly irradiated samples ($2.8 \times 10^{15}\,n_{eq}/cm^2$) showed a higher number of noisy pixels, especially at the sensor edge where the pixels are larger. For those samples the edge regions were excluded manually.

In a second step, all clusters of hit pixels were reconstructed. If a cluster was contiguous with a masked pixel or the sensor edge, it was excluded from further analysis. Clusters of different size (one pixel, two pixels, etc.) were processed separately. The charge of a cluster was summed and a binned distribution was obtained. These histograms were then fit with a Landau function convoluted with a Gaussian. The most probable value (MPV) of the Landau found from the fit was used for the quoted charge value.

4. Results

The radiation of the Sr-90 source contains a large fraction of low energy electrons which cause much higher signal than a minimum ionising particle. As the setup was not equipped with a scintillator trigger, the contamination of the low energy particles had to be reduced using the offline analysis. A particle stopped in the sensor usually causes part of the ionised electrons to travel in the plane of the sensor ionising further electrons in the flight path. This results in large clusters of hit pixels. Fig. 1 shows the distribution of the cluster size for four irradiation fluences.

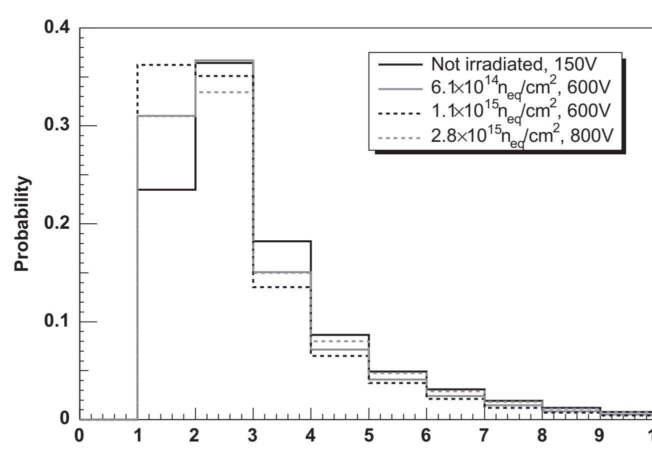

Fig. 1. Distribution of cluster size for four irradiation fluences.

Naively one would expect a spectrum dominated by one-hit clusters with a small fraction of clusters of size two to four caused by particles passing just in-between two pixels or close to a pixel corner. However, as shown in Fig. 1, there is a tail of events with extremely large clusters, which does not depend on irradiation or bias voltage. This supports the hypothesis of secondary particles. Therefore, it is not surprising that the signal height is a function of the cluster sizes. Fig. 2 shows the pulse height distribution of an unirradiated sensor for different cluster sizes. Clusters with more than four hit pixels tend to have very large signals and their distribution can no longer be described by a Landau function. What is more surprising is that in clusters with less than four pixels, the most probable value of the pulse height distribution depends on the cluster size. To reduce contamination from low energy particles, the pulse height is only extracted from clusters of size one.

In the samples irradiated to $2.8 \times 10^{15}\,\mathrm{n_{eq}/cm^2}$, many "good" pixels showed a certain number of noise hits which lead to a second peak in the pulse height spectra. It was well separated from the signal for voltages above 200 V.

Fig. 3 shows the bias dependence of the signal for all measured samples. For the unirradiated samples the steep rise of the signal at the full depletion voltage of $V_{\mathrm{depl}} \approx 55\,\mathrm{V}$ is visible. The signal plateau is reached very fast.

The samples irradiated to fluences in the $10^{14}\,\mathrm{n_{eq}/cm^2}$-range also show a saturation of the signal above roughly 300 V. However, the variation of the saturated signal for the same irradiation fluence is of the same order of magnitude as the reduction of the signal from 4.3 to $6.2 \times 10^{14}\,\mathrm{n_{eq}/cm^2}$. A distinction of the irradiation fluence of the samples from the height of the plateau is not possible. This strong variation cannot be explained by differences in the sensor thickness and is probably caused by the imperfection of the pulse height calibration. It relies on the assumption that the injection mechanism for test pulses is equal for all readout chips, which is not the case. Variations of the injection capacitor are larger than 15%.

The difference in the irradiation fluence is better reflected in the "low" voltage part of the curves, where the voltage from which the signal starts to rise reflects the radiation-induced increase of the space charge.

For the samples irradiated to fluences above $10^{15}\,\mathrm{n_{eq}/cm^2}$, no saturation of the signal with increasing bias is visible. It is remarkable that even after a fluence of $2.8 \times 10^{15}\,\mathrm{n_{eq}/cm^2}$ a charge of more than 10 000 electrons can be collected if a bias voltage over 800 V is applied. This complements the results for n-in-p strip detectors shown in this conference [9,10].

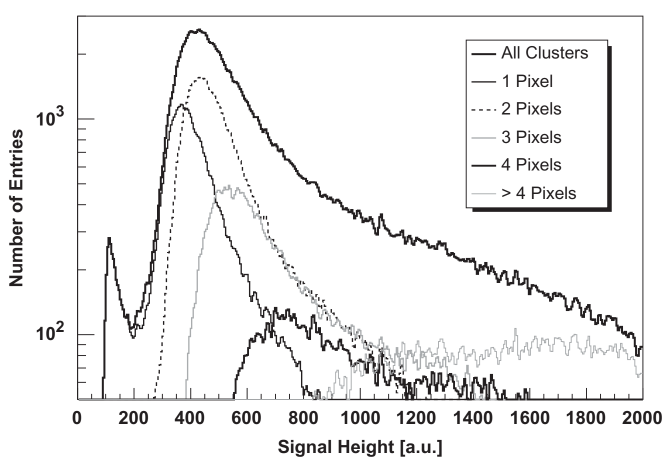

Fig. 2. Pulse height distribution of an unirradiated sensor in arbitrary units (1 unit is about 65 electrons).

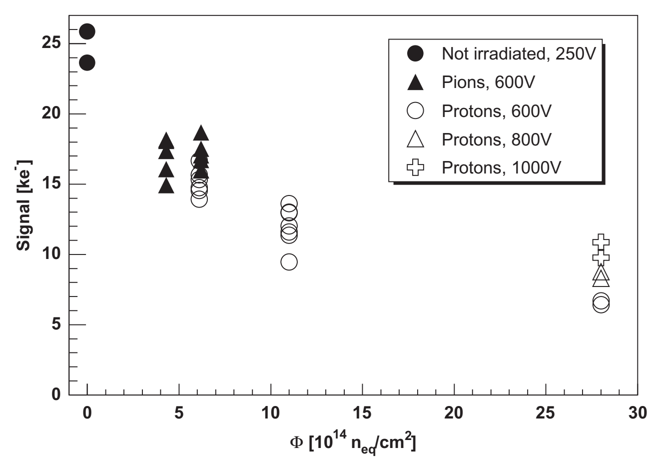

Fig. 4. Most probable signal as a function of the irradiation fluence. Each point represents one sample (apart from the highest fluence where each of the two samples is shown at three bias voltages).

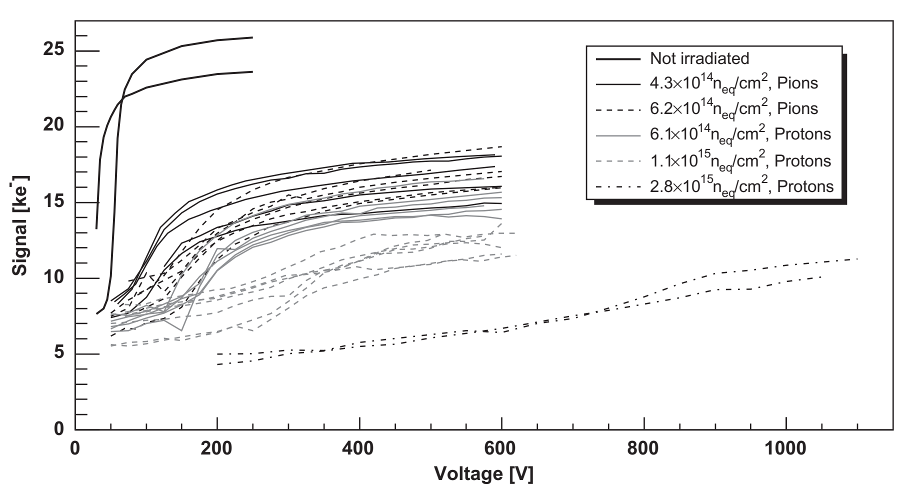

Fig. 3. Most probable value of the signal from single pixel clusters as a function of the sensor bias. Each line represents one sample.

To display the development of the signal height as a function of the fluence, the charge at 600 V was measured for each sample (250 V for the unirradiated ones) and plotted in Fig. 4. In addition, values for 800 and 1000 V are shown for the highest fluence. Apart from the large fluctuations the reduction of the charge with fluence is visible. Further it becomes obvious that it pays to go to very high bias voltages if the fluences exceed $10^{15}\,\mathrm{n_{eq}/cm^2}$.

5. Conclusion

To estimate the survivability of the present CMS barrel pixel detector in a harsh radiation environment, single chip detectors (sensors bump bonded to a readout chip) have been irradiated to fluences up to $5\times10^{15}\,\mathrm{n_{eq}/cm^2}$ and tested with a Sr-90 source. The samples that received fluences up to about $10^{15}\,\mathrm{n_{eq}/cm^2}$ could be used without any modification of the chip calibration procedure and obtained a signal charge of above 10 000 electrons at a bias voltage of 600 V. From this point of view their performance is perfectly adequate for the CMS experiment, even at fluences twice as high as the $6\times10^{14}\,\mathrm{n_{eq}/cm^2}$ specified in the Technical Design Report [3]. The samples irradiated to $2.8\times10^{15}\,\mathrm{n_{eq}/cm^2}$ could be operated with slightly adjusted chip settings and also showed a signal of about 10 000 electrons, however, at a bias voltage of 1000 V. This indicates the suitability of such devices for a use at an upgraded LHC. The samples which received $5\times10^{15}\,\mathrm{n_{eq}/cm^2}$ could not yet be operated. Their examination is the subject of further studies.

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