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 thoroughly been tested 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. In order 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.

Key words: LHC, super LHC, CMS, tracking, pixel, silicon, radiation hardness

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 disks at each side. The barrels are 53 cm long and placed at radii of 4.4 cm, 7.3 cm, and 10.2 cm. They cover an area of about $0.8\,m^2$ with roughly 800 modules. The end disks are located at a mean distance from the interaction point of 34.5 cm 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 dens track environment

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close to the LHC interaction point. The precision of the measurement is used to identify 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 LHC is currently being discussed. With a minor hardware upgrade a luminosity above $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ might be reached. Later major investments will aim for a luminosity of $10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [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 $\Phi \approx 10^{16}\,n_{eq}/\mathrm{cm}^2$ 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 $6\times10^{14}\,n_{eq}/\mathrm{cm}^2$ [3].

2. Sensor samples

The sensors for the CMS pixel barrel follow the so called "n-in-n" approach. The collection of electrons is of advantage in a highly radiative environment as they have a higher mobility than holes and therefore suffer less from trapping. Furthermore, the highest electric field after irradiation induced space charge sign inversion is located close to the collecting n-electrodes. The need of a double sided processing leading to a significant price increase compared to truly single sided p-in-n sensors is used as a chance to implement a guard ring scheme keeping all sensor edges on ground potential. This feature simplifies the design of the detector modules considerably. For n-side isolation the so called moderated p-spray technique [4] has been chosen and a punch through biasing grid has been implemented.

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 material prior to irradiation was $3.7\,\mathrm{k\Omega cm}$. The approximately $285\,\mu\mathrm{m}$ thick sensors had the size of a single readout chip and contain 52×80 pixels with a size of $150\times100\,\mu\mathrm{m}^2$ each. In contrast to previous studies [6] the standard bump bond and flip chip procedure described in [7] was applied to the samples. As this includes processing steps at elevated temperature, this was done before irradiation which simplified the whole procedure considerably and resulted in a very good bump yield. In return it means that the readout chips were also irradiated. 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 $6\times10^{14}\,n_{eq}/\mathrm{cm}^2$ and with 26 GeV/c protons at CERN-PS up to $5\times10^{15}\,n_{eq}/\mathrm{cm}^2$.

All irradiated samples were kept in a commercial freezer at $-18\,^\circ\mathrm{C}$ 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 amount of a signal caused by minimum ionising particle (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 m.i.p. well. However there is also a large number of "low energy" particles which are stopped in the sensor and cause much larger signals. Those have to be filtered during the data analysis.

The samples were mounted on a water cooled Peltier element and kept at $-10\,^\circ\mathrm{C}$. 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 method 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 in a way that about 80% of the triggers showed hit pixels.

A measurement sequence consists of the following steps:

- Cool down the sample while flushing the box with dry nitrogen.
- The "pretest" adjusts basic parameters of the readout chip.
- The "full test" checks the functionality of each pixel.
- Fine tune the threshold in each pixel to a value of 4000 electrons as uniform as possible ("trim" the chip).
- The pulse height calibration relates for each pixel the pulse height to the DAC values used to inject test pulses. The analogue response is fitted to an hyperbolic arc-tangent function [8] and the four fit parameters are calculated for each pixel. With procedure an absolute calibration of each pixel is possible.

This procedure was identical to what is used to test and calibrate the modules installed in the CMS experiment. It was perfectly adequate for all samples up to a fluence of $1\times10^{15}\,n_{eq}/cm^2$.

For the samples irradiated to $2.8\times10^{15}\,n_{eq}/cm^2$ 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 DAC which controls this setting is 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 (instead of 4000). 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 $5\times10^{15}\,n_{eq}/cm^2$ 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 these steps data is 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 $1\times10^{15}\,n_{eq}/cm^2$, and 1100 V for the samples which received a fluence of $2.8\times10^{15}\,n_{eq}/cm^2$. The change of the sensor bias has no effect on the calibration performed before. The temperature can be kept stable during the bias scan within $0.2\,^{\circ}$C. The effect of such small temperature variations has been tested to be negligible.

The data was analysed offline. First all analogue pulse height information were converted into an absolute charge value, using the parametrisation described above. After this a pixel mask is generated which excludes faulty pixels. A pixel was masked if it shows much less ("dead") or more ("noisy") hits than its neighbours, and if the pulse height calibration failed. In addition a manually generated list of pixels can be excluded. In a second step all clusters of hit pixels are reconstructed. If a cluster touches a masked pixel or the sensor edge, it is excluded from further analysis. Clusters of different size (one pixel, two pixels, etc.) are processed separately. To measure the pulse height, the charge of a cluster is summed and histogrammed. To those histograms a Landau function convoluted with a Gaussian is fitted. The quoted charge value is the most probable value (MPV) of the Landau.

Due to the low threshold of only 2000 electrons the highly irradiated samples ($2.8\times10^{15}\,n_{eq}/cm^2$) showed a higher number of noisy pixels, especially at the sensor edge where the pixels are larger. However, also some "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. The origin of the 2 peaks could easily be distinguished:

- The signal peak moves with higher bias to higher values while the noise peak stays at the same position but becomes more prominent (more noise hits at higher bias).
- The spatial distribution of the signal shows the intensity profile of the source, while the noise hits are randomly distributed.
- The signal peak has a typical Landau shape, while the noise peak is more Gaussian.

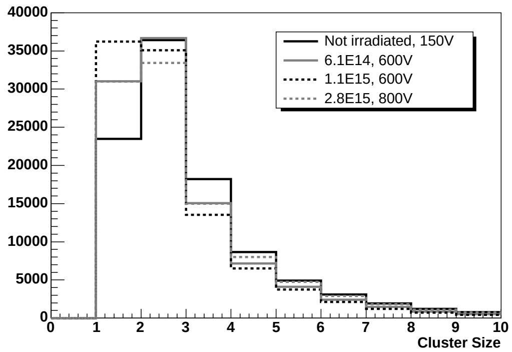

Fig. 1. Distribution of cluster size for four irradiation fluences.

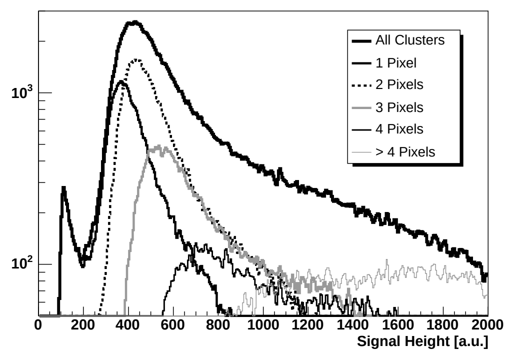

Fig. 2. Pulse height distribution of an unirradiated sensor in arbitrary units (1 unit is about 65 electrons).

The quoted signal is again the MPV of a convoluted Landau-Gauss fit.

4. Results

Because the radiation of the Sr-90 source contains a large graction of low energy betas which cause much higher signal than a minimum ionising particle and as the setup was not equipped with a scintillator which triggered only if a particle penetrated the sample, the contamination of the low energy particles had to be reduced using the off-line 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. Figure 1 shows the distribution of the 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 visible in Fig. 1, there is a tail of events with extremely large clusters, which does not dependent on irradiation or bias voltage. This supports the hypothesis of secondary particles. Therefore it is not surprising that the signal is a function of the cluster sizes. Figure 2 shows the pulse height distribution of an unirradiated sensor for different cluster sizes. In particular clusters with more than 4 hit pixels tend to have very large signals and their distribution can no longer be described by a Landau function. More surprising is the fact that already in small clusters with less than four pixels the most probable value of the pulse height distribution clearly depends on the cluster size. In order to reduce a contamination of the data from low energy particles, the pulse height is only extracted from clusters of size one.

Figure 3 shows the bias dependence of the signal for all measured samples. For the unirradiated samples the sudden rise of the signal at the full depletion voltage of $V_{depl} \approx 55$ V is nicely visible. The signal then saturates very fast. The samples irradiated to fluences in the 10^{14} n_{eq}/cm^2-range also show a nice saturation of the signal above roughly 300 V. The onset of the signal in the "low" voltage range clearly displays the increase of the space charge due to radiation. There is a strong variation of the saturated signal for samples with the same irradiation fluence which cannot be explained with differences in the sensor thickness. The reason for this is probably the imperfection of the pulse height calibration, which 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 %, and also the resistor network in the DAC shows variations, which are, however, much smaller. For the samples irradiated to fluences above 10^{15} n_{eq}/cm^2, no saturation of the signal with increasing bias is visible. It is remarkable that even after a fluence of $2.8 \cdot 10^{15}$ n_{eq}/cm^2 a charge of more than 10 000 electrons can be achieved if it is possible

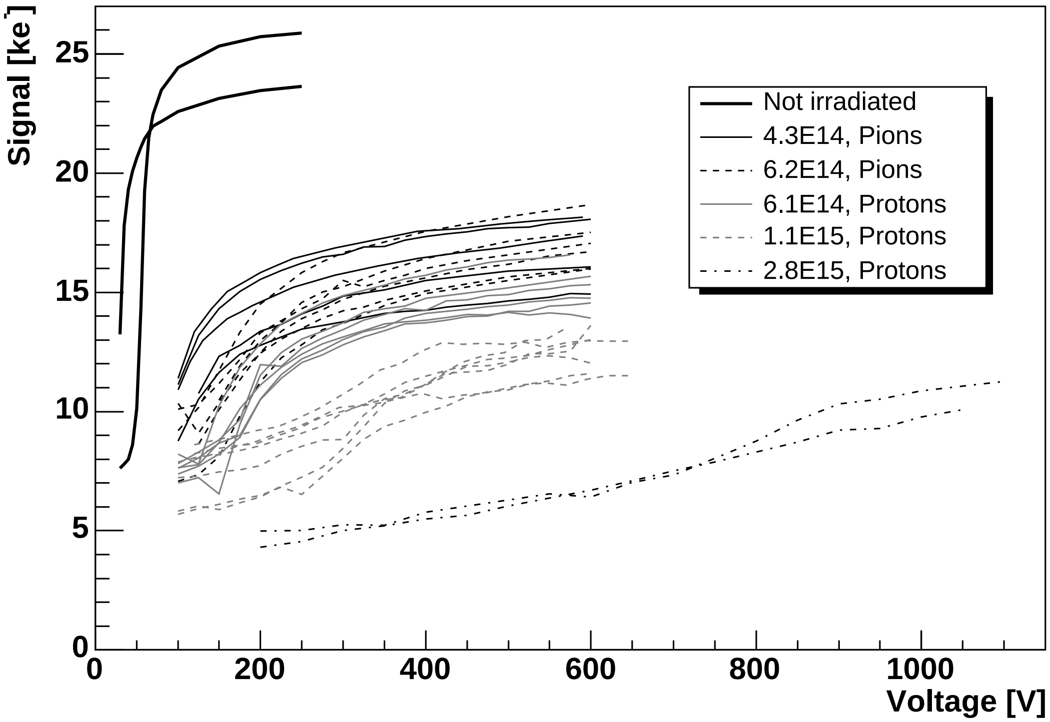

Fig. 3. Signal from single pixel clusters as a function of the sensor bias. Each line represents one sample.

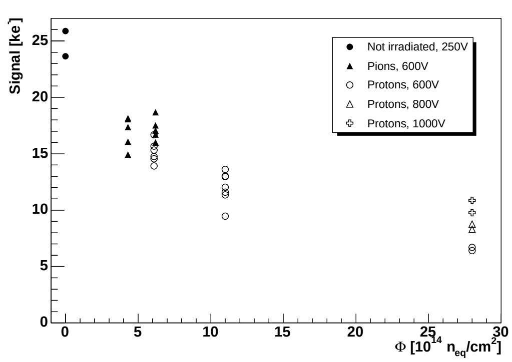

Fig. 4. Most probable signal as a function of the irradiation fluence. Each point represents one sample (apart from the highest fluence where each of the two samples is shown at three bias voltages).

to apply a bias voltage above 800V. This nicely complements the results for n-in-p strip detectors shown in this conference [9,10].

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

5. Conclusion

In order 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 uences up to 5 $10^{15}\,n_{eq}$=cm ^{2} and tested with a Sr-90 source. The samples that received uences up to about $10^{15}\,n_{eq}$=cm ^{2} could be used without any modi cation 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 uences twice as high as the 6 $10^{14}\,n_{eq}$=cm ^{2} speci ed in the Technical design report [3]. The samples irradiated to 2:8 $10^{15}\,n_{eq}$=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 $10^{15}\,n_{eq}$=cm ^{2} could not yet be operated. Their examination is subject of further studies.

Acknowledgement

The pion irradiation at PSI would not have been possible without the beam line support by Dieter Renker and Konrad Deiters, PSI, the logistics provided by Maurice Glaser, CERN, and the great effort of Christopher Betancourt and Mark Gerling, UC Santa Cruz (both were supported by a nancial contribution of RD50 and PSI).

The proton irradiation was carried out at the CERN irradiation facility. The authors would like to thank Maurice Glaser and the CERN team for the outstanding service.

The work of J.Acosta, A.Bean, C.Martin, V.Radicci and J.Sibille is supported by the PIRE grant OISE-0730173 of the US-NSF.

The work of S.Dambach, U.Langenegger, and P.Trub is supported by the Swiss National Science Foundation (SNF).

The sensors were produced by CiS GmbH in Erfurt, Germany.

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