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Characterization of thin irradiated epitaxial silicon sensors for the CMS phase II pixel upgrade

M. Centis Vignali, D. Eckstein, T. Eichhorn, E. Garutti, A. Junkes, and G. Steinbrück

Abstract

The high-luminosity upgrade for the large hadron collider foreseen for 2023 resulted in the decision to replace the tracker system of the CMS experiment. The innermost layer of the new pixel detector will experience fluences in the order of $\phi_{eq} \approx 10^{16} \text{ cm}^{-2}$ and a dose of $\approx 5 \text{ MGy}$ after an integrated luminosity of 3000 fb^{-1} . Several materials and designs are under investigation in order to build a detector that can withstand such high fluences. Thin planar silicon sensors are good candidates to achieve this goal since the degradation of the signal produced by traversing particles is less severe than for thicker devices.

A study has been carried out in order to characterize highly irradiated planar epitaxial silicon sensors with an active thickness of $100 \mu\text{m}$. The investigation includes pad diodes and strip detectors irradiated up to a fluence of $\phi_{eq} = 1.3 \times 10^{16} \text{ cm}^{-2}$.

The electrical properties of diodes have been characterized using laboratory measurements, while measurements have been carried out at the DESY II test beam facility to characterize the charge collection of the strip detectors. A beam telescope has been used to determine precisely the impact position of beam particles on the sensor. This allows the unbiased extraction of the charge deposit in the strip sensor and a good identification of the noise.

In this paper, the results obtained for p-bulk sensors are shown. The charge collection efficiency of the strip sensors is 90% at 1000 V after a fluence of $\phi_{eq} = 3 \times 10^{15} \text{ cm}^{-2}$. The irradiated diodes show charge multiplication effects. The impact of the threshold applied to a detector on its efficiency is also discussed.

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Characterization of thin irradiated epitaxial silicon sensors for the CMS phase II pixel upgrade

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M. Centis Vignali^{a*}, D. Eckstein^b, T. Eichhorn^b, E. Garutti^a, A. Junkes^a, and G. Steinbrück^a

^a*Institut für Experimentalphysik, Universität Hamburg,
Luruper Chaussee 149, 22761 Hamburg, Germany*

^b*Deutsches Elektronen Synchrotron, DESY
Notkestraße 85, 22607 Hamburg, Germany*

E-mail: matteo.centis.vignali@desy.de

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KEYWORDS: Radiation-hard detectors; Si microstrip and pad detectors.

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*Corresponding author.

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1. Introduction

The high-luminosity upgrade of the Large Hadron Collider (HL-LHC) foreseen for 2023 will allow the experiments at the collider to collect data at a luminosity of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, enhancing the discovery potential for new physics. The precise determination of vertices in the high radiation environment close to the HL-LHC interaction points demands the development of solid state detectors that can withstand unprecedented fluences.

The CMS experiment strategy to overcome this challenge consists in the replacement of the whole tracking system, the so-called phase II tracker upgrade. The outer layers of the tracker will consist of planar silicon sensors, while the innermost layers of the pixel detector require the study and development of new materials and designs. The innermost layers of the upgraded pixel detector will experience fluences in the order of $\phi_{eq} \approx 10^{16} \text{ cm}^{-2}$ after an integrated luminosity of 3000 fb^{-1} [1]. The expected dose is $\approx 5 \text{ MGy}$ and the hit rate will be in the range of $1\text{--}2 \text{ GHz cm}^{-2}$ [2]. Several options are under investigation to provide sensors still operational after such fluences. Thin planar silicon sensors are candidates to achieve this goal since they show a less severe degradation of the charge collection efficiency with irradiation than thicker devices [3]. In this study silicon sensors with an active thickness of $100 \mu\text{m}$ have been characterized.

2. Sensors

The sensors under study are pad diodes and strip detectors produced during the CMS HPK campaign [4]. The active thickness of the sensors is $100 \mu\text{m}$, corresponding to the thickness of the epitaxial layer. The epitaxial silicon is grown on top of a low resistivity substrate that is assumed

Figure 1. Single channel noise as a function of applied bias voltage. Four ADC counts correspond to $\approx 700 e^-$.

to play no role in the measurements presented in this paper. The total thickness of the sensors is $330 \mu\text{m}$.

Both n- and p-bulk sensors were examined in the study, the latter having p-spray and p-stop insulation. In this paper only the results of p-bulk sensors are presented. The strip sensors have 64 strips with a pitch of $80 \mu\text{m}$, their sensitive area is $2.5 \times 0.512 \text{ cm}^2$. The pad diodes have different areas, namely $0.5 \times 0.5 \text{ cm}^2$ and $0.25 \times 0.25 \text{ cm}^2$. The sensors were irradiated at the CERN PS ¹ with 23 GeV protons (hardness factor $\kappa = 0.62$) up to a fluence $\phi_{eq} = 1.3 \times 10^{16} \text{ cm}^{-2}$. Some devices were irradiated at the LANSCE facility ² with 800 MeV protons ($\kappa = 0.71$), they accumulated a fluence $\phi_{eq} = 10^{15} \text{ cm}^{-2}$.

3. Test beam setup

In order to characterize the strip sensors, measurements have been performed at the DESY II beam lines. A monochromatic beam of electrons with energies between 3 and 5 GeV was used. The setup consisted of the sensor under test read out by the ALiBaVa system [5]. This system provides the analog readout of all the channels of the strip detector and the possibility to read out both positive and negative signals. The sensor under test can be cooled down to -28°C and is contained in a light tight box flushed with nitrogen. The box is placed in between the arms of the AIDA telescope [6] present in the beam area. The trigger is defined by the coincidence of four scintillators mounted in pairs in the front and in the back of the telescope. The scintillators define also the geometrical acceptance of the system.

4. Noise of the strip sensors

Using the tracking information from the telescope, strips without traversing particles are identified. With this information the noise figure of the detector can be accurately determined. The single

¹<https://irradiation.web.cern.ch/irradiation/irrad1.htm>

²<http://lansce.lanl.gov/>

Figure 2. Charge distribution of an irradiated p-bulk, p-stop sensor. The fluence is $\phi_{eq} = 3 \times 10^{15} \text{ cm}^{-2}$ and the bias is 800 V. The fit parameters are the height of the Gaussian peak centered at 0, the width and the most probable value of the Landau distribution, the area of the convoluted distribution and the σ of the convoluted Gaussian distribution.

channel noise as a function of the applied bias voltage for various fluences is shown in figure 1. The noise is dominated by the electronics and by the sensor capacitance for bias voltages up to 800 V. For the irradiated sensors at higher bias values the rise of the dark current results in an increase of the noise level.

5. Charge collection efficiency

The charge collection efficiency (CCE) of the strip detectors was determined using the test beam data. The value of the collected charge for a hit is defined using the track information from the telescope according to [7]. A cluster of 5 strips is formed around the extrapolated hit position on the sensor and the charge collected by the strips is summed up. This approach eliminates the distortion of the measured charge distributions that can be introduced using a clustering algorithm with a cut on the measured hit signal. A charge distribution obtained with this method is shown in figure 2. The distribution is described using a convolution of a Landau and a Gaussian distribution and another Gaussian distribution to describe the noise peak present around 0 ADC counts. The noise peak is due to inefficiencies of the test beam setup. It is described using the mean and σ of the noise distribution of the sensor. The most probable value (MPV) of the Landau distribution is used to measure the CCE of the sensors.

The CCE of the p-bulk strip detectors characterized at the test beam is shown in figure 3. The break down voltage for the sensors irradiated with 23 GeV protons exceeds 1000 V. The normalization is obtained using the data from the non-irradiated sensors with bias voltages in the range 200-400 V. The CCE of the irradiated devices reaches 90% at 1000 V bias. There is no visible signal degradation from 1.5×10^{15} to $3 \times 10^{15} \text{ cm}^{-2}$ fluence equivalent.

In figure 4 the CCE of p-bulk pad diodes with p-spray insulation is shown. The CCE for diodes was obtained integrating the pulses recorded during transient current technique (TCT) measurements [8]. The measurement was performed using an infrared laser, the temperature of the samples was 0 and -20°C . For high values of the bias voltage the CCE of the irradiated sensors

Figure 3. CCE of the strip sensors. The Landau MPV of a non-irradiated $100\ \mu\text{m}$ thick sensor is $\approx 7500\ \text{e}^-$. The error bars express only the statistical uncertainties.

Figure 4. CCE of p-bulk diodes with p-spray insulation. The temperature of the samples was $0\ ^\circ\text{C}$ (open symbols) and $-20\ ^\circ\text{C}$ (full).

exceeds the one of the non-irradiated ones. This result is interpreted as charge multiplication taking place in the detectors [8].

6. Efficiency estimation for the strip sensors

The degradation of the signal due to irradiation can result in a loss of efficiency in a system where a threshold is applied in the readout electronics in order to attain zero suppression. It is possible to study this kind of inefficiency using the signal distribution of the seed strip of the clusters defined in section 5, the seed strip being the one with the highest charge in the cluster. The charge distribution of the seed strip for a non-irradiated p-bulk sensor is shown in figure 5. The peak close to 0 ADC counts is attributed to noise due to inefficiency of the test beam setup. The distribution for an irradiated device is shown in figure 6. The signal distribution is broader for the irradiated sensor with respect to the unirradiated one. The cumulative distribution of the seed strip signal gives, after the subtraction of the noise peak, the measure of the inefficiency as a function of applied threshold. It is then possible to estimate which is the highest threshold applicable to the detector

Figure 5. Signal distribution of the seed strip for a p-bulk, p-stop sensor. The sensor is not irradiated, the applied bias voltage is 300 V. The peak close to 0 ADC counts is noise due to setup inefficiency.

Figure 6. Signal distribution of the seed strip for a p-bulk, p-stop sensor. The sensor is irradiated to a fluence of $\phi_{eq} = 3 \times 10^{15} \text{ cm}^{-2}$, the applied bias voltage is 800 V. The blue distribution is the result of the measurement. In the red distribution the noise peak has been subtracted.

Figure 7. Threshold value to get 95% efficiency. Ten ADC counts correspond to $\approx 1800 \text{ e}^-$.

still maintaining a certain detection efficiency. The result for 95% detection efficiency is shown in figure 7. With this information it is possible to derive constraints to the noise figure of the detector after irradiation.

7. Conclusions

The CCE of epitaxial silicon pad diodes and strip detectors with 100 μm active thickness have been measured. The break down voltage of the sensors irradiated with 23 GeV protons exceeds 1000 V. The p-bulk strip detectors have a CCE of 90% at 1000 V after a fluence of $\phi_{eq} = 3 \times 10^{15} \text{ cm}^{-2}$. The irradiated diodes show charge multiplication effects.

The maximum threshold to achieve 95% detection efficiency in the strip detectors has been estimated to be greater than $\approx 1800 \text{ e}^-$. This allows an efficient detector operation if the noise figure of the system is below $\approx 200 \text{ e}^-$ after irradiation. The modification of the shape of the charge distribution of the seed strip in irradiated samples plays a major role in the degradation of this parameter.

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