The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

21 November 2014 (v3, 28 November 2014)

Energy Dependence of Proton Radiation Damage in Si-Sensors

Alexandra Junkes for the CMS Collaboration

Abstract

Irradiation experiments on silicon sensors are used to mimic the radiation environment at collider experiments with the aim to forecast the change of the electrical properties of a detector with irradiation. Measurements on irradiated sensors are invaluable in choosing a material well suited for a silicon tracking detector. This is especially true for the upgraded detectors to be used in the high-luminosity phase of the LHC (HL-LHC), where silicon sensors as currently used would suffer severe loss in signal from irradiation with charged and neutral hadrons.

The CMS Tracker Collaboration has initiated irradiation studies with protons with energies ranging from 23 MeV to 23 GeV. They are often used instead of charged hadrons, their radiation induced damage to the silicon being rather similar. However, in oxygen rich silicon, NIEL violation concerning the full depletion voltage has been observed.

In this paper results from investigations on bulk defects compared to the change of the electrical properties of silicon pad-sensors will be summarized after irradiations with 23 MeV and 23 GeV protons. Differences in the generation of specific defects in the bulk were observed depending on the proton energy. A possible impact of such defects on the electrical properties will be evaluated.

Presented at *IEEE-NSS-MIC-2014 2014 IEEE Nuclear Science Symposium and Medical Imaging Conference*

Energy Dependence of Proton Radiation Damage in Si-Sensors

Alexandra Junkes for the CMS tracker collaboration, E. M. Donegani and C. Neubüser

Abstract—Irradiation experiments on silicon sensors are used to mimic the radiation environment at collider experiments with the aim to forecast the change of the electrical properties of a detector with irradiation. Measurements on irradiated sensors are invaluable in choosing a material well suited for a silicon tracking detector. This is especially true for the upgraded detectors to be used in the high-luminosity phase of the LHC (HL-LHC), where silicon sensors as currently used would suffer severe loss in signal from irradiation with charged and neutral hadrons.

The CMS Tracker Collaboration has initiated irradiation studies with protons with energies ranging from 23 MeV to 23 GeV. They are often used instead of charged hadrons, their radiation induced damage to the silicon being rather similar. However, in oxygen rich silicon, NIEL violation concerning the full depletion voltage has been observed.

In this paper results from investigations on bulk defects compared to the change of the electrical properties of silicon pad-sensors will be summarized after irradiations with 23 MeV and 23 GeV protons. Differences in the generation of specific defects in the bulk were observed depending on the proton energy. A possible impact of such defects on the electrical properties will be evaluated.

Index Terms—Defects, Silicon, radiation hardness

I. INTRODUCTION

THE upgrade of the Large Hadron Collider to the High-Luminosity Large Hadron Collider (HL-LHC) aims to increase the luminosity by a factor of 5 to $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. This in turn has an impact on the radiation damage expected for the experiments at the HL-LHC [1]. For the CMS experiment a fluence of up to $\Phi_{eq} = 2 \times 10^{16} \text{ cm}^{-2}$ is expected for the inner-most layer of the silicon pixel detector, decreasing to a still very high fluence of $\Phi_{eq} = 1.5 \times 10^{15} \text{ cm}^{-2}$ in the inner-most layer of the outer tracker. The radiation damage consists of a mixture of charged and neutral hadrons, with a dominant fraction of charged hadrons in the pixel detector and the inner layers of the outer tracker.

Irradiations with protons are often used to investigate the impact of the expected radiation damage created by charged hadrons. Recently, a NIEL violation for irradiations with protons of different energies has been reported [2]. The depletion voltages of sensors after irradiations with low-energy and high-energy protons are different for oxygen rich material. This difference is expected to originate from the generation of bulk defects with impact on the space charge. Previous studies on p-in-n silicon pad diodes identified several donor- and acceptor-type defects with impact on

Fig. 1. Oxygen profile of pad-diodes measured by Secondary Ion Mass Spectroscopy.

the depletion voltage [3], [4], [5] for neutron and 23 GeV proton irradiations. For obtaining more information about the generation of defects in high- and low-energy proton irradiated silicon, defects studies have been performed on sensors with different oxygen concentrations irradiated with protons with energies of 23 MeV and 23 GeV.

II. SAMPLES, IRRADIATIONS AND METHODOLOGY

The samples used in this study were all produced by Hamamatsu Photonics K. K. within the CMS effort to identify the most suited silicon material for the future CMS silicon tracker detector [6]. Three different materials were used to produce pad-diodes. The main difference between these materials is the oxygen content of the bulk material, defined by the growth and production process of the wafers. Figure 1 presents the oxygen profiles of the silicon bulk material measured by Secondary Ion Mass Spectroscopy (SIMS). Since the profiles are not homogeneous over the thickness of the sensors, an average oxygen concentration was calculated ($[O]$) and included in Figure 1 and summarized in Table I. Magnetic Czochralski (MCZ) and Float Zone (FZ) sensors with 200 μm thickness were produced and furthermore 320 μm thick deep-diffused FZ with an active bulk thickness of 200 μm . The samples were produced with n-type as well as p-type bulk, allowing a direct comparison of the defects generated by proton irradiation.

TABLE I
OVERVIEW OF MATERIALS AND IRRADIATIONS USED IN THIS WORK.

Material	Type	[O] [10^{17} cm^{-3}]	Proton energy	Fluence [10^{13} cm^{-2}]
MCZ	p-in-n	5.6	23 MeV	3, 5, 10
MCZ	n-in-p	4.6	23 MeV	3, 5, 10
dd-FZ	p-in-n	2.5	23 MeV	3, 5, 10
dd-FZ	n-in-p	4.1	23 MeV	3, 5, 10
FZ	p-in-n	0.6	23 MeV	3, 5, 10
FZ	n-in-p	0.8	23 MeV	3, 5, 10
MCZ	p-in-n	5.6	23 GeV	1, 30
MCZ	n-in-p	4.6	23 GeV	1, 30
dd-FZ	p-in-n	2.5	23 GeV	1, 30
dd-FZ	n-in-p	4.1	23 GeV	1, 30

The samples were irradiated with protons with two different energies. Protons with an energy of 23 GeV from the PS¹ cyclotron at CERN, Switzerland ($\kappa=0.62$) and 23 MeV protons from ZAG², Karlsruhe, Germany ($\kappa=2.00$) were used to irradiate the samples to several fluences in the range of $\Phi_{eq}=1\text{-}30 \times 10^{13} \text{ cm}^{-2}$. These fluences are in the measurement range of the thermally stimulated current (TSC) technique, which is used to obtain defect concentrations in this work. An overview of the fluences is given in table I.

Defect concentrations were extracted with the thermally stimulated current (TSC) technique [7]. At a temperature of 10 K the sensor is forward biased for 30 s in order to fill the traps with majority and minority charge carriers. The sensor is then heated up with a constant heating rate of 0.187 K/s. At temperatures corresponding to defect levels in the band gap, the trapped charge carriers are emitted. This emission process can be measured as a current peak. The defect concentration can be extracted from the area under such a peak. Capture cross sections and energies can be extracted from peak simulations.

III. RESULTS

A. Comparison of defects in n- and p-type silicon

The generation of defects is supposed to be similar for n-type and p-type material, except for defects that are related to the doping atoms in the respective bulk. However, previous studies were focussed on n-type material only. With the CMS collaboration's decision to produce the sensors for the outer tracker in n-in-p technology [8], the analysis of p-bulk silicon has become the focus of the investigations. Figure 2 presents the TSC spectra for dd-FZ samples in n- and p-bulk pad-diodes irradiated with 23 MeV protons to a fluence of $1 \times 10^{14} \text{ cm}^{-2}$.

The defects with impact on the change of the depletion voltage are marked with colored labels. The two donors E(30K) and BD are labelled in red and the so-called deep acceptors, a group of three acceptors in the range of 110 K to 150 K with negative contribution to the space charge,

Fig. 2. TSC spectra for 23 MeV proton irradiated n- and p-type dd-FZ pad-diodes with a fluence of $\Phi_{eq} = 1 \times 10^{14} \text{ cm}^{-2}$.

are presented in blue. These defects are generated with a similar concentration, except for the BD defect, that cannot be evaluated correctly for the p-bulk sample because it is overlapping with an unidentified defect signature. The energy level of this defect was extracted to be 0.234 eV. This defect might be attributed to the interstitial boron-oxygen complex (B_iO_i), which has been reported [9] to be a donor at $E_C - 0.23 \text{ eV}$. In order to confirm this assumption, more tests need to be performed.

Figures 3a and 3b present close-ups of the low temperature region around the E(30K) defect. In contrast to the dd-FZ spectra, the E(30K) defect shows a dependence on the oxygen concentration for MCZ and FZ materials. A higher introduction of E(30K) is observed in n-bulk material with increasing oxygen concentration, and vice versa for the p-bulk samples.

Fig. 3. Close-up of the low-temperature region of TSC spectra for 23 MeV proton irradiated n- and p-type FZ and MCZ pad-diodes.

Figure 4 presents the summary of the evaluation of the concentrations of the sum of all donors and acceptors for

¹<http://www.irradiationfacilities-cern.ch>

²<http://zyklotron-ag.de>

Fig. 4. Dependence of the mean introduction rates for the sum of acceptors and for the sum of donors on the oxygen concentration. Irradiation: 23 MeV protons.

the 23 MeV irradiated samples depending on the oxygen concentration. The defect concentrations were divided by the fluence resulting in the introduction rate of the defect. Whenever more than one fluence was available for the same oxygen concentration, an average was taken.

The sum of the acceptors is constant for the investigated sensors and fluences and shows no dependence on the oxygen concentration. For the sum of the donors a dependence on the oxygen concentration can be observed. With increasing oxygen concentration, the introduction rate of E(30K) decreases for n-type silicon bulk and increases for p-type material. Not taken into account is the impact of the E-center, the phosphorus doping concentration for the n-type sensors and the boron concentration for p-type sensors.

B. Annealing-time-dependence of the E(30K) defect

Annealing studies were performed on all sensors in order to reduce the impact of pre-annealing during the irradiation process or the transportation. An example is shown in Figure 5. The concentration of the E(30K) donor at 32 K is presented for several annealing steps at 80 °C. The concentration is increasing with annealing time. A defect at 27 K can be observed directly after irradiation. This defect seems to disappear after 8 minutes at 80 °C.

The defect concentrations for 3 different sensors during the annealing process are presented in Figure 6. The MCZ sample irradiated with a low fluence of $3 \times 10^{13} \text{ cm}^{-2}$ has been normalized to the same fluence as the other samples. The time dependence of the annealing is similar for both MCZ samples, and apart from an offset also agrees with the time dependence of the dd-FZ sample.

Fig. 5. Close-up of the low-temperature region of TSC spectra for different annealing steps for MCZ pad-diodes.

Fig. 6. Time dependence of the E(30K) defect concentration as a function of the annealing time for 23 MeV proton irradiated pad-diodes.

C. Defects in 23 GeV proton irradiated sensors

A comparison between n- and p-type MCZ pad-diodes after irradiation with 23 GeV protons is presented in Figure 7. The concentration of deep acceptors and donors is similar for the n- and the p-type sample. A strange double peak at around 70 K was observed for the p-bulk sample, that is most likely an artifact of problems during the measurement. Such “distortions” can be observed for several of the measurements. Similar to the observation in low-energy proton irradiated samples, a defect signature is found in the p-bulk sample at about 95 K which might be attributed to B_iO_i . The BD defect is overlapping with this defect and the concentration has to be deduced from the difference between the defect concentration in the n-bulk and the p-bulk sensor.

In comparison to similar MCZ pad-diodes with a 30 times higher fluence presented in Figure 8, the IO_2 complex at 52 K is suppressed in the highly irradiated sample. The evaluation of the introduction rates for the 23 GeV proton irradiated sensors is presented in Figure 9. For technical reasons, the annealing times of the sensors are different from the annealing times of the 23 MeV proton irradiated samples in Figure 4.

Fig. 7. TSC spectra for 23 GeV proton irradiated MCZ pad-diodes with a fluence of $\Phi_{eq} = 1 \times 10^{13} \text{ cm}^{-2}$.

Fig. 8. Close-up of the low-temperature region of TSC spectra for 23 GeV proton irradiated MCZ pad-diodes with a fluence of $\Phi_{eq} = 3 \times 10^{14} \text{ cm}^{-2}$.

Therefore, a comparison of the different introduction rates is only possible in a qualitative way.

The concentrations of the acceptors are similar and do not show a distinct dependence on the oxygen concentration. The same can be observed for the sum of the donors. However, the overall concentration of the donors is smaller than observed for 23 MeV proton irradiated samples.

IV. CONCLUSION AND SUMMARY

The generation of defects in p- and n-bulk silicon was found to be very similar after 23 MeV proton irradiation. Therefore, models developed for n-bulk silicon can generally be applied to p-type silicon. However, there are indications for a dependence of the generation of the shallow donor

Fig. 9. Dependence of the mean introduction rates for the sum of acceptors and for the sum of donors on the oxygen concentration. Irradiation: 23 GeV protons.

E(30K) on the oxygen concentration and on the doping type. For a quantitative statement a larger sample size has to be investigated.

For 23 GeV proton irradiated samples a suppression of point defects in the TSC spectra was observed. This might be attributed to shielding processes of point defects in or near to cluster regions. It will cause an incomplete defect filling process with charge carriers at low temperatures, thus causing a much lower introduction rate for point-like defects. Since the known donors are considered to be point-like defects or small clusters [4], they will be affected by the shielding effect of cluster defects to a larger extend.

ACKNOWLEDGMENT

The research leading to these results has received funding from the European Commission under the FP7 Research Infrastructures project AIDA, grant agreement no. 262025 and the Helmholtz Alliance: Physics at the Terascale. The authors wish to thank M. Glaser and F. Ravotti for performing the PS-irradiations.

REFERENCES

- [1] E Shaposhnikova, *Intensity Upgrade Plans for CERN-LHC Injectors*, CERN-AB-2008-065, (2008).
- [2] J. Erle, *Irradiation study of different silicon materials for the CMS tracker upgrade*, PhD Thesis, University of Hamburg, March 2014.
- [3] I. Pintilie, E. Fretwurst, G. Lindström, *Cluster related hole traps with enhanced- field-emission-the source for long term annealing in hadron irradiated Si diodes*, APL 92 (2008) 024101.
- [4] I. Pintilie, G. Lindström, A. Junkes, E. Fretwurst, *Radiation-induced point- and cluster-related defects with strong impact on damage properties of silicon detectors*, NIM A 611 (2009) 5268.
- [5] A. Junkes, *Influence of radiation induced defect clusters on silicon particle detectors*, PhD Thesis, University of Hamburg, July 2011. DESY-THESIS-2011-031.

- [6] A. Dierlamm, *Characterization of silicon sensor materials and designs for the CMS Tracker Upgrade*, Presented at the VERTEX conference, Jeju, South Korea 2012, CMS CR -2012/370
- [7] L. R. Weisberg and H. Schade, *A Technique for Trap Determinations in Low-Resistivity Semiconductors*, J. Appl. Phys., 39(11):5149-5151, 1968.
- [8] D. Eckstein, *CMS outer tracker detector upgrade plans.*, CMS CR - 2014/008.
- [9] P. M. Mooney, et al., Phys. Rev. B 15, 3836 (1977).