The Compact Muon Solenoid Experiment

Conference Report

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

07 December 2012 (v6, 08 January 2013)

Analysis of Testbeam Data of Irradiated Silicon Prototype Sensors for the CMS Tracker Upgrade

Georg Auzinger for the CMS Collaboration

Abstract

CMS is working on identifying suitable radiation-hard silicon materials for the Tracker upgrade in the high luminosity era of LHC. A large number of 6 inch wafers made from p and n-type, float zone, Magnetic Czochralski and Epitaxial Silicon in thicknesses ranging from 50 to 320 μm were ordered from Hamamatsu. The wafers contain many different test structures as well as strip sensors called Multi Geometry Silicon Strip Detector (MSSD), that feature pitches from 70 to 240 μm and different strip widths. The structures were irradiated to a fluence of $1.5 \times 10^{15} \text{ 1MeV } N_{eq} \text{ cm}^{-2}$ which corresponds to the fluence that the sensors will receive in a future Tracker at a distance of 20 centimeters from the beam. This contribution will focus on the results obtained in various test beams with these strip sensors. The evolution of parameters such as resolution, signal and noise with increasing fluences will be addressed as well as the relation between geometry, thickness and technology.

Presented at *RESMDD12: 9th International Conference on Radiation Effects on Semiconductor Materials Detectors and Devices*

Analysis of Testbeam Data of Irradiated Silicon Prototype Sensors for the CMS Tracker Upgrade

Georg Auzinger on behalf of the CMS Tracker Collaboration

CERN & Vienna University of Technology

Abstract

CMS is working on identifying suitable radiation-hard silicon materials for the Tracker upgrade in the high luminosity era of LHC. A large number of 6 inch wafers made from p and n-type, float zone, Magnetic Czochralski and Epitaxial Silicon in thicknesses ranging from 50 to 320 μm were ordered from Hamamatsu. The wafers contain many different test structures as well as strip sensors called Multi Geometry Silicon Strip Detector (MSSD), that feature pitches from 70 to 240 μm and different strip widths. The structures were irradiated to a fluence of 1.5×10^{15} 1MeV $N_{\text{eq}} \text{ cm}^{-2}$ which corresponds to the fluence that the sensors will receive in a future Tracker at a distance of 20 centimeters from the beam. This contribution will focus on the results obtained in various test beams with these strip sensors. The evolution of parameters such as resolution, signal and noise with increasing fluences will be addressed as well as the relation between geometry, thickness and technology.

Keywords: HL-LHC; CMS Upgrade; Radiation-Hard Silicon

1. Introduction

The future High Luminosity upgrade for the LHC will dramatically change the conditions under which the upgraded silicon strip tracker of the CMS detector will have to operate. This includes a tenfold increase in luminosity which leads to an increased track density and a much harsher radiation environment. Therefore it is vital to build the new strip tracker using radiation-hard silicon materials as simulations show that the innermost strip layer at a radius of 20 cm from the interaction point will have to withstand fluences of up to 1.5×10^{15} 1MeV $N_{\text{eq}} \text{ cm}^{-2}$ (Figure 1).

CMS is currently in the process of identifying a suitable mate-

of radiation tolerance, material budget and production cost. A large number of 6 inch wafers, containing many different prototype sensors and test structures, was ordered from Hamamatsu Photonics. The wafers come in both p-on-n and n-on-p (p-stop and p-spray production methods) forms, made out of standard float zone, Magnetic Czochralski and epitaxial silicon. The latter is not covered in this work. The thicknesses range from 50 to 320 μm . Sensors and test structures have been extensively tested in laboratory measurements and particle beam tests and have been irradiated to various fluences corresponding to different radii in the future tracker. Here, the results obtained with a structure called the Multi-Geometry Silicon Strip Detector (MSSD) in two test beams — before irradiation and after receiving the highest fluence of 1.5×10^{15} 1MeV $N_{\text{eq}} \text{ cm}^{-2}$ — will be presented.

Figure 1: Simulated Fluence vs. Radius in the CMS Tracker at HL-LHC [1]

2. The Testbeam Setup

2.1. The Multi-Geometry Silicon Strip Detector

The Hamamatsu wafer layout contains different structures and mini sensors that allow the investigation of material properties, the technology used and different physical parameters. The MSSD was designed to explore the impact of thickness, strip geometry and doping technology on resolution, signal and signal-to-noise ratio. It features 12 regions, each with 32 strips, 4 different strip pitches and three different strip-width over pitch ratios in a repetitive pattern (Figure 2). The physical thickness of all float zone detectors is 320 μm which is different from their active thickness, this being limited using a technology called deep diffusion¹. The active thickness was found to be around

¹the backside implant layer is diffused into the material during heat treatment

rial to meet the challenges presented by the HL-LHC in terms

220 μm whereas it nominally should be 200 μm and 300 μm for the 320 μm version when extracted from capacitance measurements on diodes. Magnetic Czochralski sensors are all physically 200 μm thick.

The n-on-p sensors are available in p-stop isolation and p-spray. In the latter case the whole detector surface gets sprayed with p implants instead of having individual p-implanted electrodes around the readout strips to achieve electrical separation of the former. The strip properties were determined in laboratory measurements and the signal, signal-to-noise ratio and resolution were tested with a particle beam. For testing purposes the sensors were mounted on an aluminium plate and wire bonded to APV25 readout chips [2] (Figure 2).

Tracker layout simulations [3] and considerations regarding power dissipation and material budget suggest thicknesses in the range of 200 μm and pitches between 80 and 120 μm for the future strip tracker. Thus, in the presented work the focus was on the regions with these parameters.

Figure 2: MSSD Sensor mounted on aluminium plate and wire-bonded to APV25 readout chips.

2.2. The Silicon Beam Telescope

The Silicon Beam Telescope [4] was used to test the MSSD in a particle beam (15 to 150 GeV electrons, 50 to 300 GeV pions and 150 GeV muons). It consists of a thermoelectrically cooled box and eight planes of strip reference detectors with a pitch of 60 μm and intermediate strips between the readout strips. The reference planes were rotated by $\pm 45^\circ$ around the beam-axis (z-axis) while the MSSD as detector under test was mounted with the strips parallel to the x-axis. The whole system was read out using an early version of the current CMS tracker data-acquisition system.

The arbitrary ADC scale allows for relative comparison of the materials to each other which was the primary goal of this work.

2.3. The Analysis Framework

The framework that was used for analyzing the data from the various test beams is based on the Eutelescope [5] Pack-

age initially developed for the Eudet Telescope within the ILC-SOFT [6] framework. A slightly modified version, along with some standalone code, was used to account for the special geometry of the MSSD. The framework was used to:

- Reconstruct the reference telescope tracks;
- Calculate the pedestal and noise values for the detector under test using a standard mean / RMS algorithm with 30 strip-wise common mode correction;
- Export calibrated raw data and track parameters.

3. Analysis

3.1. Procedure

Since the beam telescope provides well defined reference tracks, a track based approach was chosen for the analysis. First, the expected impact point of the track on the MSSD was calculated and then the signal distribution of the three closest strips was built. Additionally, another signal distribution was built on three strips of the same region far from the hit. The distance between the peak of the two distribution was defined as a-priori signal (Fig. 3) and a threshold of 0.4 times this signal was used to select all strips that contribute to a cluster in the vicinity of a track and to suppress noise, thus minimizing any biasing of the signal by applying cuts (as in a normal cluster search) or similar restrictions.

Figure 3: Signal distribution at the impact point of the track and noise distribution away from the track in a 80 μm Region on an unirradiated MSSD made out of 200 μm thick n-on-p float zone.

The signal and signal-to-noise ratio distributions obtained with these clusters were fitted with a convolution of a Landau distribution and a Gaussian distribution, whereas the noise peak was fitted with a pure Gaussian. The signal-to-noise ratio is defined as

$$SNR = \frac{\sum_{Cluster} S_i}{N_{leadingStrip}} \quad (1)$$

where S_i are the signals from strips contributing to a cluster and $N_{leadingStrip}$ is the noise in the seed strip of the cluster.

3.2. Parameters

The parameters studied are:

- The signal as a function of the bias voltage and fluence;
- The signal-to-noise ratio as a function of the bias voltage and fluence.

Datasets from two different test beams taken prior to and after irradiation of the MSSDs have been analyzed. The second dataset corresponds to the integrated fluence the sensors are expected to receive at a radius of 20 cm (see Fig. 1) from the interaction point over the whole lifetime of the future CMS tracker, therefore representing the maximum damage it is expected to undergo during its life. Table 1 summarizes what materials have been tested in which state.

Table 1: Summary of tested materials and fluences

Material	unirradiated	$1.5 \times 10^{15} \text{ 1MeV } N_{eq} \text{ cm}^{-2}$
320 μm FZ	N P Y	N P Y
200 μm FZ	N P Y	N P Y
200 μm MCZ	N	N P Y
120 μm FZ	N	

N: p-on-n, P: n-on-p p-stop, Y: n-on-p p-spray
FZ ... float zone, MCZ ... Magnetic Czochralski

Due to the radiation damage the detectors suffered at this high fluence and a grounding issue with the readout system that introduced a lot of pick-up noise, it was not always possible to extract a clean signal from the data.

3.3. Results

Cluster Charge Distribution for Region 3

Figure 4: Signal distribution at the impact point of the track in a 80 μm Region on an unirradiated MSSD made out of 320 μm thick p-on-n float zone.

With the track-related clusters obtained with the method described in 3.1, the distributions of cluster charge and signal-to-noise ratio were built and fitted with the convoluted Landau and Gaussians which reproduced the histograms very accurately (Fig. 4). From the fit, the most probable value (MPV) was extracted and plotted as a function of bias voltage.

Figure 5: Signal versus bias voltage of different p-on-n and n-on-p detectors made out of 320 μm FZ material before and after irradiation.

Figure 5 shows the signal as a function of bias voltage for selected regions with 80 and 120 μm pitch and a strip-width over pitch ratio of 0.25 for 320 μm thick float zone material before and after irradiation.

Before irradiation n-on-p technology is equivalent in terms of signal to p-on-n, which is also used in the present CMS experiment. The signal observed in the p-spray material, which is known to be inferior to that observed in unirradiated p-stop material, is found to be superior to it when comparing the signals after receiving an integrated fluence of $1.5 \times 10^{15} \text{ 1MeV } N_{eq} \text{ cm}^{-2}$.

Figure 6: Signal versus bias voltage of different p-on-n and n-on-p detectors made out of 200 μm FZ material before and after irradiation.

The p-on-n detector had a very high dark current after irradiation and thus high noise which made it impossible to extract a clean signal.

The trend of n-on-p silicon being superior after irradiation to high fluences is also confirmed when looking at thinner float zone (Figure 6) and Magnetic Czochralski materials (Figure 7) where the signal is also only present for some regions and at higher bias voltages.

When looking at figures 5, 6 and 7 it is apparent that the bias

Figure 7: Signal versus bias voltage of different p-on-n and n-on-p detectors made out of 200 μm MCZ material before and after irradiation. Only p-on-n material was tested unirradiated.

voltages of the irradiated detectors were not high enough for the signal to saturate. In practice, very high dark currents — a well known effect of radiation damage — effectively limited the voltages since over-biasing could cause thermal runaway of the detector and thus damage it. While the tested voltages are not high enough to fully understand the behavior of materials and geometries at full depletion, they still indicate which materials might be better suited for use in the future tracker.

The behaviour of Magnetic Czochralski material after irradiation is very similar to the equivalent float zone material. The signal is almost identical with any differences most likely arising from the 10% difference in active thickness. When looking at the signal to noise ratio in figure 8, Magnetic Czochralski material performs at a similar level to the standard float zone material for n-on-p. The absolute value of signal-to-noise ratio was affected by the grounding-related pick-up noise that was found to be present after the data was recorded. However, this does not affect the relative values for the different doping schemes as all tested detectors suffered from the same problem, thus the comparison is valid.

Figure 8 confirms the conclusion drawn from the previous figures that n-on-p silicon is superior in terms of signal and signal-to-noise to p-on-n at the tested voltages. However it seems that the Magnetic Czochralski material has higher signal and slightly higher signal-to-noise than float zone silicon, despite being thinner.

The other conclusion is that p-spray isolation results in higher signal/signal-to-noise after irradiation to high fluences. This is particularly surprising since the production method was found to be error prone with respect to breakdown voltage during laboratory qualification and also had a lower signal before irradiation (Figures 5 and 6). So far, no reasonable explanation has been found for this behavior.

4. Summary

Multi-Geometry Silicon Strip Detectors in thicknesses of 200 and 320 μm made of standard float zone and Magnetic

Figure 8: Signal-to-noise ratio of different 200 μm materials after irradiation to $1.5 \times 10^{15} 1\text{MeV} N_{\text{eq}} \text{cm}^{-2}$ for 80 μm regions with a strip-width over pitch ratio of 0.25.

Czochralski silicon from the wafer that CMS ordered from Hamamatsu have been tested in particle beams before and after irradiation. It has been shown that it is possible to extract a usable signal from detectors that have received fluences up to $1.5 \times 10^{15} 1\text{MeV} N_{\text{eq}} \text{cm}^{-2}$ in the range of bias voltages tested. This fluence corresponds to that expected at the radius of the innermost strip layer in the proposed future CMS tracker. Whilst p-on-n silicon, especially 320 μm thick material, suffers heavily from radiation damage, which manifests itself through high current and high noise, n-on-p doped detectors exceed their p-on-n equivalents in terms of collected charge and signal-to-noise. It has been found that the p-spray production method works as intended to insulate electrodes on n-on-p devices and that Magnetic Czochralski silicon performs equally well to float zone silicon.

5. Acknowledgements

The research leading to these results has received funding from the European Commission under the FP7 Research Infrastructures project AIDA, grant agreement no. 262025.

References

- [1] S. Mueller, The Beam Condition Monitor and the Radiation Environment of the CMS Detector at the LHC, CMS-TS-2010-042
- [2] M. Raymond *et al.*, LEB 2000, CERN-2000-010
- [3] S. Mersi *et al.*, Software package for the characterization of Tracker layouts, Proceedings of the 13th ICATPP Conference, Como, Italy, Oct. 2011, CMS-CR-2011-261
- [4] T. Maenpaa *et al.*, Silicon beam telescope for LHC upgrade tests, NIMA Volume 593(3) 2008, p. 523-529, 10.1016/j.nima.2008.05.012
- [5] EUTelescope URL <http://atlas.desy.de/ib1/EUTelescope/>
- [6] F. Gaede, J. Engels, Marlin *et al.* - A Software Framework for ILC detector RD, EUDET-Report-2007-11