The Compact Muon Solenoid Experiment

Conference Report

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The CMS Tracker Upgrade for HL-LHC Sensor R&D

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Abstract

At an instantaneous luminosity of $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, the high-luminosity phase of the Large Hadron Collider (HL-LHC) is expected to deliver a total of 3000 fb^{-1} of collisions, hereby increasing the discovery potential of the LHC experiments significantly. However, the radiation environment of the tracking system will be severe, requiring new radiation hard sensors for the CMS tracker. Focusing on the upgrade of the outer tracker region, the CMS tracker collaboration has almost completed a large material investigation and irradiation campaign to identify the silicon material and design that fulfils all requirements of a new tracking detector at HL-LHC. Focusing on the upgrade of the outer tracker region, pad diodes as well as fully functional strip sensors have been implemented on silicon wafers with different material properties and thicknesses. The samples were irradiated with a mixture of neutrons and protons corresponding to fluences as expected for various positions in the future tracker. The measurements performed on the structures include electrical sensor characterization, measurements of the collected charge and bulk defect characterization. In this paper, the performance and limitations of the different materials are presented.

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The CMS Tracker Upgrade for HL-LHC Sensor R&D

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Keywords: High luminosity LHC, Outer tracker, Silicon material, Sensor characterization.

1. Introduction

The foreseen upgrade of the LHC is expected to increase the instantaneous luminosity by a factor of five. This operating condition leads to a higher particle density and hereby to radiation damages in the silicon tracker. Due to their position in the detector, the silicon modules are subjected to a high level of irradiation, which leads to more challenges in track identification. Therefore, new silicon sensors need to be radiation hard and have adequate granularity. The thinnest silicon sensor in the current tracker is $320 \mu\text{m}$

thick. The usage of thinner sensors in the new tracking system will be beneficial to reduce the material of the sensors as well as the material budget of the tracker. Given these requirements, the CMS tracker upgrade group seeks to choose a suitable material and sensor design with high performance for the future outer tracker at the high luminosity phase of the LHC.

2. Tracker Layout and Radiation

In the high luminosity LHC, the CMS tracker will have to provide satisfactory tracking in a more challenging environment with over 200 collisions per bunch crossing. At such conditions, the expected dose in units of 1 MeV neutron equivalent integrated fluence is between $1.5 \times 10^{15} \text{ } n_{eq} \text{ cm}^{-2}$ at a radius of 20cm and $\sim 1 \times 10^{14} \text{ } n_{eq} \text{ cm}^{-2}$ at a radius of 120cm . A significant fraction of the fluence is generated by protons, charged pions and neutrons. The different radial dependency of charged and neutral hadron fluences leads to a variation of the charged to neutral hadron ratio with radius ¹ . It is well known that the radiation damage produced by charged and neutral hadrons lead to different effects in different materials ^{2,3} . Therefore, it is vital to study this radiation damage on different materials. Since it is impossible to cover all positions in the tracker, only some interesting points are studied (see Tab. 1).

Table 1. Summary of fluences at different radii of the foreseen CMS tracker.

Radius [cm]	Proton $\phi_{eq} [\text{cm}^{-2}]$	Neutron $\phi_{eq} [\text{cm}^{-2}]$	Total $\phi_{eq} [\text{cm}^{-2}]$
40	3×10^{14}	4×10^{14}	7×10^{14}
20	1×10^{15}	5×10^{14}	1.5×10^{15}
15	1.5×10^{15}	6×10^{14}	2.1×10^{15}
10	3×10^{15}	7×10^{14}	3.7×10^{15}
5	1.3×10^{16}	1×10^{15}	1.4×10^{16}

3. Materials, Thicknesses and Production Technologies

The oxygen content, which is introduced during the growth process of the silicon, varies between different silicon materials. Therefore, materials produced with different growth techniques are thoroughly evaluated within the tracker collaboration:

- Float-zone which is the standard production technique, is used as a reference to compare the new design with the sensors of the current tracker system.
- Magnetic Czochralski, which is known as a high oxygen concentration technique.
- Epitaxially grown silicon to produce very thin sensors.

The structures are available in three different types: standard p-in-n (denoted as n-type) and n-in-p (denoted as p-type), which can be produced by p-spray and p-stop isolation techniques. Also, the selected materials cover the relevant combination of thicknesses (see Tab. 2).

The thin sensors are found to have a smaller degradation of the collected charge with increasing fluence compared to thick ones ⁴. Therefore, upgrade test-sensors were produced in various thicknesses (50 μm to 320 μm). Moreover, less thick sensors are preferred since they also have a smaller expected full depletion voltage and leakage current compared to the sensors in the current tracker system. In order to qualify sensor properties, various

Table 2. Physical versus active-thickness of HPK wafers.

Material	Active thickness	Physical thickness
FZ	120,200,320	320
FTH	200	
MCZ	200	200
Epi	50,100	

structures have been implemented in one wafer (produced by Hamamatsu Photonics K.K.) to ensure comparability (Fig.1 a). In this wafer each device is intended for a different purpose. The diodes and Baby-STD's are used to investigate material properties and defects after irradiation for different steps of annealing. The Multi-SSD and Multi-Pixel structures are used to evaluate the effect of geometry on sensor properties such as resolution and signal to noise ratio. In order to qualify the production process and sensor characterization, the standard test-structures are used. The Lorentz angle behavior is studied for various voltages, B-fields and radiation doses by Add-baby structure ⁵.

To evaluate the radiation-hardness, these structures are irradiated with neutrons or (and) protons to the expected fluences corresponding to specific positions in the outer tracker. The structures are initially exposed to neutron irradiation and then receive a proton irradiation and vice versa,

Fig. 1. a) The layout of the R&D wafer with ~ 30 different structures and b) Irradiation procedure for the HPK campaign.

followed by a further annealing stage. This sequence allows to understand the properties of the materials after pure and mixed irradiation using a minimum number of samples. The Fig.1 b) gives an overview of the procedure.

4. Results

4.1. Charge Collection

The signal over noise ratio is an important factor of detector performance (track identification and noise occupancy). The different radiation effects (eg. change of full depletion voltage, leakage current and trapping) lead to a reduction of this ratio and also the induced signal which has to be far away from noise. Figure 2 a) shows the signal as a function of fluence up to $1.5 \times 10^{15} n_{eq} cm^{-2}$ for three annealing steps and various silicon sensors. It can be seen that at very high doses the collected charge for p-bulk type is larger than for n-bulk sensors. This collected charge must be higher than the CMS binary chip threshold at HL-LHC. The similar behavior (less evident) is observed for Magnetic Czochralski sensors. Furthermore, a comparison of n-bulk and p-bulk sensors reveals that the signal is more stable as a function of annealing time for p-bulk devices, whereas n-bulk sensors show decreasing to a low level consistent with the CMS binary read out threshold (Fig. 2b) and 2c)). Moreover, thin sensors do not show a significant decrease of charge collection with longer annealing time, hence we can profit from annealing of the leakage current to reduce the noise contribution, which result in an increase of the signal to noise ratio.

Fig. 2. Seed signal as a function of a) $1 MeV n_{eq}$ fluences at 600V, b) Annealing after mixed irradiation with $7 \times 10^{14} n_{eq} cm^{-2}$ and c) Annealing after mixed irradiation with $1.5 \times 10^{15} n_{eq} cm^{-2}$.

Fig. 3. Noise distribution which shows fake hits.

Fig. 4. Fake hits for different sensors, radiation and fluences. Left: FZ320N neutron irradiated (no fake hits due to thickness), center: FZ200N neutron irradiated and Right: FZ200N mixed irradiated.

4.2. Non Gaussian Noise

In general, a Gaussian noise distribution is expected before and after irradiation. But some measurements reveal fake hits on n-bulk sensors which

are more evident at higher bias voltages (see Fig. 3). This effect leads to faked signal and also increasing occupancy. Regarding the various effects of different materials, voltages, annealing and type of irradiation, a large phase space has been scanned. The measurements show that this effect is more visible for the thin n-bulk sensors after charged hadron irradiation (Fig. 4) and it increases for higher doses. Studies of this effect with multi geometry sensors as a function of bias voltage show that it firstly starts to be significant for regions with higher pitches.

5. Conclusions

The HPK campaign was used to find a suitable silicon material with high performance for the CMS outer tracker detector at high luminosity LHC. Due to fake hits, p-in-n materials cannot be safely operated at the highest fluence and higher voltages, whereas no significant noise issue was observed for thin n-in-p bulk types. Moreover, the flat annealing behavior of n-in-p materials is beneficial to decrease leakage current without spoiling the signal. Furthermore, n-in-p materials show higher seed charge for the highest fluence compared to p-in-n types. The measurements performed within the campaign result in p-bulk material as the preferred choice and hereby the suggestion is to focus on the optimization of this type.

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