The Compact Muon Solenoid Experiment

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

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Towards Radiation Hard Sensor Materials for the CMS Tracker Upgrade

Georg Steinbrück for the CMS Tracker Collaboration

Abstract

During the high luminosity phase of the LHC starting around 2020 (HL-LHC), the machine is expected to deliver an instantaneous luminosity of $5 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. A total of 3000 fb^{-1} of data is foreseen to be delivered, hereby increasing the discovery potential of the LHC experiments significantly. However, the radiation dose of the inner tracking systems will be severe, requiring new radiation hard sensors for the CMS tracker. Up to now, typically p-in-n float zone devices with a thickness of at least 300 micrometers have been used for silicon strip detectors at CMS and other experiments. However, the signal-to-noise ratio for sensors implemented in this technology would be severely reduced for the inner layers of the tracker at the HL-LHC. Many measurements are described in literature, performed on a variety of silicon materials and technologies, but they are often hard to compare, because they were done under different conditions. To systematically compare the properties of different silicon materials and design choices and identify a solution suited for the upgrade, CMS has initiated a large irradiation and measurement campaign. Several test structures and sensors have been designed and implemented on 18 different combinations of wafer materials, thicknesses and production technologies. The structures are electrically characterized before and after irradiation with different fluences of neutrons and protons, corresponding to the expected fluences at different radii of the outer tracker after 3000 fb^{-1} . The tests performed include studies with β -sources, lasers and beam tests. In this talk, results from the ongoing campaign are presented.

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Abstract—During the high luminosity phase of the LHC starting around 2020 (HL-LHC), the machine is expected to deliver an instantaneous luminosity of $5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. A total of 3000 fb^{-1} of data is foreseen to be delivered, hereby increasing the discovery potential of the LHC experiments significantly. However, the radiation dose of the inner tracking systems will be severe, requiring new radiation hard sensors for the CMS tracker. Up to now, typically p-in-n float-zone devices with a thickness of at least 300 micrometers have been used for silicon strip detectors at CMS and other experiments. However, the signal-to-noise ratio for sensors implemented in this technology would be severely reduced for the inner layers of the tracker at the HL-LHC. Many measurements are described in literature, performed on a variety of silicon materials and technologies, but they are often hard to compare, because they were done under different conditions. To systematically compare the properties of different silicon materials and design choices and identify a solution suited for the upgrade, CMS has initiated a large irradiation and measurement campaign. Several test structures and sensors have been designed and implemented on 18 different combinations of wafer materials, thicknesses and production technologies. The structures are electrically characterized before and after irradiation with different fluences of neutrons and protons, corresponding to the expected fluences at different radii of the outer tracker after 3000 fb^{-1} . The tests performed include studies with β -sources, lasers and beam tests. In this talk, results from the ongoing campaign are presented.

I. MOTIVATION

Finely segmented silicon sensors are used in almost all high energy physics experiments for particle tracking. Due to their typical position close to the beam pipe they are subjected to high levels of irradiation with neutral and charged particles. By removing silicon atoms from their lattice sites and hereby creating pairs of vacancies and interstitial atoms, energy levels in the silicon band gap are created. Dependent on their properties, these energy levels have a threefold impact on basic silicon sensor properties:

- Energy levels close to the middle of the band gap tend to increase the leakage current, which increases the power consumption of a sensor and the noise.
- Charged defects can change the effective space charge concentration (N_{eff}), changing the voltage needed to fully deplete the silicon of free charge carriers.
- Some defects can act as trapping centers for electrons or holes, hereby reducing the number of collectible electron-hole pairs.

The sensors in the current CMS microstrip tracker are produced from oxygen-lean float-zone silicon in p-in-n technol-

ogy. They are designed to withstand an integrated luminosity corresponding to 10 years of nominal LHC running (300 fb^{-1}). However, during the high luminosity running phase of the LHC (from around 2020 onwards)[1][2], the luminosity will be increased by a factor of 10 with respect to the nominal LHC. Several new materials and production processes have been proposed and studied in recent years [3]. However, these sensors were produced for different experiments and the corresponding measurements are often hard to compare because they were done under different conditions, making strong conclusions difficult. CMS has therefore embarked on a large campaign to systematically compare silicon materials, sensor designs and layout parameters under otherwise identical conditions. The same small silicon sensors and test structures for specific measurements were implemented by an industrial supplier on a variety of silicon wafers differing in bulk material, thickness, production process and polarity (see table I).

II. IMPLEMENTED STRUCTURES AND WAFER LAYOUT

To study the properties of the different materials and production processes before and after irradiation, more than thirty structures have been specifically designed for this manufacturing run (figure 1). We have implemented several fully functional strip and pixel sensors. Large areas of the wafer have been devoted to structures with different strip and pixel geometries. The remaining part of the wafer has been filled with specialized test structures which give access to parameters that cannot be measured on a sensor. The results presented in this paper were obtained from measurements on pad diodes, which are used to study basic material properties.

III. MATERIALS, THICKNESSES AND PRODUCTION TECHNOLOGIES

The selected materials and thicknesses cover the relevant combination of parameters (see table I), including the standard $320 \mu\text{m}$ float-zone (FZ) material as a reference. For the materials denoted with *dd* the active thickness is defined by a special treatment called *deep diffusion*. The physical thickness of these wafers is always $320 \mu\text{m}$ and the active thickness is reduced to the desired value by the diffusion of dopants from the backside. This highly doped backside serves effectively as ohmic contact to the remaining active region. The main advantage of this technique is to lower the cost compared to physically thinned wafers. Also, for mechanical stability, very thin wafers might have to be bonded to a carrier wafer, an additional step that is not needed for the wafers treated with the deep diffusion process. The differences in the electrical

Fig. 1. Layout of the wafer with more than thirty different structures.

material	active thickness					
	320	200	120	100	70	50
FZ	X	X	X	-	-	-
FZ dd	-	X	X	-	-	-
MCz	-	X	-	-	-	-
Epi	-	-	-	X	X	X

FZ ...float-zone silicon

MCz ...magnetic Czochralski silicon

Epi ...epitaxially grown silicon

dd ...deep diffusion on the wafer backside to achieve desired active thickness on 320 μm wafers

TABLE I

WAFER MATERIALS AND THICKNESSES WHICH ARE STUDIED FOR THE CMS TRACKER UPGRADE.

properties of these two techniques, before and after irradiation, are studied as well.

The structures on all the selected materials have been manufactured in three different processes: standard p-on-n, n-on-p with p-stop strip isolation and n-on-p with p-spray strip isolation. The exception is Epi 70 which was only delivered in standard p-on-n technology.

IV. IRRADIATION CAMPAIGN

All structures are electrically characterized before irradiation, followed by either neutron or proton irradiations to different fluences. After each irradiation, the structures are annealed and again electrically characterized. The structures initially exposed to neutron irradiation then receive a proton irradiation and vice versa, followed by another annealing treatment and electric characterization. This strategy allows us to investigate the properties of the materials after pure proton and neutron irradiation, and with mixed irradiation using a minimum number of material samples. The fluence for charged and neutral hadrons expected at CMS for an integrated luminosity of 3000 fb^{-1} at the HL-LHC is shown in figure 2. Table II shows the fluence steps for neutron and proton irradiation corresponding to different radii of the outer tracker of CMS as chosen for this study. The samples are irradiated with 1 MeV neutrons at the TRIGA reactor in Ljubljana. To study

the energy dependence of radiation damage effects, several facilities are utilized for proton irradiation: The Karlsruhe cyclotron (23 MeV), Los Alamos (800 MeV) and the CERN Proton Synchrotron (23 GeV). In this paper results for samples irradiated with reactor neutrons and 23 GeV and 23 MeV protons, respectively, are shown.

Fig. 2. Fluence versus radius expected at CMS [4].

radius [cm]	proton $\phi_{eq} [\text{cm}^{-2}]$	neutron $\phi_{eq} [\text{cm}^{-2}]$	total $\phi_{eq} [\text{cm}^{-2}]$	active thickness
40	$3 \cdot 10^{14}$	$4 \cdot 10^{14}$	$7 \cdot 10^{14}$	$\geq 200 \mu\text{m}$
20	$1 \cdot 10^{15}$	$5 \cdot 10^{14}$	$1.5 \cdot 10^{15}$	$\geq 200 \mu\text{m}$
15	$1.5 \cdot 10^{15}$	$6 \cdot 10^{14}$	$2.1 \cdot 10^{15}$	$\geq 200 \mu\text{m}$
10	$3 \cdot 10^{15}$	$7 \cdot 10^{14}$	$3.7 \cdot 10^{15}$	$\leq 200 \mu\text{m}$
5	$1.3 \cdot 10^{16}$	$1 \cdot 10^{15}$	$1.4 \cdot 10^{16}$	$< 200 \mu\text{m}$

TABLE II

FLUENCES CHOSEN (1 MeV NEUTRON EQUIVALENT) IN THE IRRADIATION STUDY FOR DIFFERENT RADII OF THE OUTER TRACKER OF CMS. THE LAST COLUMN INDICATES THAT THICKER MATERIALS ARE STUDIED FOR THE OUTER RADII WHILE THIN SILICON IS CONSIDERED FOR THE INNERMOST REGIME.

V. RESULTS

First results from the measurement campaign were presented at last year's IEEE conference [5]. While the focus was on the initial characterization of devices before irradiation, in this talk we will present results from measurements before and after irradiation with protons and neutrons.

A. Leakage Current

Figure 3 shows the volume generation current as a function of particle fluence. To obtain reliable results, the measurements, taken at 5% above the depletion voltage, are plotted after annealing for 10 minutes at 60°C . The depletion voltage is determined from capacitance-voltage measurements at 1kHz (455 Hz for $T = -20^\circ\text{C}$). It is taken as the voltage where the linear rise of $1/C^2$ versus voltage turns into saturation. The

320 μm float-zone diodes with and without the deep diffusion treatment are labeled "FZ" in all the plots, while thinned-down float-zone devices are labeled "FZTH". The measurements are compared to a fit to previous measurements [6]. It can be seen that the measurements fit the expectation and are independent of the type of silicon material used (within errors). The well-known reduction of the leakage current with annealing time can be seen in figure 4.

Fig. 3. Volume current as a function of particle fluence measured at 0 °C and scaled to 20 °C.

Fig. 4. Volume current as a function of annealing time at 60 °C shown for samples irradiated with neutrons to $\phi_{eq} = 4 \cdot 10^{14} \text{ cm}^{-2}$.

B. Depletion Voltage and Effective Space Charge Concentration

One of the key parameters for a silicon sensor is the full depletion voltage, V_{dep} which is measured using capacitance-voltage measurements. The depletion voltage for the diodes under study can be seen in figure 5. The 320 μm thick materials have very high depletion voltages at fluences at or above 10^{15} cm^{-2} , for example above 1000V for the p-type float-zone.

The effective space charge concentration, N_{eff} , is related to the depletion voltage by $|N_{eff}| = \frac{2\epsilon\epsilon_0}{e} \frac{V_{dep}}{d^2}$ where d is the thickness of the device. Note that this measurement only yields the absolute value of N_{eff} while the charge sign has to be inferred from additional measurements like the transient current technique (TCT) or the annealing of N_{eff} (see below). Figure 6 shows N_{eff} as a function of particle fluence for irradiation with neutrons. Two observations can be made: All diodes end up with negative space charge after neutron irradiation. The n-type diodes tend to have lower N_{eff} after irradiation. This difference can be attributed to the initial doping concentration. Figure 7 shows N_{eff} as a function of particle fluence after irradiation with protons. Here we observe that n-type magnetic Czochralski silicon still shows positive space charge after irradiation with 23 GeV protons, while the n-type float-zone silicon shows negative space charge for fluences larger than $3 \cdot 10^{14} \text{ cm}^{-2}$. In contrast, after irradiation with 23 MeV protons, magnetic Czochralski and float-zone silicon both show signs of negative space charge.

Fig. 5. Depletion voltage as a function of fluence. Voltages around 1000 V are estimated due to limitations in the measurement setup.

Figure 8 shows the development of N_{eff} after annealing at 60 °C for diodes irradiated with 23 MeV protons at $\phi_{eq} = 3.0 \cdot 10^{14} \text{ cm}^{-2}$. This type of curve displaying a minimum is typical for irradiated diodes with negative space charge: They show p-type behaviour. This behaviour can be attributed to donor recovery which dominates the first phase of annealing (beneficial annealing). For n-type bulk silicon, this increases the effective space charge concentration, while for p-type silicon or type-inverted n-type, N_{eff} is reduced. Figure 9 shows the development of N_{eff} after annealing at 80 °C for diodes irradiated with 23 GeV protons at $\phi_{eq} = 3.0 \cdot 10^{14} \text{ cm}^{-2}$. For comparison, the plot contains a second scale showing the annealing time scaled to 60 °C. While the p-type diodes show a typical p-type dependence of N_{eff} as a function of annealing time, the n-type magnetic Czochralski displays the opposite behaviour: A local maximum. Sometimes it is stated that n-type magnetic Czochralski silicon does not type-invert after irradiation with GeV protons. However, with highly nonlinear electric fields present in highly irradiated sensors, the label

Fig. 6. Effective space charge concentration, N_{eff} , as a function of particle fluence for different silicon materials (neutron irradiation).

Fig. 7. Effective space charge concentration, N_{eff} , as a function of particle fluence for different silicon materials (proton irradiation).

Fig. 8. Effective space charge concentration, N_{eff} , as a function of annealing time for diodes irradiated with 23 MeV protons, $\phi_{eq} = 3.0 \cdot 10^{14} \text{ cm}^{-2}$. Note that all diodes show p-type behaviour.

type-inversion is not meaningful anymore.

Fig. 9. Effective space charge concentration, N_{eff} , as a function of annealing time for diodes irradiated with 23 GeV protons, $\phi_{eq} = 3.0 \cdot 10^{14} \text{ cm}^{-2}$. Note that the MCZ-N-diode shows an n-type annealing curve.

C. Charge Collection Efficiency

The reduction of the charge collection efficiency (CCE) due to trapping of charge carriers in radiation induced defect levels in the silicon band gap is one of the main problems at the HL-LHC. The charge collection efficiency is defined as the fraction of the signal collected for an irradiated diode compared to that of a non-irradiated diode of the same type. Charge carriers for this measurement can be injected either using an infrared laser or a β -source. While the latter provides a well-defined mean energy deposited in the silicon, the advantage of the laser is that the signal can be increased to be well above the noise. Figure 10 shows the CCE as a function of bias voltage for a non-irradiated and an irradiated diode, measured each with a laser and with a β -source (Strontium-90), respectively. It can be seen that both measurements agree rather well.

Figure 11 shows the charge collection efficiency (CCE) for pad diodes using an infrared laser. The CCE is measured at 100 V above the depletion voltage as determined by capacitance-voltage measurements and each measurement is normalized to a non-irradiated reference diode of the same type (with CCE=1). The typical drop in CCE with fluence can be seen. While there is no clear difference between n- and p-type silicon, a lower CCE for the thicker material can be observed. Note that the drop in CCE is partially compensated by the fact that the measurements are performed at voltages increasing with fluence.

VI. CONCLUSION

CMS has initiated a measurement and irradiation campaign to find a suitable silicon material to be used in the outer tracking detectors for the high luminosity phase of the LHC. A number of segmented detectors, special purpose test structures and pad diodes have been implemented by a single producer on a variety of bulk wafers. In this paper we present

Fig. 10. Charge collection efficiency (CCE) measured with an infrared laser (red symbols) and a β -source (blue symbols). Shown are curves for a non-irradiated diode and for a diode irradiated with protons to $\phi_{eq} = 10^{15} \text{ cm}^{-2}$.

Fig. 11. Charge collection efficiency (CCE), measured with an infrared laser, as a function of fluence.

preliminary results of measurements on pad diodes with the aim to understand the material properties. Results on the leakage current, the full depletion voltage and the effective space charge concentration and the charge collection efficiency are shown before and after irradiation with reactor neutrons, and protons of different energies. The results confirm that in a harsh irradiation environment, thicker silicon loses its advantage. While for the 320 μm thick diodes the depletion voltages get very large and the charge collection efficiency drops fast, 200 μm might be a good compromise between a reasonable signal on the one hand and depletion voltage on the other. The diodes in this thickness (p-type or n-type, magnetic Czochralski or float-zone) all show promising properties up to the radiation levels expected in the outer tracker of CMS. Differences in magnetic Czochralski silicon have been observed when comparing the annealing behaviour of the effective space charge concentration for samples irradiated with 23 MeV and 23 GeV protons, respectively. Further studies are needed to fully understand this. Also, due to the weighting field the charge collection is different between diodes and segmented sensors. Detailed studies on strip sensors are underway.

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REFERENCES

- [1] E. Shaposhnikova, Intensity Upgrade Plans for CERN-LHC Injectors, CERN-AB-2008-065, 2008.
- [2] CMS Collaboration, Technical Proposal for the Upgrade of the CMS Detector through 2020, CERN-LHCC-2011-006, 2010, June 2011.
- [3] The RD50 Collaboration, RD50 Status Report 2008, CERN-LHCC-2010-012, 2010.
- [4] Steffen Müller, The Beam Condition Monitor and the Radiation Environment of the CMS Detector at the LHC, PhD thesis KIT Karlsruhe, IEKP-KA/2011-1.
- [5] Matthias Bergholz for the CMS Tracker Collaboration, CERN-CMS-CR-2011-308, 2011.
- [6] Michael Moll, Radiation Damage in Silicon Particle Detectors - Microscopic Defects and Macroscopic Properties, PhD thesis, Hamburg University, 1999.