Radiation hardness and precision timing study of silicon detectors for the CMS High Granularity Calorimeter (HGC)

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The high luminosity upgraded LHC or Phase-II is expected to increase the instantaneous luminosity by a factor of 10 beyond the LHC’s design value, expecting to deliver 250 fb⁻¹ per year for a further 10 years of operation. Under these conditions the performance degradation due to integrated radiation dose will need to be addressed.

The CMS collaboration is planning to upgrade the forward calorimeters. The replacement is called the High Granularity Calorimeter (HGC) and it will be realized as a sampling calorimeter with layers of silicon detectors interleaved. The sensors will be realized as pad detectors with sizes of less than 1.0 cm² and an active thickness between 100 and 300 μm depending on the position, respectively, the expected radiation levels.

For an integrated luminosity of 3000 fb⁻¹, the electromagnetic calorimetry will sustain integrated doses of 1.5 MGy (150 Mrads) and neutron fluences up to 10¹⁶ neq/cm². A radiation tolerance study after neutron irradiation of 300, 200, and 100 μm n-on-p and p-on-n silicon pads irradiated to fluences up to 1.6 × 10¹⁶ neq/cm² is presented. The properties of these diodes studied before and after irradiation were leakage current, capacitance, charge collection efficiency, annealing effects and timing capability. The results of these measurements validate these sensors as candidates for the HGC system.

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1. Introduction

LHC upgrade. The basic goal of the Phase-II upgrade is to maintain the excellent performance of the CMS detector in terms of efficiency, resolution, and background rejection for all the physics objects used in the analysis of the data. The main challenges that must be overcome to achieve this goal are radiation damage to the CMS detector from the high integrated luminosity of the HL-LHC and the very high pileup that comes from the high instantaneous luminosity.

HGC. For an integrated luminosity of 3000 fb⁻¹ and in the region η ~3, the electromagnetic calorimetry near shower max will sustain integrated doses of 1.5 MGy (150 Mrad) and neutron fluences of 10¹⁶ neq/cm². At the same time, the effects of pileup will become even more severe, making the identification of electromagnetic objects more challenging. To address these challenges, CMS proposes the replacement of the endcap calorimeters, which cover 1.5 < |η| < 3.0, with a new high-granularity sampling calorimeter. The proposed design incorporates a silicon/tungsten electromagnetic section followed by two hadronic sections, both using brass as the primary absorber material. In the front section, the active material is silicon while the back section uses plastic scintillator. The design is targeted to achieve very high performance for physics objects reconstructed in the presence of high levels of pileup [1].

HGC sensors. At the HL-LHC the silicon sensors of the HGC will be exposed to hadron fluences ranging from about 2 × 10¹⁴ up to about 10¹⁶ 1 MeV neutron equivalent per cm² (neq/cm²) as it is...
shown in Fig. 1. These fluences are similar to those in the tracker and pixel volumes for the HL-LHC. The basic parameters for the HGC sensor design are based on results obtained for the CMS Phase-II Tracker R&D [2,3], and complemented by further dedicated measurements using neutron fluences up to 1.5 × 10^{16} neq/cm^{2}. The main difference between the tracker and the HGC is that whereas in the tracker the fluence is dominated by charged hadrons, in the case of the HGC it is neutrons that dominate. A dedicated campaign is underway to determine if the performance of the sensors is affected differently by neutrons. This study includes both p-in-n and n-in-p sensors, with active thickness of 300, 200 and 100 μm, exposed to fluences up to the highest to which the HGC will be exposed. First results from neutron irradiation are summarized.

2. Sensors description

The sensors under investigation are deep-diffused float-zone silicon pads (dd-FZ) of different active thickness produced by Hamamatsu within the framework of the CMS tracker upgrade campaign [4]. These sensors have different polarities, n-on-p (p-type) and p-on-n (n-type), different physical thickness: 320, 200 and 120 μm and an area of 25 mm^{2}. This manufacturer was selected for the very good quality and capability to produce the quantity needed for a large scale production.

The diodes have been irradiated to fluences up to 1.6 × 10^{16} neq/cm^{2} at the Triga reactor in Ljubljana, Slovenia [5]. Table 1 shows the different fluences reached for each type of diodes according to Fig. 1. After the irradiation and after an annealing of 10 min at 60 °C, the following properties have been measured: bulk current (IV), capacitance (CV), charge collection efficiency (CCE) with laser and MIP characterization with beta source.

The operation temperature of these diodes will be below −30 °C, and the bias voltage between 600 and 800 V. In order to compare results with the study carried out for the CMS tracker upgrade with protons irradiation and now extended to this neutron irradiation, most of the measurements have been done at −20 °C.

3. Characterization after neutron irradiation

IV and CV measurements. Several characteristics of these Si pads are important to be measured and compared before and after irradiation. Full depletion voltage, capacitance at full depletion voltage and leakage current at different bias voltages are the most important parameters to be extracted from the IV and CV characterization. Measured capacitances ranged between 10 pF for the thicker diodes to 20 pF for the thinner ones. The full depletion voltage and the end capacitance increased with the fluence. One important parameter that can be extracted from the CV curve is the real thickness of these dd-FZ diodes. At full depletion, the thickness of the diodes can be calculated by Eq. (1), where: \( \epsilon_0 \) is the vacuum permittivity, \( \epsilon \) is the silicon relative permittivity, Area is the pad’s area, \( W \) is the pad’s thickness, \( C \) is the measured pad’s capacitance and \( V \) is the applied voltage. The values of the full depletion voltage and the real thickness for the unirradiated sensors are summarized in Table 2:

\[
W(V) = \frac{\epsilon_0 \times \epsilon \times \text{Area}}{C(V)} \quad (1)
\]

The leakage current is increasing with particle fluence. The proportionality factor is called alpha value (\( \alpha \)) and given by Eq. (2) [6]:

\[
\Delta I = \alpha \Phi_{eq} \cdot V \quad (2)
\]

If the value of the leakage current measured (\( \Delta I \)) is normalized by the volume of the diode (\( V \)) and it is plotted vs the fluence (\( \Phi_{eq} \)) according to Eq. (2), it is possible to compare this results with the alpha value that can be found in the bibliography [6]. Fig. 2 shows how the leakage current normalized by the volume of the diodes scales with the fluence. The results are shown at −20 °C and at two different bias voltages 600 and 800 V, and compared with the alpha value taken from [6] and scaled according to the temperature dependence described in [7]. The agreement between the alpha value (9.0 × 10^{-19} A/cm) and the leakage current as a function of fluence is remarkable.

Charge collection efficiency. In order to estimate the charge collected by the diodes after their anticipated lifetime (3000 fb^{-1}), the charge collection efficiency (CCE) after irradiation has been measured. For this purpose the Transient Current Technique (TCT) is used [8]. The principle of TCT measurements is to observe the signal created by drifting charge carriers in the silicon detector bulk after illumination with a laser. In this case, an infrared laser of 1060 nm and a pulse width of 250 ps was used. The diodes were illuminated from the top with an intensity of ~40 mW. The collection time of the carriers last few ns. The amplified pulses are integrated in order to calculate the charge collected.

At these high fluences the charge collection is lower after irradiation, see Fig. 3. Collection time and rise time of TCT pulses decrease after irradiation, see Fig. 4. This point could be relevant for the timing purposes and it will be studied. Fig. 5 shows that for the 320 dd-FZ, placed in the region of smaller fluence, p-type diodes exhibit lower values of CCE that n-type. This difference was

<table>
<thead>
<tr>
<th>Thickness (μm)</th>
<th>Fluences (neq/cm²)</th>
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<tbody>
<tr>
<td>320</td>
<td>4.0 × 10^{14}</td>
</tr>
<tr>
<td>200</td>
<td>1.5 × 10^{15}</td>
</tr>
<tr>
<td>120</td>
<td>6.25 × 10^{15}</td>
</tr>
</tbody>
</table>

Table 1: Sensor status after irradiation.
not expected and the reason is under investigation. For the rest of the thicknesses p-type and n-type behave the same after irradiation. The lowest value of the charge measured is 4 ke\textsuperscript{-}/C\textsubscript{0}, lower than expected with a pure proton irradiation.

Radioactive source measurements. The purpose of the Radioactive source characterization is to evaluate the Landau parameters distribution after irradiation with MIPs. Measurements were conducted using a \textsuperscript{90}Sr source in a new setup built for this purpose. The measurements are underway and the first results for the 320 n-on-p diodes are shown in Fig. 6, where the charge distribution (fitted with Landau–Gaussian convolution) at 600 V and \( -20 ^\circ \text{C} \) is shown. The two main changes observed after irradiation are the reduction of the Landau MPV and the narrowing of the Landau width with fluence.

The measurements were done at two different temperatures, \( -20 ^\circ \text{C} \) and \( -30 ^\circ \text{C} \), and no significant differences were observed. The sensors were measured at different bias voltage from 0 V to 1000 V and it was possible to compare the CCE measured with the \textsuperscript{90}Sr source (1 MIP) at \( -20 ^\circ \text{C} \) and \( -30 ^\circ \text{C} \), with the CCE measured with the IR laser (\( \sim 40 \) MIPs) at \( -20 ^\circ \text{C} \). This comparison is shown in Fig. 7 and the agreement between the laser and the \textsuperscript{90}Sr source measurements is quite good.

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**Fig. 2.** Leakage currents, as a function of neutron fluence, measured at \( -20 ^\circ \text{C} \).

**Fig. 3.** CCE for the 200 \( \mu \text{m} \) p-on-n sensors, measured at \( -20 ^\circ \text{C} \), with an infrared laser. CCE decreases with the fluence.

**Fig. 4.** TCT spectra for the 200 \( \mu \text{m} \) p-on-n sensors, measured at \( -20 ^\circ \text{C} \), with an infrared laser. Pulses become shorter and the rise time decreases with the fluence.

**Fig. 5.** CCE in \( \text{e}^-/\mu \text{m} \) for 300 \( \mu \text{m} \) (leftmost set of points), 200 \( \mu \text{m} \) (middle set of points), and 120 \( \mu \text{m} \) silicon sensors (rightmost set of points). Signal normalized to 73 \( \text{e}^-/\mu \text{m} \) for the unirradiated silicon sensors.

**Fig. 6.** Distribution of the charge collected after \textsuperscript{90}Sr measurements for the dd-FZ 300 \( \mu \text{m} \) diodes n-on-p at 600 V and \( -20 ^\circ \text{C} \). For the Landau reconstruction, 20,000 events have been taken for each sensor.

**Fig. 7.** Comparison between the charge collected with \textsuperscript{90}Sr and the TCT with the infrared laser for the dd-FZ 300 \( \mu \text{m} \) n-on-p silicon diodes.
4. Timing studies

For understanding the timing capability of these diodes a test beam was carried out at the SPS H4 line at CERN [9]. Two silicon sensors of each thickness and polarity were measured at the same time. Micro Channel Plates (MCP) were used as a time reference and the readout was done with a V1742 fast (5GS/s) digitizer, ~700 MHz bandwidth. Several layers of absorbers were used to generate signals from 1 MIP to ~100 MIPs. Very similar resolution comparing sensors of different thickness for signals above 20 MIPs was observed. Fig. 8 shows the results for the 300 μm n-on-p diodes: 350 ps for 1 MIP signals and ~14 ps for signals above 20 MIPs.

5. Conclusions

An exhaustive radiation hardness study of silicon pads is being carried out and will be completed in the following months. Deep-diffused float-zone diodes of 25 mm² of area and thickness between 100 μm and 300 μm, p-on-n and n-on-p have been irradiated with neutrons up to a fluence of 1.6 x 10¹⁹ neq/cm² and the first results of the characterization have been presented. Leakage current scales linearly with the fluence and it is in agreement with the alpha value that can be found in the bibliography. The charge measured is reduced from 22, 15 and 9 ke (for thicknesses 300, 200 and 120 μm) to 10, 6 and 4 ke⁻, respectively, in the worst scenario. These values are somewhat lower than expected from purely proton irradiation and the reason is being investigated. A set-up for radioactive source measurements was built and the characterization of the Landau parameters is underway. Timing capability were studied for the unirradiated diodes. At the time of writing this, a new test beam with the irradiated diodes is already underway.

References