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Radiation hardness and precision timing study of Silicon Detectors for the CMS High Granularity Calorimeter (HGCAL)

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Abstract

The high luminosity LHC (HL-LHC or Phase-II) is expected to increase the instantaneous luminosity of the LHC by a factor of about five, delivering about 250 fb⁻¹ per year between 2025 and 2035. Under these conditions the performance degradation of detectors due to integrated radiation dose/fluence will need to be addressed. The CMS collaboration is planning to upgrade many components, including the forward calorimeters. The replacement for the existing endcap preshower, electromagnetic and hadronic calorimeters is called the High Granularity Calorimeter (HGCAL) and it will be realized as a sampling calorimeter, including 30 layers of silicon detectors totalling 600m². *These sensors will be realized as pad detectors with a 1.0cm² and an active thickness between 100µm and 300µm depending on their location in the endcap the thinner sensors will be 1, the electromagnetic calorimetry will sustain integrated doses of 1.5 MGy (150 Mrads) and neutron fluences of 10x10¹⁶ n/cm² on-p and p-on-n silicon pads irradiated to fluences up to 1.6x10¹⁶ n/cm² is presented. The main properties of these diodes are*

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Radiation hardness study of Silicon Detectors for the CMS High Granularity Calorimeter (HGCAL)

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ABSTRACT: The high luminosity LHC (HL-LHC or Phase-II) is expected to increase the instantaneous luminosity of the LHC by a factor of about five, delivering $\sim 250 \text{ fb}^{-1}$ per year between 2025 and 2035. Under these conditions the performance degradation of detectors due to integrated radiation dose/fluence will need to be addressed. The CMS collaboration is planning to upgrade many detector components, including the forward calorimeters. The replacement for the existing endcap preshower, electromagnetic and hadronic calorimeters is called the High Granularity Calorimeter (HGCAL) and it will be realized as a sampling calorimeter, including 40 layers of silicon detectors totalling 600 m^2 . The sensors will be realized as pad detectors with cell size between 0.5 and 1.0 cm^2 and an active thickness between $100 \text{ }\mu\text{m}$ and $300 \text{ }\mu\text{m}$ depending on their location in the endcaps. The thinner sensors will be used in the highest radiation environment. For an integrated luminosity of 3000 fb^{-1} , the electromagnetic calorimeter will have to sustain a maximum integrated dose of 1.5 MGy and neutron fluences of $1.0 \times 10^{16} \text{ n}_{eq}/\text{cm}^2$. A tolerance study after neutron irradiation of $300 \text{ }\mu\text{m}$, $200 \text{ }\mu\text{m}$, $100 \text{ }\mu\text{m}$ and $50 \text{ }\mu\text{m}$ n-on-p and p-on-n silicon pads irradiated to fluences up to $1.6 \times 10^{16} \text{ n}_{eq}/\text{cm}^2$ is presented. The main properties of these diodes have been studied before and after irradiation: leakage current, capacitance, charge collection efficiency with laser and MIP sensitivity with radioactive source (^{90}Sr). The results show a good performance even after the most extreme irradiation.

KEYWORDS: PIN diodes, Radiation-hard detectors, Calorimeters

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1 Introduction

CMS at HL-LHC CERN began planning to increase the luminosity of the LHC above the original design even before the machine went into operation. Major revisions to the machine or the experiments require access to the accelerator tunnels and the experimental areas that can only be accomplished efficiently during long shutdown periods. The current plan calls for a series of long periods of data-taking, referred to as Run-I, Run-II, etc. interleaved with long shutdowns, designated LS1(2013-2015), LS2(2019-2020) and LS3(2024-2026).The HL-LHC will begin after LS3. Major upgrades to the CMS detector are thus foreseen during LS3.

CMS 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 ($\sim 3000 \text{ fb}^{-1}$) and the very high pileup (maximum ~ 200 simultaneous events) that comes from the high instantaneous luminosity. CMS will need to upgrade many elements of the detector, including major changes to the trigger and data acquisition system (necessitating replacement of the front-end electronics on nearly all subsystems) as well as the full replacement of the tracker and endcap calorimeters.

HGCAL Electromagnetic and hadronic endcap calorimeters, will suffer significant radiation damage by LS3, and so must be replaced. The replacement is called the High Granularity Calorimeter (HGCAL) and features electromagnetic and hadronic sections with excellent transverse and longitudinal segmentation. It will provide detailed three dimensional images of particle showers. The electromagnetic section (EE) consists of 28 tungsten plates interleaved with silicon sensors as active material. The sensors have pads of variable sizes between 0.5 and 1.0 cm^2 . The electromagnetic section has $25X_0$ and 1.3λ . The hadronic part has a front section (FH) comprising 12 stainless

Figure 1. Equivalent 1 MeV neutron fluence for Phase-II endcap calorimetry at HL-LHC [5].

steel plates interleaved with silicon sensors for a depth of 3.5λ . This covers the hadronic shower maximum measurement. It is followed by a backing hadron (BH) calorimeter of similar design to the current CMS endcap hadronic calorimeter (HE) detector, stainless steel plates interleaved with plastic scintillator. The design of the HGCAL draws upon the ILC/CALICE [8] concepts for 3D measurement of shower topologies.

For an integrated luminosity of 3000 fb^{-1} and in the region $\eta \sim 3$, the electromagnetic calorimetry near shower maximum will sustain integrated doses of 1.5 MGy (150 Mrad) and neutron fluences of 10^{16} 1 MeV neutron equivalent per cm^2 (n_{eq}/cm^2). The effects of pileup will become ever more severe, making the identification of electromagnetic objects more challenging. The HGCAL design is targeted to achieve very high performance for physics objects reconstructed in the presence of high levels of pileup [5].

HGCAL sensors At the HL-LHC the silicon sensors of the HGCAL will be exposed to hadron fluences ranging from about 2×10^{14} up to about 10^{16} cm^2 (n_{eq}/cm^2) as shown in figure 1. These fluences are similar to those in the tracker and pixel volumes for the HL-LHC. The basic parameters for the HGCAL sensor design are based on results obtained for the CMS Phase-II Tracker R&D [4, 7], and complemented by further dedicated measurements using neutron fluences up to $1.6 \times 10^{16}\text{ n}_{eq}/\text{cm}^2$. The main difference between the tracker and the HGCAL is that whereas in the tracker the fluence is dominated by charged hadrons, in the case of the HGCAL 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-on-n and n-on-p sensors, with active thickness of 320, 200, 100 and $50\text{ }\mu\text{m}$ and an area of 25 mm^2 .

The sensors under investigation are deep-diffused float-zone (dd-FZ) and epitaxial (Epi) silicon pads of different active thickness produced by Hamamatsu [3] within the framework of the CMS tracker upgrade campaign [10]. This manufacturer was selected for the good quality and capability to produce the amount of sensors needed for a large scale production, although other producers are being considered for the mass production phase.

The diodes have been irradiated to fluence up to $1.6 \times 10^{16} \text{ n}_{eq}/\text{cm}^2$ at the Triga reactor in Ljubljana (Slovenia) [13]. Table 1 shows the different fluences ranges investigated for each type of diode in accordance with figure 1 and planned position in the HGAL. In order to cover the full fluence range expected in the HGAL and to understand irradiations performed in several exposure steps, 4 diodes have been irradiated twice. For the dd-FZ 320 μm and dd-FZ 200 μm two diodes have been re-irradiated after the first measurement to reach the next higher fluence given in table 1 (1 diode from lowest to middle and 1 diode from middle to highest fluence). The corresponding measurement results are included in the data analyses and have not been found to differ significantly from identical diodes irradiated in a single irradiation step.

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 an infrared laser and MIP sensitivity with radioactive source. Some results of the characterization have already been published in [9]. The operation temperature of these diodes will be below -30°C , at a bias voltage between 600 V and 800 V (up to ~ 400 V for the 50 μm thick devices). In order to compare results with the study carried out for the CMS tracker upgrade with proton irradiation and now extended to this neutron irradiation, most of the measurements have been done at -20°C .

Type, thickness	Fluences, $\text{n}_{eq}/\text{cm}^2$		
dd-FZ 320 μm	4.0×10^{14} (2)	6.0×10^{14} (3)	9.0×10^{14} (1)
dd-FZ 200 μm	1.5×10^{15} (2)	2.5×10^{15} (3)	4.0×10^{15} (1)
dd-FZ 120 μm	6.25×10^{15} (2)	1.0×10^{16} (1)	1.6×10^{16} (1)
Epi 100 μm	6.25×10^{15} (2)	1.0×10^{16} (2)	-
Epi 50 μm	-	1.0×10^{16} (2)	1.6×10^{16} (2)

Table 1. Summary of sensor types and irradiation fluences covered in this work. The number of diodes measured at the given fluence is indicated in brackets.

2 Characterization after neutron irradiation

2.1 IV measurements

IV measurements were performed for all the diodes after neutron irradiation and after an annealing of 10 min at 60°C . All measurements were done at -20°C except for the non-irradiated diodes, which were measured at room temperature (20°C). The bias voltages applied reached 1000V in steps of 10V with the exception of the 50 μm epitaxial diodes biased up to 400V. The bias voltage was applied from the back and the guard ring was connected to ground [11]. Figure 2 summarizes all the IV measurements done for the irradiated diodes; the unirradiated diodes are excluded in these plots.

The pad current of a reverse biased diode consists of two components: the diffusion current and the generation current, which is the dominant in highly irradiated sensors. The generation current density arises from e/h-pair generation, which depends on voltage respond and depleted volume. This current saturates at depletion voltage. Irradiation of Si detectors causes the introduction of deep-level defects in the band gap. These defects act as generation centres and result

Figure 2. IV measurements for all the irradiated diodes at -20°C .

macroscopically in an increase in reverse (leakage) current. The leakage current increases linearly with particle fluence. The proportionality factor is called alpha (α) and is given by equation 2.1 [14].

$$\Delta I = \alpha \Phi_{eq} V \quad (2.1)$$

The current-related radiation damage can be compared for different detector geometries if the increment of the leakage current measured after irradiation (ΔI) is normalized by the depleted volume of the diode (V). If this normalized value of the current is plotted as a function of the fluence (Φ_{eq}) according to equation 2.1, it is possible to compare this results with the alpha value that can be found in the literature [14]. Figure 3 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 [14] and scaled according to the temperature dependence described in [6]. The agreement between the reference alpha value ($9.0 \times 10^{-19} \text{ A/cm}$) and the alpha value calculated from the leakage current at 600 V and at 800 V as a function of fluence is within 15%.

2.2 CV measurements

CV measurements were performed for all the diodes after the neutron irradiation and after an annealing of 10 min at 60°C . Measurements were done at two different frequencies: 455Hz and

Figure 3. Leakage currents, as a function of neutron fluence, measured at -20°C . Epi 100P diodes are included in the plot but they were not considered for the fit.

1MHz. Bias and temperature were the same as for IV measurements. The bias voltage was applied from the back side of the diode and the guard ring was connected to ground in order to estimate properly the capacitance of the diodes. The circuit model used to determine the capacitance was a parallel RC circuit. Figure 4 summarizes all the CV measurements done for these diodes at 455 Hz.

Full depletion voltage, and end capacitance (C_{end}) are the most important parameters to be extracted from the CV characterization. Measured C_{end} ranged between 10 pF for the thicker diodes to 50 pF for the epitaxial 50 μm . The full depletion voltage and the C_{end} increased with the fluence. Another important parameter that can be extracted from the CV curve is the active thickness of the diodes, more relevant for the dd-FZ ones. At full depletion, the thickness of the diodes can be calculated by equation 2.2, where ϵ_0 is the vacuum permittivity, ϵ is the silicon relative permittivity, A 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 thickness calculated using equation 2.2 for the unirradiated diodes are summarized in table 2.

$$W(V) = \frac{\epsilon_0 \epsilon A}{C(V)} \quad (2.2)$$

2.3 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 [12]. The principle of TCT measurements is to observe the signal created by drifting charge carriers in the silicon detector bulk after illumination with a pulsed 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 equivalent to ~ 40 MIPs. The collection time of the carriers is few ns. The pulses are amplified using a broadband current amplifier [1]. The amplified pulses are integrated in order to calculate the charge collected.

Figure 4. CV measurements for all the diodes at -20°C and 455 Hz

Measurements were done in steps of 10 V up to 1 kV (400 V for the 50 μm thick devices) at -20°C . In this case, the guard ring was floating and all the dd-FZ were measured after 10 min at 60°C of annealing. The epitaxial diodes were measured after 30 min at 60°C of annealing.

After irradiation CCE, collection time and rise time decrease. Figure 5 shows the CCE for all the diodes. The reference value is the charge collected for the unirradiated diode at 400V, which is normalized to 1 and then the irradiated are scaled using this value.

Figure 6 and figure 7 show the charge collected, in $e^{-}/\mu\text{m}$ and in ke^{-} respectively, extracted from the TCT measurements at 600 V (300 V for the epitaxial 50 μm) using the thickness given in table 2. The charge expected for each thickness before irradiation is plotted in dashed lines and

Bulk type	Nominal thickness, μm	Full depletion, V	Measured thickness, μm	C_{end} , pF
dd-FZ p-on-n	320	210	298	8.912
dd-FZ n-on-p	320	229	291	9.13
dd-FZ p-on-n	200	110	228	11.63
dd-FZ n-on-p	200	85	209	12.72
dd-FZ p-on-n	120	100	148	17.85
dd-FZ n-on-p	120	71	133	19.87
Epi n-on-p	100	100	95.8	27.70
Epi p-on-n	50	30	49.71	53.43
Epi n-on-p	50	35	47.81	55.55

Table 2. Pad sensors' main parameters before irradiation.

is calculated using the reference value of $73 \text{ e}^-/\mu\text{m}$. In figure 6 can be seen clearly that thinner sensor give more charge that thicker ones after high levels of radiation, which is why HGCal plans to use thin sensors at the highest eta region.

Figure 5. CCE measurements for all the diodes using an infrared laser and performed at -20°C .

2.4 Radioactive source measurements

The purpose of the radioactive source characterization is to evaluate with MIPs the parameters of the Landau distribution after irradiation. Measurements were conducted using a ^{90}Sr source and performed at two different temperatures, -20°C and -30°C . No significant difference was observed. The sensors were measured at different bias voltages from 0 V to 1 kV (400 V for the

Figure 6. Signal ($e^-/\mu m$) extracted from the TCT measurements for the different diodes at 600 V, 300 V for the 50- μm epitaxial silicon.

Figure 7. Signal (ke^-) extracted from the TCT measurements for the different diodes at 600 V, 300 V for the 50- μm epitaxial silicon.

50 μm Epi). A photomultiplier was used in conjunction with a scintillator to detect the electrons. The signal was measured with a charge shaping amplifier [1]. It was not possible to measure the irradiated p-on-n diodes due to the high noise that appeared during the biasing. This problem did not affect the unirradiated n-on-p and p-on-n or the irradiated n-on-p. However, at the highest fluences: $1.0 \times 10^{16} n_{eq}/cm^2$ and $1.6 \times 10^{16} n_{eq}/cm^2$, the signal was very low and it was not possible

to distinguish it from the noise efficiently.

A convoluted Landau and Gaussian fitting function was used. The Gaussian parameter of the distribution (Gsigma) was not fixed to the measured electronic noise [2]. The rest of the parameters were extracted from the Landau function: most probable value (MPV) and width of the Landau. The Gaussian contribution in the charge depositions was higher than the measured electronic noise which implies that there are more Gaussian components that are not coming from the electronic noise.

It is possible to compare the CCE measured with the ^{90}Sr source (1 MIP) at -20°C and -30°C , with the CCE measured with the IR laser (~ 40 MIPs) at -20°C . Figure 8 shows that there is a good agreement between the laser and the ^{90}Sr source measurements.

More results for the dd-FZ 320 n-on-p diodes are shown in figure 8, where the charge distribution (fitted with a Landau-Gaussian convolution) at 600 V and -20°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.

Figure 8. Left plot: distribution of the charge collected after ^{90}Sr measurements for the dd-FZ 300 μm diodes n-on-p at 600 V and -20°C . Right plot: Comparison between the charge collected with ^{90}Sr and infrared TCT for the dd-FZ 300 μm n-on-p silicon diodes.

3 Analysis

As indicated in the previous section, the leakage current increases linearly with the fluence. At the highest fluences, the leakage current as a function of the voltage increases continuously and does not reach a plateau below 1 kV. Only in the case of dd-FZ 320 p-on-n a plateau is observed which is not visible on the dd-FZ 320 n-on-p and can be an indication of under depletion in the n-on-p diodes. For the rest of the thicknesses, both bulk types behave the same. The leakage current ranges from a few μA to $\sim 70 \mu\text{A}$ after irradiation. Notice that a change in the slope of the epitaxial diodes at high voltage is observed, figure 2. This exponential effect can be an indication of some amplification mechanism. In figure 3 it can be seen that the current for the Epi 100 n-on-p is higher than expected at 600 V.

From the CV characterization it is possible to make a similar analysis. Only in the case of dd-FZ 320 p-on-n a plateau is observed after irradiation. At a fixed voltage (e.g. 600 V) the

capacitance of the n-on-p irradiated diodes is much higher than on the p-on-n, that could mean that the active volume is smaller and the charge collection capability would be reduced. For the rest of the thicknesses there are no big differences. Only on the epitaxial diodes the full depletion is visible in the plots, figure 4. The increase of the capacitance above 300 V in the irradiated 50 μm p-on-n epitaxial diodes happens only when the guard ring is floating; when it is connected to ground this effect disappears. The capacitance ranges from 10 pF to 50 pF after irradiation.

The collected charge decreases with the fluence as can be observed in figure ???. With the exception of the dd-FZ 320 diodes, where the n-on-p diodes collect less charge than the p-on-n ones, both bulk types behave similarly. This difference was not expected and needs to be further investigated. A possibility is that it could be due to a smaller depletion volume in the n-on-p diodes, that would be in agreement with what was discussed in the previous paragraphs about the IV and CV analyses. Nevertheless, it is important to remark that at the highest fluence, in the worst scenario, it is still possible to collect more than 20 $\text{e}/\mu\text{m}$ at 600 V. The lower degradation of the Epi diodes in comparison with the dd-FZ is surprising, in the worst case it is possible to collect more than 50 $\text{e}/\mu\text{m}$. These results need to be cross-checked and a new irradiation with more epitaxial diodes is planned.

All unirradiated diodes were measured with the ^{90}Sr with a signal-to-noise ratio (SNR) between 18, for the thicker diodes, and 5, for the thinner ones. The SNR decrease with irradiation making it difficult to get a signal from the highly irradiated diodes. The signal measured in the unirradiated diodes with the ^{90}Sr source (MPV) was in between ~ 20.2 ke (for the dd-FZ 320 p-on-n) and ~ 3.5 ke (for the Epi 50 p-on-n). Aforementioned, only the n-on-p irradiated diodes could be measured. However, in the case of 50 μm epitaxial and the dd-FZ 120 the signal was already too small to be measured in the set-up. Nevertheless, the ones that were measured are in agreement with the TCT measurements, as shown in figure 8 for the dd-FZ 320 n-on-p.

4 Conclusions

A detailed radiation hardness study of silicon pads has been carried out. Deep-diffused float-zone and epitaxial diodes of 25 mm^2 and thickness between 50 μm and 320 μm , p-on-n and n-on-p have been irradiated with neutrons up to a fluence of $1.6 \times 10^{16} \text{ n}_{eq}/\text{cm}^2$. A complete set of results of the characterization has been presented. Leakage current scales linearly with the fluence as expected, there are no major differences with respect to a pure proton irradiation in this aspect. The charge measured reduces from 22, 16, 10 and 7 ke (for thicknesses 320, 200, 120 and 100 μm) to 10, 6, 4 and 6 ke^- , respectively, in the worst scenario. These values are lower than expected from pure proton irradiation and the reason is being investigated. Epitaxial diodes revealed a superior radiation tolerance after neutron irradiation at high fluences in comparison with the dd-FZ. At $1.0 \times 10^{16} \text{ n}_{eq}/\text{cm}^2$ and at the same voltage (600 V) the charge in the dd-FZ 120 n-on-p is ~ 3.5 ke while for the Epi100 n-on-p is ~ 5 ke. The reason for this is not clear and a further investigation will be required. MIP measurements were performed satisfactorily with a ^{90}Sr source for all the unirradiated diodes, and it was possible to measure all the n-on-p irradiated diodes up to fluences of $1.0 \times 10^{16} \text{ n}_{eq}/\text{cm}^2$.

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