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Results of irradiation quality assurance of CMS silicon microstrip detectors

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Abstract

The Large Hadron Collider (LHC) at CERN is a proton–proton collider with a maximum luminosity of $10^{34}/\text{cm}^2\,\text{s}$ and will be working for 10 years. The Compact Muon Solenoid (CMS) will be one of the two general purpose detectors. In order to guarantee the functionality of the 24 328 single-sided silicon sensors in the heavy irradiation environment of the LHC a fraction of all sensors have been irradiated in the two Irradiation Qualification Centers (IQC) in Karlsruhe (Germany) and Louvain-la-Neuve (Belgium). In Karlsruhe the sensors are irradiated with 26 MeV protons and in Louvain-la-Neuve they are irradiated with a neutron spectrum with an average energy of 20 MeV. The following sections show observed coupling capacitances, bias resistances and interstrip capacitances before and after irradiation and after varying annealing times at 60 °C.

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Keywords: CMS; Radiation hardness; Tracker; Leakage current; Signal to noise ratio; Poly-crystalline silicon resistor; Coupling capacitance; Interstrip capacitance

1. Introduction

The sensors of the CMS tracker are single-sided strip sensors with p^+-implants on n-bulk material. The inner barrel part will receive a maximum 1 MeV neutron equivalent fluence of about $1.6 \times 10^{14}\,\text{n}_{1\text{MeV}}/\text{cm}^2$ and the outer barrel part will receive a maximum 1 MeV neutron equivalent fluence of $0.35 \times 10^{14}\,\text{n}_{1\text{MeV}}/\text{cm}^2$ after 10 years of LHC operation. The CMS tracker is separated into two parts: the inner barrel for the region close to the beam pipe and the outer barrel for the outer part. The sensors in the outer barrel have larger strips and correspondingly higher currents and higher noise. Therefore, outer barrel sensors are thicker (500 μm) than the inner barrel sensors (320 μm).

The irradiation induces damage in the bulk of the sensor. For starting n-bulk material with thickness d and full depletion voltage U_{FD} the effective doping concentration, which is defined as the difference between donor N_{D} and acceptor N_{A} concentration,

$$N_{\text{eff}} = |N_{\text{D}} - N_{\text{A}}| = \frac{U_{\text{FD}} 2\varepsilon_0 \varepsilon_R}{d^2 e} \quad (1)$$

at first decreases to zero [1]. After this point, called type inversion, the full depletion voltage increases and therefore a sufficiently high operation voltage is required [1]. This requires a reduced electric field concentration in the bulk, which can be achieved by having an aluminum metalization on the strips, the bias ring and the guard ring 4 μm wider than the strip p^+-implants. The p^+ strips are connected to low potential via bias-resistors, while the opposite n^+-side is connected to a high potential. The bias-resistors are made of poly-silicon with resistance values between 1 and 2 MΩ [2]. The guard-ring forms the field configuration at the edges of the bulk material whilst defining the volume of the sensor.

In the irradiation facilities in Karlsruhe and Louvain-la-Neuve, the sensors are irradiated with 26 MeV protons and a spectrum of fast neutrons with an average energy of 20 MeV. For comparison, all fluences are multiplied by the

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hardness factor κ from the NIEL[1]-hypothesis. The basic assumption of the NIEL hypothesis is, that any displacement damage scales linearly with the amount of energy imparted in displacing collisions, irrespective of the spatial distribution of the introduced displacement defects in one cascade, and irrespective of the various annealing sequences taking place after the initial damage event. For 26 MeV protons the hardness factor $\kappa = 1.85$ is used [3], which defines the radiation damage relative to 1 MeV neutrons and is defined as

$$\kappa = \frac{\int D(E)\phi(E)\,\mathrm{d}E}{D(E_n = 1\,\mathrm{MeV})\int \phi(E)\,\mathrm{d}E}. \quad (2)$$

Here $D(E)$ is the damage factor for energy E and $\Phi(E)$ is the fluence at this energy [5].

The neutron spectrum in Louvain-la-Neuve is produced by shooting 50 MeV deuterons on a fixed target. The neutrons behind the target have a spectrum with an average neutron energy of 20 MeV and have a hardness factor of $\kappa = 1.95$. The beam impurities of 2.4% gammas and 0.03% charged particles are included in the hardness factor [4].

For safety reasons, the sensors are irradiated with 50% higher fluences than expected in order to guarantee the functionality during the service life of 10 years of CMS with a reliable safety margin.

In the tracker the sensors will be cooled down to $-10\,^{\circ}\mathrm{C}$ (or less) during operation and during as much as possible of repair and service periods in order to reduce the sensor leakage current and to avoid long term reverse annealing of the sensors' full depletion voltage [2].

2. Leakage current under irradiation

In addition to changes in the full depletion voltage the number of defects between the conduction and valence band increases the number of thermally produced electron–hole pairs, resulting in an increase of the total sensor leakage current. The increase of the leakage current ΔI is proportional to the fluence Φ and bulk volume V with

$$\Delta I = \alpha \Phi V \quad (3)$$

where α is the proportionality factor, called current related damage rate. The value for α is $3.99(\pm 0.03) \times 10^{-17}$ A/cm after 14 days of annealing at a temperature of $20\,^{\circ}\mathrm{C}$ [6].

Fig. 1 shows the leakage current after proton irradiation as a function of fluence at a bias voltage of 450 V at $-10\,^{\circ}\mathrm{C}$ for 320 μm mini-sensors at fluences up to $2.4 \times 10^{14}\,\mathrm{n_{1MeV}/cm^2}$, and for 500 μm mini-sensors up to $0.8 \times 10^{14}\,\mathrm{n_{1MeV}/cm^2}$. All structures have been annealed for 80 min at $60\,^{\circ}\mathrm{C}$ before the measurements, corresponding to a yearly annealing of the tracker for around 28 days at $+10\,^{\circ}\mathrm{C}$ [7].

The sensors total leakage currents are a little above the sum of all single strip leakage currents. This fact can be explained by edge effects around the active sensors volume. For this reason it is reliable to approximate the upper limit of the single strip leakage currents by dividing the sensors total leakage current by the number of strips. This corresponds well to observations in the IQC centers.

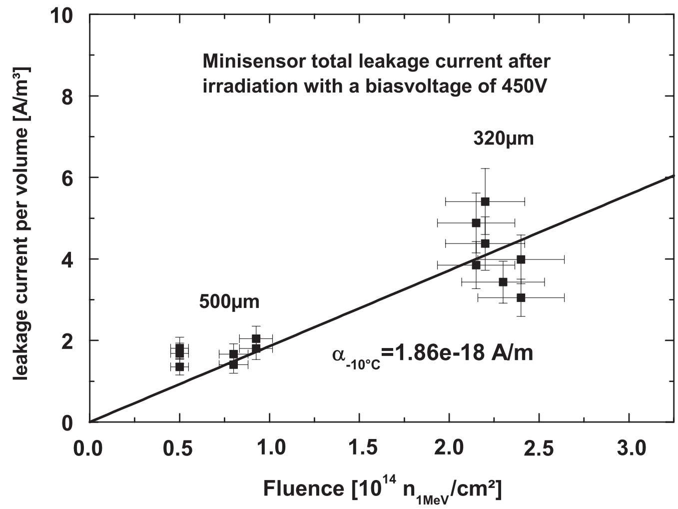

Fig. 1. The leakage current per volume increases linearly with fluence. The mini-sensors with a thickness of 500 μm are irradiated up to $0.8 \times 10^{14}\,\mathrm{n_{1MeV}/cm^2}$ and the mini-sensors with a thickness of 320 μm are irradiated up to $2.4 \times 10^{14}\,\mathrm{n_{1MeV}/cm^2}$. The total leakage current before irradiation of around 20 nA is very small compared to the leakage current after irradiation. The value for α, given on the plot, is for $-10\,^{\circ}\mathrm{C}$, where the measurements were taken, and for 80 min annealing time at $60\,^{\circ}\mathrm{C}$ [7].

3. Coupling capacitance under irradiation

Fig. 2 shows the evolution of a 320 μm CMS sensor's coupling capacitances with fluence (proton irradiated) and annealing time at $60\,^{\circ}\mathrm{C}$. The coupling capacitance decreases around 1−2% at a fluence of $2.4 \times 10^{14}\,\mathrm{n_{1MeV}/cm^2}$. Fig. 2 shows the results for up to 70 min annealing time. Even after 17 h of annealing at $60\,^{\circ}\mathrm{C}$ no change in the coupling capacitance was observed. This hints to charged defects in the coupling capacitances dielectric layer, which decrease the capacitance and which are stable in time—contrary to bulk damages as written above and observed with the change in full depletion voltage. Another possible explanation is the change of the electric field configuration below the dielectric layer. The influence to the signal to noise ratio by the coupling capacitances decrease is limited to a small decrease only depending on fluence.

4. Interstrip capacitance under irradiation

Fig. 3 shows the interstrip capacitance between the strip implants of the same CMS sensor as in Fig. 2 at a measurement frequency of 1 MHz. Neither the irradiation nor even after annealing times over 13 h affects the interstrip capacitances. The main influence to the interstrip capacitances comes from the charge states in the interface

[1]Non-Ionising Energy Loss.