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3D silicon pixel sensors for the CMS experiment tracker upgrade

Davide Zuolo on behalf of the Tracker Group of the CMS Collaboration

Abstract

The upgrade program of the CMS experiment in view of the LHC High Luminosity phase (HL-LHC) includes a replacement of the silicon pixel tracker. This is necessary to guarantee the same tracking performance of the current detector under harsher operating conditions, including higher radiation fluences and hit rates. The first layer of the central (barrel) detector will be located at radial distance of 3 cm from the interaction point where the radiation fluence after 7 years of operation will be 1.9×10^{16} n_{eq}/cm^2. Following an extensive R and D program, comprising both laboratory and test beam measurements, 3D sensors will be employed in this layer due to their higher radiation tolerance and lower power consumption after irradiation. The final design of the sensors will be presented, together with the most recent laboratory measurements. The main focus will be on the most recents test beam measurements, before and after irradiation up to 1.5×10^{16} n_{eq}/cm^2, that proved a hit detection efficiency larger than 96% at normal incidence with less than 2% masked pixels, for applied bias voltages larger than 120 V.

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3D silicon pixel sensors for the CMS experiment tracker upgrade

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Abstract

The upgrade program of the CMS experiment [1] in view of the LHC High Luminosity phase (HL–LHC) includes a replacement of the silicon pixel tracker. This is necessary to guarantee the same tracking performance of the current detector under harsher operating conditions, including higher radiation fluences and hit rates. The first layer of the central (barrel) detector will be located at radial distance of 3 cm from the interaction point where the radiation fluence after 7 years of operation will be $1.9 \times 10^{16} \mathrm{n_{eq}/cm^2}$. Following an extensive R&D program, comprising both laboratory and test beam measurements, 3D sensors will be employed in this layer due to their higher radiation tolerance and lower power consumption after irradiation. Test beam measurements after irradiation up to $1.6 \times 10^{16} \mathrm{n_{eq}/cm^2}$ showed a hit detection efficiency larger than 96% at normal incidence with less than 2% masked pixels, for applied bias voltages between 100 V and 130 V.

Keywords: 3D Pixel, Silicon, Sensors, CMS experiment, High-Luminosity LHC, Radiation hardness.

1. Introduction

The High Luminosity upgrade of the Large Hadron Collider at CERN (HL–LHC) calls for an upgrade of the Compact Muon Solenoid (CMS) experiment to operate with higher istantaneous luminosities (up to $7.5 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$) and number of collisions per bunch crossings (up to 200). The innermost section of the CMS Tracker detector, composed by hybrid silicon pixel modules, will be entirely replaced [2]. The upgraded CMS Inner Tracker (IT) extends the tracking coverage up to pseudorapidity $|\eta| = 4.0$, optimizes the layer arrangement, and improves the pixel granularity by a factor of six. It consists of three substructures: the Tracker Barrel Pixel (TBPX) with four layers, the Tracker Forward Pixel (TFPX) with eight small double–discs per side, and the Tracker Endcap Pixel (TEPX) with four additional large double–discs per side. Planar n–in–p sensors will be employed in the three sections but the innermost layer of TBPX, which will be located at a radial distance of 3 cm from the interaction point. At such distance the irradiation fluence after 7 years of operation will be $1.9 \times 10^{16} \mathrm{n_{eq}/cm^2}$. Following an extensive R&D program involving Fondazione Bruno Kessler (FBK, Italy) and Centro Nacional de Microelectrónica (CNM, Spain), comprising both laboratory and test beam measurements, 3D sensors will be employed in this layer due to their higher radiation tolerance and lower power consumption after irradiation. 3D pixel sensors have columnar electrodes penetrating the bulk perpendicular to the sensor surface as can be seen in Figure 1. Unlike in planar sensors, the inter–electrode distance is decoupled from the device active thickness opening the possibility to a large reduction of charge trapping after irradiation. For both planar and 3D sensors the pixel cell dimensions will be $25 \times 100 \times 150\ \mu m^3$. A production contract with FBK has been signed at the beginning of 2023 and the first sensor wafers are expected by July 2024.

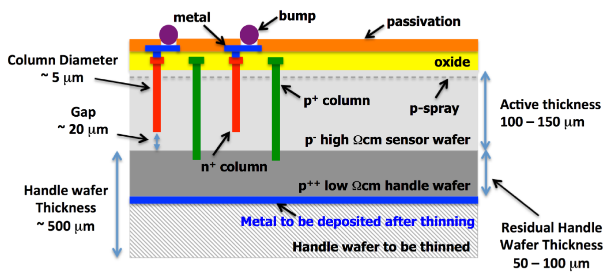

Figure 1: Cross-section of a typical FBK 3D silicon pixel sensor, showing the high resistivity (HR) and low resistivity (LR) layers, together with the p^+ ohmic columns and the n^+ junction columns.

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2. Test Beam results

Test beam characterization of single chip assemblies composed by a sensor bump bonded to the CROCv1 readout chip (ROC) developed by the RD53 collaboration have been carried out at the CERN SPS (120 GeV pions), Fermilab FTBF (120 GeV protons) and DESY (5.2 GeV electrons) facilities during 2022 and 2023. Unirradiated samples showed a detection efficiency at normal incidence larger than 98% already at 5 V bias voltage, compatible with the columns inactive area. Efficiencies larger than 99.5% are achieved once the modules are tilted by few degrees. The same angular scan allows measurement of the hit position resolution which is found to be as low as 2 μm. Several assemblies have been irradiated at the CERN PS (24 GeV protons) and KIT (25 MeV protons). Hit detection efficiencies larger than 96% at normal incidence with less than 2% masked pixels can be achieved with sensors irradiated at $1.6 \times 10^{16} \mathrm{n_{eq}/cm^2}$ for applied bias voltages between 100 V and 130 V as can be seen in Figure 2.

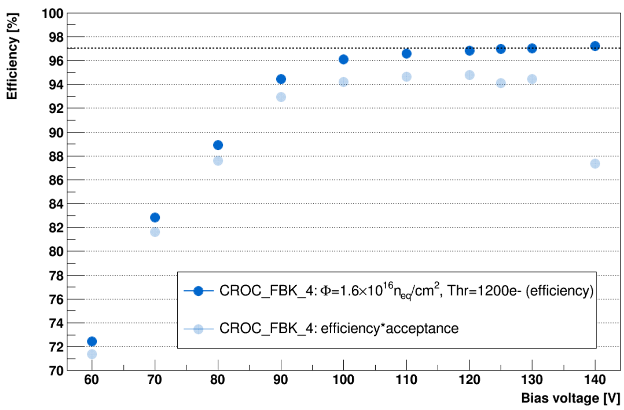

Figure 2: Hit detection efficiency as a function of the applied bias voltage for a single chip assembly irradiated at $1.6 \times 10^{16} \mathrm{n_{eq}/cm^2}$. The light color points represents the product of efficiency and acceptance, defined as $1 - \frac{N_{masked}}{N_{total}}$ where $\mathrm{N_{masked}}$ is the number of masked pixels and $\mathrm{N_{total}}$ is total number of pixels in the sensor.

3. Bump bonding

Detector modules of TBPX Layer 1 will be composed of two 3D sensors bump bonded to two ROCs. Few test modules have already been assembled and the bump bonding quality has been assessed using two different methodologies. The first consists in exposing the module to X–rays or beta sources for a time long enough to guarantee uniform absorption and identify the pixels that do not register hits. In order to reduce the duration of the test a new methodology, based on the study of pixel threshold and noise, has been adopted. The module is first supplied the typical reverse bias voltage (i.e. −20 V) and then a small direct bias voltage (+ 0.5 V) is applied. The ROCs are calibrated to an average threshold of 6000 electrons and per–pixel threshold and noise are measured with both voltages: pixels connected to damaged bumps are expected to see no changes in their values.

4. Serial powering

Power distribution in the current tracker detector of CMS is based on DC–DC converters. Such a powering scheme cannot be applied to the new IT because the number of DC–DC converters required to power a significantly larger number of channels would impact severely the material budget of the detector. Furthermore, such devices are not sufficiently radiation hard to be deployed in every section of the detector. Detector modules of the Inner Tracker, composed by a single sensor bump bonded to 2 or 4 ROCs, will be connected in serial powering chains composed by up to 11 modules. Shunt-LDO (Low DropOut) regulators [3] on every ROC will ensure that the correct bias voltage is supplied to the analog and digital domains of the chip and will provide shunt functionality for excess currents not consumed by the chip. An example of V–I curve of a ROC belonging to a serial powering chain is shown in Figure 3.

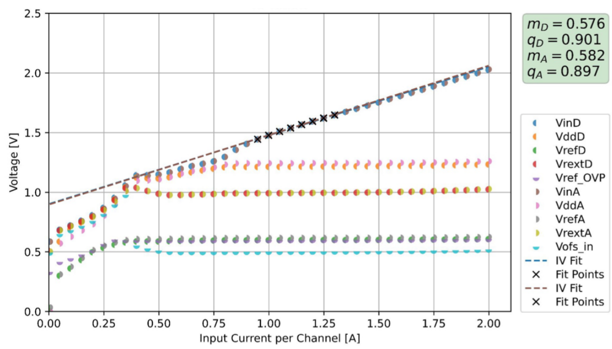

Figure 3: V–I curve of the ROC bonded to a 3D sensor belonging to a chain of 10 modules. The curve shows the ROC is working in an ohmic regime as expected and that the digital and analog voltages remain constants once the operation point of 1.2 V is reached.

Acknowledgements

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