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Study of irradiated 3D pixel sensors from CNM

Clara Lasaosa for the CMS Tracker Group

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Study of irradiated 3D pixel sensors from CNM

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Abstract

The High-Luminosity upgrade of the Large Hadron Collider will force the experiments to cope with harsh radiation environments. The CMS Collaboration has decided to install 3D pixel sensors in the innermost barrel layer of the tracking system, which has to face a fluence of 2×10^{16} $n_{eq}cm^{-2}$ before replacement. This pixel technology should maintain high detection efficiency and manageable power dissipation at such unprecedented fluences. Results from beam test experiments with 3D pixel sensors fabricated at IMB-CNM and bump-bonded to RD53A readout chips are presented. The irradiation with protons of 400 MeV-momentum to fluences of roughly 1.3–2.0 $\times 10^{16}$ $n_{eq}cm^{-2}$ as well as the measurement of these sensors in a test beam have been both performed at Fermilab.

Keywords: High Luminosity, CMS, Tracker detector, Upgrade, 3D pixel silicon sensors, CNM

1. Introduction

1.1. High-Luminosity phase of the LHC

The High-Luminosity Large Hadron Collider (HL-LHC) [1] environment will feature a peak instantaneous luminosity of around 7.5×10^{34} cm^2s^{-1} with up to 200 collisions per bunch crossing. This will allow the CMS experiment [2] to collect up to an integrated luminosity of 4000 fb^{-1} over the lifetime of the experiment. In order to cope with such unprecedented high luminosity, the CMS detector needs to be upgraded. In particular, its innermost region called Inner Tracker (IT), which is made of pixel modules and whose layout is depicted in Figure 1, will be fully replaced to sustain the foreseen high radiation levels. The expected fluence and Total Ionizing Dose (TID) in the innermost layer of the Tracker Barrel Pixel, which is the closest to the interaction point, are 1.88×10^{16} $n_{eq}cm^{-2}$ and 1.03 Grad after the first two runs (Run 4 and Run 5) of operation.

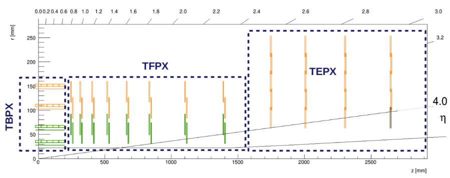
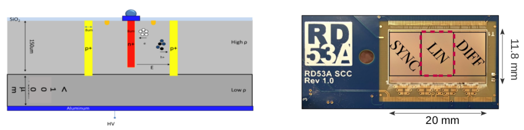


Figure 1: One quarter of the upgraded IT layout in the longitudinal view. It consists of three substructures: Tracker Barrel Pixel (TBPX), Tracker Forward Pixel (TFPX) and Tracker Endcap Pixel (TEPX).

1.2. 3D pixel silicon sensors from CNM

The high radiation environment introduces constraints for the pixel sensor design, such as high radiation tolerance, increased granularity keeping the occupancy below 10^{-4}, high reconstruction efficiency and absence of thermal runaway. In this regard, 3D pixel sensors, which consist of columnar electrodes penetrating the bulk perpendicularly, have proven to be the best option for the innermost layer of the TBPX. Unlike planar sensors, the 3D pixel technology has the inter-electrode distance decoupled from the device thickness. This gives rise to a smaller depletion voltage and consequently lower power dissipation, as well as a shorter collection path for the charge carriers and therefore reduced trapping probability. However, there are some drawbacks with respect to planar sensors, such as the efficiency loss in the columns and the lower homogeneity of the electric field.

Instituto de Microelectrónica de Barcelona along with Centro Nacional de Microlectrónica in Spain (IMB-CNM) [3] is one of the main manufacturers of pixelated 3D sensors. The baseline sensor design consists of a hybrid pixel detector: an n-in-p sensor of Si-on-Si single-sided processing (Figure 2(a)) bump-bonded to an RD53A readout chip (Figure 2(b)). The sensors have a pixel cell size of either 25×100 μm^2 or 50×50 μm^2 and an active thickness of 150 μm. The RD53A chip [4] is a prototype of the final pixel readout chip for ATLAS and CMS based on 65 nm CMOS technology with a matrix of 76800 $50x50$ μm^2 pixels and three analog front-ends for development purposes.



(a) (b)

Figure 2: (a) CNM 3D pixel sensor layout, and (b) RD53A readout chip showing the three analog front-ends: synchronous, linear and differential.

2. Irradiation and characterization of 3D sensors

2.1. Irradiation and test beam setups

The irradiation of the 3D pixel sensors fabricated by CNM has been carried out at several facilities: at Institut Pluridisciplinaire Hubert Curien (IPHC) with protons at 23 MeV, at the Fermilab Irradiation Test Area (ITA) using protons at 400 MeV and at Karlsruhe Institute of Technology (KIT) with protons at 25 MeV. Concerning the target fluences, they are in the range

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of 1–2 × 10^{16} $n_{eq}cm^{-2}$. Unfortunately, the beam was off-center in the irradiation performed at ITA, so work is currently underway to reduce the systematic uncertainties for the respective fluences. It is worth mentioning that the TID in the low-energy irradiation facilities is much higher than that expected at CMS for the same fluence.

Regarding the data taking, it has also been performed at several facilities using different kinds of test beams: at Deutsches Elektronen-Synchrotron (DESY) with an electron/positron beam at 5 GeV, at Fermilab with a proton beam at 120 GeV and at the CERN Super Proton Synchrotron (SPS) with a pion beam at 120 GeV. The telescope resolution in such test beam setups is around 2–10 μm, the data acquisition systems used are BDAQ [5] and Ph2_ACF, and the results have been obtained using only the RD53A linear front-end.

2.2. *Irradiated 3D sensor characterization*

Various efficiency measurements on CNM 3D pixel modules irradiated to different fluences have been made and are presented below. In Figure 3, a small study for a 3D module with 25×100 μm^2 pixel pitch irradiated to 2×10^{16} $n_{eq}cm^{-2}$ at KIT is shown. Unfortunately, the sensor broke before reaching full depletion, so a low and a high efficiency region within the pixel cell have been analyzed to see how they evolve with the bias voltage. These efficiency regions exist because depletion occurs progressively from the central n-column (high efficiency area) towards the ohmic columns located at the corners of the pixel cell (low efficiency area). As expected, it is observed that the tendency in the high efficiency region is to increase with the bias voltage more slowly than in the low efficiency region. The plateau of efficiency, which is expected to be around 97%, would be reached at approximately 160–170 V.

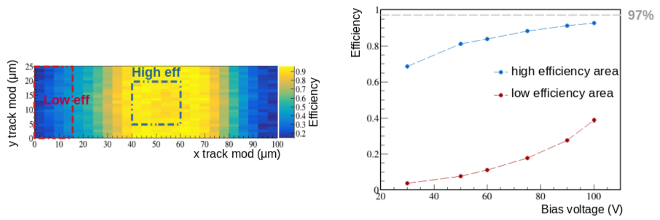

Figure 3: CNM 3D module irradiated to 2×10^{16} $n_{eq}cm^{-2}$ with 25×100 μm^2 pixel pitch: efficiency cell map showing two different efficiency regions (left) and efficiency as a function of bias voltage for both regions (right).

In Figures 4 and 5, results from two 3D modules irradiated to 1.3×10^{16} $n_{eq}cm^{-2}$ at ITA with 25×100 μm^2 and 50×50 μm^2 pixel pitch, respectively, are shown. However, the fluence estimation is possibly affected by large systematic uncertainties, as stated above. This could be the reason why the efficiencies are a bit higher than expected for the given bias voltages at such fluences. The sensor tuning was carried out ensuring a low number of noisy pixels, which are defined with a cut on occupancy of 1×10^{-5}. The I-V curves indicate that the sensors can be safely operated up to 80 V. The efficiency measurements in Figure 4(d) and Figure 5(d) reach a plateau at 99% for bias voltages higher than 80 V at an incidence angle of 10° and a plateau at 91% for bias voltages higher than 60 V at normal incidence, respectively.

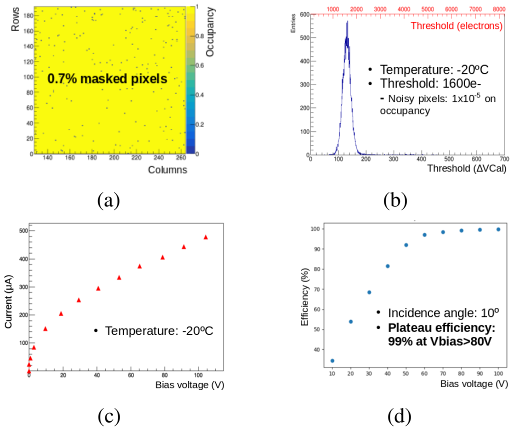

Figure 4: CNM 3D module irradiated to 1.3×10^{16} $n_{eq}cm^{-2}$ with 25×100 μm^2 pixel pitch: (a) noise masking, (b) threshold tuning, (c) I-V curve, and (d) efficiency as a function of bias voltage at an incidence angle of 10°.

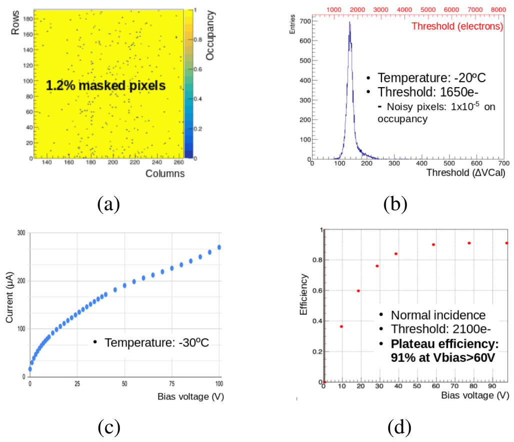

Figure 5: CNM 3D module irradiated to 1.3×10^{16} $n_{eq}cm^{-2}$ with 50×50 μm^2 pixel pitch: (a) noise masking, (b) threshold tuning, (c) I-V curve, and (d) efficiency as a function of bias voltage at normal incidence.

3. Conclusions

CNM 3D sensors have been irradiated and measured in test beams, reaching 97% efficiency at 160–170 V for a fluence of 2×10^{16} $n_{eq}cm^{-2}$ and 99% efficiency at 80 V for a fluence of roughly 1.3×10^{16} $n_{eq}cm^{-2}$. Unfortunately, several samples got damaged during handling and transportation resulting in limited data for CNM 3D sensors. Nevertheless, further irradiation programmes as well as the analysis of the beam test data are currently ongoing.

References

[1] CMS Collaboration, The Phase-2 Upgrade of the CMS Tracker, CERN-LHCC-2017-009, CMS-TDR-014, Technical Report, CERN, Geneva, 2017. URL: `https://cds.cern.ch/record/2272264`.

[2] CMS Collaboration, The CMS experiment at the CERN LHC, JINST 3 (2008) S08004. URL: `https://doi.org/10.1088/1748-0221/3/08/s08004`.

[3] D. Quirion et al., Manufacturability and Stress Issues in 3D Silicon Detector Technology at IMB-CNM, Micromachines 11 (2020). URL: `https://www.mdpi.com/2072-666X/11/12/1126`.

[4] M. Garcia-Sciveres (RD53 Collaboration), The RD53A Integrated Circuit, CERN-RD53-PUB-17-001, Technical Report, CERN, Geneva, 2017. URL: `https://cds.cern.ch/record/2287593`.

[5] M. Daas et al., BDAQ53, a versatile pixel detector readout and test system for the ATLAS and CMS HL-LHC upgrades. Nucl. Inst. Meth. A 986 (2021) 164721.