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Performance of planar pixel modules for the CMS Phase-2 Inner Tracker

Bianca Raciti, on behalf of the Tracker Group of the CMS Collaboration

Universität Hamburg, Luruper Chaussee 149, 22671, Hamburg, Germany

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ABSTRACT

During the Long Shutdown 3, the CMS pixel detector will be replaced to operate during the High Luminosity LHC (HL-LHC) running phase. Hybrid pixel modules of the new tracking detector will have to fulfill stringent requirements to operate in an extremely harsh radiation environment and cope with the high data readout rate. Sensor-readout chip assemblies have been extensively tested in the laboratory and at the DESY test beam facility. This study presents results on the analysis of test beam data acquired with HPK planar pixel sensors interconnected with the RD53B_CMS readout chip, irradiated to fluences up to $\Phi_{eq} = 1.0 \times 10^{16}\,\text{cm}^{-2}$. For all investigated fluences, the requirements for the efficiency times acceptance and the spatial resolution are met, while keeping the percentage of pixels masked as noisy below 1%. Additionally, measurements of crosstalk levels will be presented.

1. Introduction

The CMS pixel detector [1,2] will be replaced as part of the Phase-2 upgrade [3] for the HL-LHC. A new prototype readout chip, called RD53B_CMS, was developed by the RD53 Collaboration [4] and is implemented in a 65 nm CMOS radiation-hard technology. It features 336 rows and 432 columns, with a bump-bond pattern of $50\,\mu\text{m}^2 \times 50\,\mu\text{m}^2$. The top layer of the HPK planar sensor layout is shown in Fig. 1. In the final design, the n^+ implant under the bump near the passivation opening was removed to minimize the overlap between the metal layer and neighboring implants, hence reducing crosstalk (XT).

2. Experimental setup, requirements and results

The following results were obtained with RD53B_CMS single chips bump-bonded to HPK planar sensors tuned to a threshold of 1200 e^- and irradiated with 23 GeV/c protons at the Proton Irradiation Facility at CERN to 1 MeV neutron equivalent fluences up to $\Phi_{eq} = 10^{16}\,\text{cm}^{-2}$. Measurements have been performed in the laboratory and at the DESY-II test beam facility using a 5.2 GeV electron beam.

To further validate the chosen design for planar sensors, measurements of XT as a function of the injection-readout delay were performed using the internal injection circuit and are shown in Fig. 2 (top). The dependence of XT on the delay is due to the variation of the hit detection probability as a function of time, attributable to the architecture of the analog front-end. This effect can be seen measuring the average threshold of the pixel matrix, as shown in Fig. 2 (bottom). Signal sampling in CMS will happen at the moment of highest efficiency and hence lowest threshold. In the same region, XT stays well below 10% and can be addressed during the offline reconstruction analysis.

The observables evaluated at the test beam are the single hit efficiency ϵ_{hit}, the acceptance α, and the spatial resolution σ_{hit}, defined as in [5]. Modules must fulfill stringent requirements, such as keeping the amount of noisy pixels, defined as pixels with a noise occupancy $> 10^{-4}$, below 1%, while maintaining the average noise hit rate in unmasked pixels $< 10^{-6}$; the efficiency times acceptance must remain above 99% for fluences up to $\Phi_{eq} = 5.0 \times 10^{15}\,\text{cm}^{-2}$ and above 98% for higher irradiation levels; σ_{hit} must remain below the single-pixel cluster limit, corresponding to $7.2\,\mu\text{m}$ in the r-ϕ direction and $28.9\,\mu\text{m}$ in the z direction, along the $25\,\mu\text{m}$ and $100\,\mu\text{m}$ pixel pitch.

The requirements on $\epsilon_{hit} \times \alpha$ for non-irradiated modules are satisfied for bias voltages $V_{bias} \geq 5$ V. For fluences of $\Phi_{eq} = 4.8 \times 10^{15}\,\text{cm}^{-2}$, $\Phi_{eq} = 8.0 \times 10^{15}\,\text{cm}^{-2}$ and $\Phi_{eq} = 1.0 \times 10^{16}\,\text{cm}^{-2}$ they are met at 350 V, 400 V, and 450 V, respectively, as shown in Fig. 3 (top). The percentage of noisy pixels with a noise occupancy $> 10^{-4}$ never exceeds 1%, as shown in Fig. 3 (middle).

Results for σ_{hit} and the projected cluster size in the r-ϕ direction as a function of the turn angle θ_{turn}, around the $100\,\mu\text{m}$ pixel pitch axis, are shown in Fig. 3 (bottom). Charge sharing takes place in the $25\,\mu\text{m}$ pitch direction. For all fluences, $\sigma_{hit}^{r-\phi}$ and σ_{hit}^{z} remain below the respective binary limits, with a minimum around $2.5\,\mu\text{m}$ at an angle of 9.5°, where charge sharing is optimal for the sensor geometry under test.

E-mail address: bianca.raciti@cern.ch.

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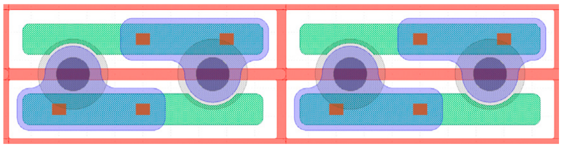

Fig. 1. Top layer of the HPK planar pixel sensor layout showing four pixels with a pitch of $25\,\mu m^2 \times 100\,\mu m^2$ and a thickness of $150\,\mu m$. Color code in [3].

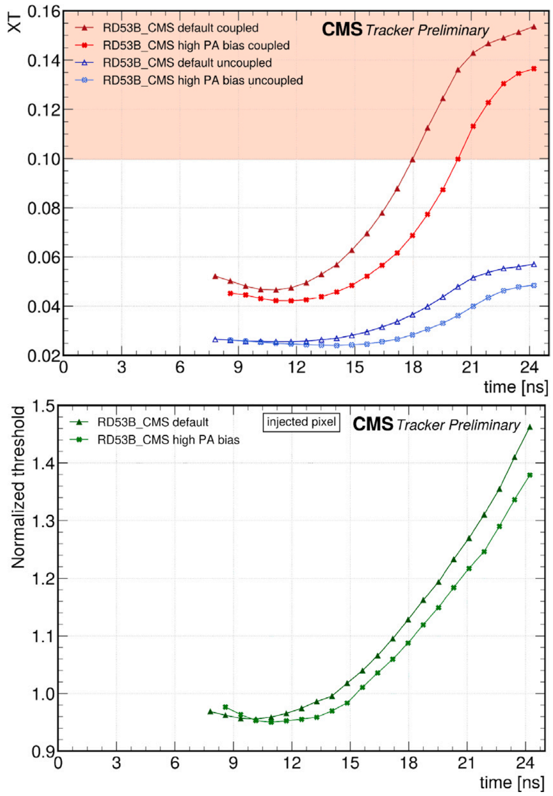

Fig. 2. Top: crosstalk for different analog front-end settings as a function of delay for highest (coupled) and second highest (uncoupled) inter-pixel capacitance. Bottom: variation of the average threshold as a function of the delay.

3. Conclusions

RD53B_CMS-based single-chip modules with HPK planar pixel sensors have been studied in the laboratory and at the test beam. Their performance for crosstalk, noise, efficiency times acceptance and the spatial resolution satisfies specifications up to fluences of $\Phi_{eq} = 10^{16}\,cm^{-2}$.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: financial support was provided by German Federal Ministry for Education and Research, BMBF. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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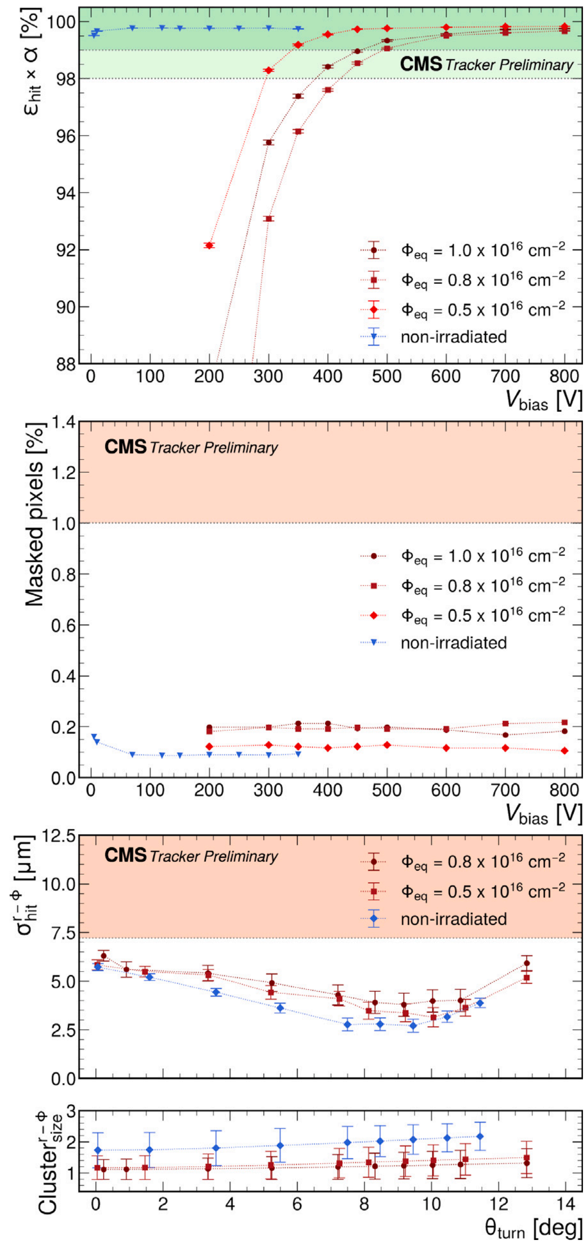

Fig. 3. Top and middle: $\epsilon_{hit} \times \alpha$ and percentage of noisy pixels as a function of V_{bias} for different fluences. Bottom: spatial resolution and projected cluster size as a function of the turn angle θ_{turn} in the r-ϕ direction.

Measurements have been performed at the Test Beam Facility at DESY Hamburg, a member of the Helmholtz Association (HGF).

References

[1] CMS Collaboration, The CMS experiment at the CERN LHC, JINST 3 (2008) http://dx.doi.org/10.1088/1748-0221/3/08/S08004.
[2] CMS Collaboration, Development of the CMS detector for the CERN LHC Run 3, 2023, http://dx.doi.org/10.1088/1748-0221/19/05/P05064.
[3] CMS Collaboration, The Phase-2 Upgrade of the CMS Tracker, CERN, 2017, http://dx.doi.org/10.17181/CERN.QZ28.FLHW.
[4] M. Garcia-Sciveres, F. Loddo, J. Christiansen, RD53B Manual, CERN, 2019, URL.
[5] M. Antonello, Test beam results of irradiated modules for the CMS Phase-2 upgrade equipped with HPK planar pixel sensors and RD53B-CMS readout chips, NIM A (2024) http://dx.doi.org/10.1016/j.nima.2024.169379.