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Characterization of Planar Pixel Sensors for the High-Luminosity Upgrade of the CMS Detector

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The luminosity of the Large Hadron Collider (LHC) at CERN will be upgraded to $7.5 \times 10^{34}\,\mathrm{cm}^{-1}\,\mathrm{s}^{-2}$. The increased luminosity leads to an increased particle fluence and ionizing dose in the detectors. The tracking detectors of the CMS experiment will be upgraded in order to cope with the new operating conditions. Prototype hybrid pixels sensors for the CMS Inner Tracker upgrade with rectangular $100\,\mu\mathrm{m} \times 25\,\mu\mathrm{m}$ pixels produced by three different manufacturers and readout by the RD53A chip were characterized before and after irradiation to fluences up to $\Phi_{\mathrm{eq}} = 2.0 \times 10^{16}\,\mathrm{cm}^{-2}$. The characterization results presented in this paper demonstrate that all sensors meet the requirements for operation at the high-luminosity LHC.

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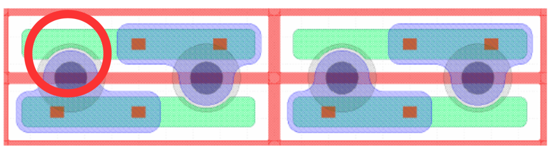
1. Introduction

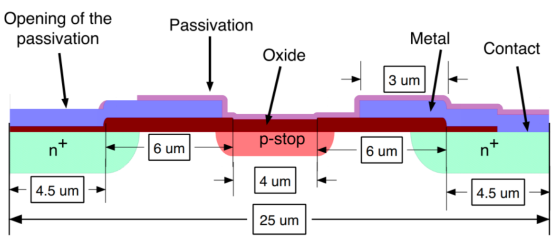
The Large Hadron Collider (LHC) will undergo an upgrade which increases its instantaneous luminosity up to $7.5 \times 10^{34}\,\mathrm{cm}^{-1}\,\mathrm{s}^{-2}$. By the end of the planned High Luminosity phase of the LHC (HL-LHC) programme [1], a total integrated luminosity of 3000 to $4000\,\mathrm{fb}^{-1}$ will be delivered at a centre-of-mass energy 14 TeV with a bunch-crossing separation of 25 ns and up to 200 collisions per crossing at the peak luminosity.

The increased luminosity will lead to an increase of the particle fluence and ionizing dose in the detectors. In the planned long shutdown before the HL-LHC run, the CMS detector will undergo a major upgrade to maintain or even improve the capability of the detector in such a challenging environment. The entire tracking system of the CMS, which consists of an Outer Tracker (OT) and an Inner Tracker (IT), will be replaced [2]. After ten years of operation, corresponding to up to $4000\,\mathrm{fb}^{-1}$ of integrated luminosity, it is expected that a fluence of particles corresponding to non-ionizing energy loss (NIEL) of $\Phi_{eq} = 2.3 \times 10^{16}\,\mathrm{cm}^{-2}$ and a total ionizing dose (TID) of 12 MGy will be reached at the innermost layer of the IT.

An IT detector module is made of hybrid pixel assemblies consisting a silicon sensor bumb-bonded to a readout chip. Modules with 3D sensors for the innermost layer and planar sensors for the three outer layers will be employed for the upgrade of the IT. The characterization results of the planar sensors before and after irradiation are presented in this paper. Sensor produced by



(a)



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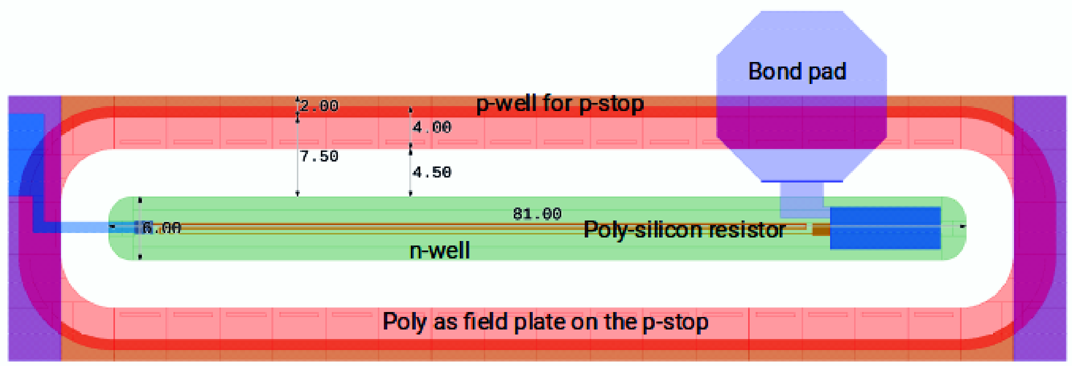


(c)

Figure 1: (a) Layout of a 2×2 pixel cell for a $100\,\mu\mathrm{m} \times 25\,\mu\mathrm{m}$ pitch sensor produced by HPK and (b) its cross section. (c) Layout of pixel in sensors produced by LFoundry.

Fondazione Bruno Kessler (FBK), Hamamatsu Photonics K.K. (HPK) [3] and LFoundry [4][5] were tested in particle beams at DESY and CERN.

The baseline planar sensors for the upgrade are produced in an n^+-p process with an active thickness of 150 µm and pixel pitch of 100 µm × 25 µm. This process is single-sided and has fewer production steps compared to the double-sided process used for the current IT detector and potentially reduces the production cost. However, the modules must be coated with Parylene for spark protection. The layout of a 2 × 2 pixel cell and a cross-section of the sensors produced by HPK are shown in Fig. 1a and 1b. The red circle in the layout marks the region of the pixel where the n^+ implant under the metal layer is cut out in order to reduce the cross-talk between neighboring pixels. Fig. 1c shows the layout of one pixel in sensors produced by LFoundry.

The sensors are bump-bonded at Fraunhofer IZM to the RD53A readout chip developed by the CERN RD53 collaboration [6]. The RD53A chip, which is a half-size prototype of the final CMS IT chip, is produced in the TSMC 65 nm technology and has a pixel pitch of 50 µm × 50 µm. It includes three different analog front-end designs. In the studies presented here, only the so-called Linear front-end which is the design selected for the final CMS chip is used. The signal from each pixel is digitized using a 4-bit time-over-threshold counter.

The assemblies were irradiated using 25 MeV protons at the ZAG Zyklotron AG in Karlsruhe, Germany [7].

2. Characterization of Sensors with Particle Beams

The hybrid assemblies have been tested using particle beams at DESY or CERN before and after irradiation. The non-irradiated assemblies where charactrized at room temperature while irradiated assemblies were cooled down to approximately −24 °C. EUDET type telescopes [8] were used for track reconstruction. A CMS IT phase-1 module [9] was used as a timing reference to reduce pileup of tracks due to the long integration time of the telescope planes.

2.1 Hit Efficiency

Hit efficiency of an assembly is defined as

$$\epsilon_{hit} = \frac{N_{\text{hit}}}{N_{\text{t}}}, \tag{1}$$

where N_{hit} is the number of reconstructed in-time tracks traversing the assembly with a hit in the assembly and N_{t} is the total number of tracks passing through the assembly. The requirements for the hit efficiency of the sensor assemblies are:

- $\epsilon_{hit} > 99\,\%$ before irradiation at vertical incidence, room temperature and a bias voltage greater than 50 V above the sensor full depletion voltage,
- $\epsilon_{hit} > 99\,\%$ after irradiation to $\Phi_{\text{eq}} = 0.5 \times 10^{16}\,\text{cm}^{-2}$ at vertical incidence, −20 °C and a bias voltage ≤ 800 V,
- $\epsilon_{hit} > 98\,\%$ after irradiation to $\Phi_{\text{eq}} = 1.0 \times 10^{16}\,\text{cm}^{-2}$ at vertical incidence, −20 °C and a bias voltage ≤ 800 V.

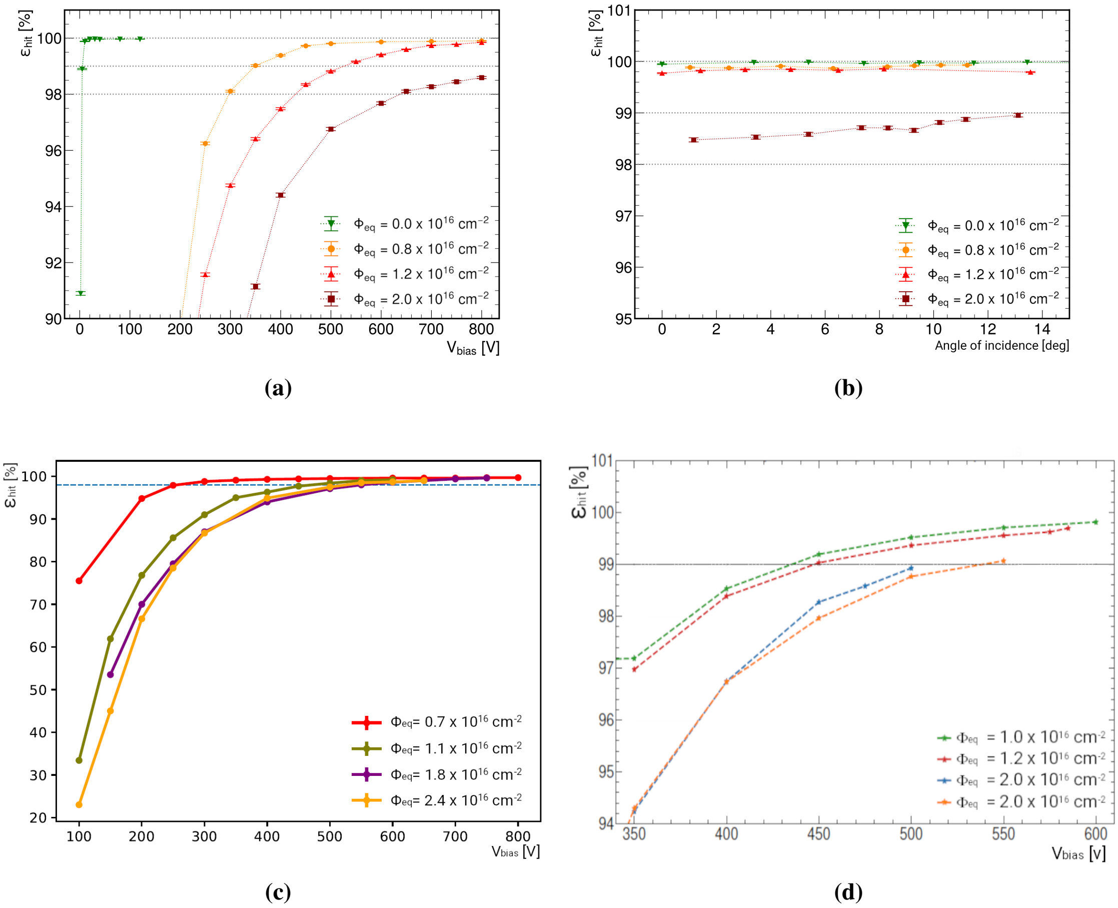
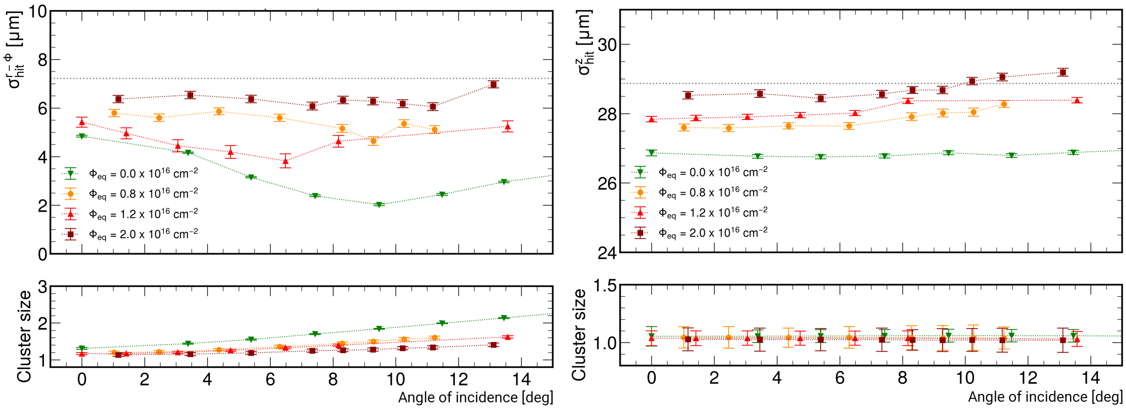


Figure 2: Hit efficiency of the assemblies with sensors produced by HPK (a) as a function of bias voltage at vertical incidence and (b) as a function of angle of incidence at a bias voltage of 120 V for non-irradiated and 800 V for irradiated assemblies. Hit efficiency as a function of bias voltage for assemblies with sensors produced by (c) FBK and (d) LFoundry.

The results of hit efficiency measurements for sensor produced by the three vendors are shown in Fig. 2. All sensors reach an efficiency in excess of 99 % for a range of bias voltages below 800 V at vertical incidence even after irradiation to fluences higher than $\Phi_{eq} = 2.0 \times 10^{16}\,\text{cm}^{-2}$. Fig. 2b shows hit efficiency as a function of angle of incidence for the assemblies with sensors produced by HPK at a bias voltage of 120 V for non-irradiated and 800 V for irradiated assemblies.

2.2 Spatial Resolution

To determine the spatial resolution of the assemblies a residual distribution is formed by subtracting the distance of a cluster in the assembly to the impact point of the telescope track extrapolated to the assembly in each event. To suppress the deteriorating effect of outliers on the RMS of the residual distribution, a truncated RMS of the residual distribution is calculated by iteratively discarding entries outside of ±3 RMS. The truncated RMS is taken to be the spatial resolution of the detector.



(a) (b)

Figure 3: Spatial resolution and cluster size of the assemblies with sensors produced by HPK as a function of angle of incidence when the assemblies were rotated around (a) the long and (b) the short pixel axes. The dotted line marks the expected resolution in absence of charge sharing.

Fig. 3a shows the spatial resolution and cluster size of the assemblies with sensors produced by HPK before and after irradiation as a function of angle of incidence when the assemblies were rotated around the long pixel axis in order to have charge sharing in the 25 µm direction. Before irradiation, at the optimal angle for 2-pixel clusters, $\tan^{-1}(25/100) \approx 9.5°$, a spatial resolution of 2 µm is obtained while at the vertical incidence, the spatial resolution is approximately 5 µm which is lower than the expected binary resolution in absence of charge sharing (7.2 µm). Fig. 3b shows a similar measurement when the assemblies were rotated around the short pixel axis in order to have charge sharing in the 100 µm direction. In this case the resolution is better than the expected binary resolution and independent of the angle of incidence. The measurements were taken at a threshold of approximately 1250 e^- and a bias voltage of 120 V. After irradiation, the cluster size remains above 1 and the resolution is better than the expected binary resolution.

3. Conclusions and Outlook

The tracking system of the CMS detector will be fully replaced for the High Luminosity phase of the LHC. Three outer layers of the Inner Tracker will consist of new planar pixel sensors. Planar pixel sensors produced by FBK, HPK and LFoundry have been characterized in a common effort by the CMS Tracker Collaboration. All sensors have reached an hit efficiency of approximately 99 % even after irradiation to fluences higher than $\Phi_{eq} = 2.0 \times 10^{16}\,\text{cm}^{-2}$. A hit resolution better than binary resolution is obtained even after irradiation to the highest fluence. These results demonstrate that sensors produced by all three vendors are qualified for the high-luminosity upgrade of the CMS pixel detector.

Prototype single-chip modules with the first version of the CROC readout chip (CMS chip with final pixel matrix for the upgrade) are currently being tested. First full modules with CROC readout with and area of 15.5 cm^2 are being assembled and will be tested in near future.

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