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Development of Novel Pixel Sensors for the CMS Upgrade for HL-LHC

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Abstract

The LHC is planning an upgrade program which will bring the luminosity up to about $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in 2027, with the goal of an integrated luminosity of 3000 fb^{-1} by the end of 2037. This High Luminosity scenario, HL-LHC, will present new challenges of higher data rates and unprecedented radiation levels for the CMS Inner Tracker (IT): $\Phi_{eq} = 2 \times 10^{16} \text{ cm}^{-2}$, and 10 MGy, are expected at the inner layer of the pixel detector for 3000 fb^{-1} integrated luminosity. To maintain or even improve the performance of the present vertex detector, new technologies have to be fully exploited for the so-called Phase-2 upgrade. Among them is the future version of front-end chips in 65-nm CMOS by the CERN RD53 Collaboration which supports small pixel sizes of 50×50 or $25 \times 100 \mu\text{m}^2$ and lower charge thresholds ($\approx 1000 \text{ e}^-$).

Thin planar n-in-p type silicon sensors (of thickness $100\text{--}150 \mu\text{m}$), segmented into pixel sizes of $25 \times 100 \mu\text{m}^2$ or $50 \times 50 \mu\text{m}^2$ are expected to allow for a good detector resolution that is expected to be more robust with respect to radiation damage compared to the Phase-1 detector. For the innermost detector layer, the option to use 3D silicon sensors is pursued, offering intrinsically higher radiation resistance because of the combination of a short charge collection distance with relatively thick sensors.

CMS has launched several R&D submissions for the development of suitable silicon sensors at HPK photonics and FBK Trento (planar), and FBK Trento and CNM (3D sensors). We will present results for measurements on such prototype sensors bump bonded to the ROC4Sens R&D readout chip from PSI, Switzerland, and to the RD53A prototype chip developed by the RD53 collaboration at CERN. Different pixel cell designs are compared and evaluated in testbeams at DESY and CERN for charge collection, efficiency and spatial resolution before and after irradiation.

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Thin planar n-in-p type silicon sensors (of thickness 100–150 μm), segmented into pixel sizes of $25 \times 100 \mu\text{m}^2$ or $50 \times 50 \mu\text{m}^2$, are expected to allow for a good detector resolution that is expected to be more robust with respect to radiation damage compared to the Phase-1 detector. For the innermost detector layer, the option to use 3D silicon sensors is pursued, offering intrinsically higher radiation resistance because of the combination of a short charge collection distance with relatively thick sensors.

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I. INTRODUCTION

In the High Luminosity running phase of the LHC (HL-LHC), starting in 2026, the instantaneous luminosity will be increased by a factor of 5–7 compared to the nominal LHC, and a total integrated luminosity of 3000 or even 4000 fb^{-1} will be delivered. To maintain and even improve the physics capability of the CMS experiment in this challenging environment, CMS will undergo a major upgrade in the long shutdown before the HL-LHC, LS3. The entire tracking system will be replaced, as seen in Fig. 1 [1]. It consists of an Outer Tracker (OT) and an Inner Tracker (IT) with a pseudorapidity-coverage up to about 3.8. In this paper, pixel sensors for the IT are discussed. For vertex detection, CMS will reduce the pixel size by a factor of six with respect to the current detector. Currently, both square pixels, $50 \times 50 \mu\text{m}^2$, and rectangular pixels, 25×100

Fig. 1. Layout of the CMS Tracker for Phase-2, consisting of the OT and IT. The IT comprises a short barrel section (TBPX), eight endcap discs (TFPX), and four forward discs (TEPX) on each side. In the IT, pixel detector modules with four readout chips (2x2), yellow, and two readout chips (1x2), green, are used [1].

μm^2 , are considered. Since both options are compatible with the $50 \times 50 \mu\text{m}^2$ bump bond pattern of the readout chip under development by the RD53 Collaboration, the final decision can be taken when the two options will have been studied in more detail. Several R&D submissions of prototype pixel sensors for the CMS Phase-2 Upgrade were launched at HPK photonics, FBK, and CNM. These wafers contain small sensors for a variety of readout chips including the current CMS readout chip PSI46dig, the ROC4Sens R&D readout chip available since summer 2017, and the RD53A chip [2] developed by the CERN RD53 Collaboration. The two latter chips have $50 \times 50 \mu\text{m}^2$ bump bond patterns, allowing for the first studies of sensors with small pixel sizes within CMS.

Here, we report on studies of sensor modules with the ROC4Sens chip, which allows for detailed charge collection studies due to its non-sparsified readout, and the RD53A chip.

The RD53A chip is a half-size prototype for the final ATLAS and CMS chip, with 77 k pixels, produced in 65 nm CMOS at TSMC. It is radiation hard and features serial powering capabilities. It contains three sections with different analog front-ends, called synchronous, linear and differential front-end. All three front-end designs have been successfully used with sensor-chip assemblies.

II. SENSOR REQUIREMENTS

The fluence expected in the CMS IT at the end of the HL-LHC running period (3000 fb^{-1}) is shown in Fig. 2. The lifetime fluences for the four barrel pixel layers are shown in Tab. I. The numbers apply also to modules in the forward disks mounted at the same radii, as the dependence of the fluence on z is rather weak.

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Fig. 2. Lifetime fluence in the CMS IT in 1 MeV neutron equivalent in silicon per cm^2 as a function of radius and z . The estimate corresponds to an integrated luminosity of 3000 fb^{-1} of pp collisions at a center-of-mass energy of 14 TeV and has been obtained with the CMS FLUKA geometry version 3.7.2.0 [1].

TABLE I
FLUENCES FOR IT BARREL LAYERS.

Layer	Radius	Total fluence $\Phi_{eq} [10^{16} \text{cm}^{-2}]$
L1	3 cm	2.3
L2	7 cm	0.5
L3	12 cm	0.2
L4	16 cm	0.15

Detector modules comprising a pixel sensor and two or four readout chips will be used in the IT to detect hits of charged particle tracks. The goal of this work is to develop pixel sensors which perform well over the lifetime of the CMS experiment. Important figures of merit studied in this context are pixel hit efficiency and spatial resolution. The efficiency is determined by the distribution of the collected charge and the threshold applied in the readout chip. The charge collected in a pixel sensor with an active thickness of 100 and 150 μm biased to 800 V was simulated in Synopsis TCAD for four fluences using the new *Hamburg Pentatrap Model* (HPTM) [3], Fig. 3. Up to $\Phi_{eq} = 8 \times 10^{15} \text{ cm}^{-2}$, the collected charge is higher for the thicker sensor and always in excess of three times the foreseen threshold of the CMS pixel chip of 1200 electrons.

Fig. 3. Simulated collected charge versus fluence for 100 and 150 μm thick pixel sensors biased to 800 V.

The cluster size as a function of bias voltage for a simulation

of CMS pixel modules in a 3.8 T magnetic field is shown in Fig. 4 (top) before and after irradiation to fluences up to $\Phi_{eq} = 4 \times 10^{15} \text{ cm}^{-2}$. The sensor thickness is 150 μm and the pixel cells are $25 \times 100 \mu\text{m}^2$. The optimal spatial resolution is reached for two-pixel clusters. Before irradiation bias voltages around 400 V are needed to reduce the cluster size in a 3.8 T magnetic field. The current-voltage curves before irradiation are shown for sensors produced at Hamamatsu (bottom), indicating that the sensors can be operated beyond 400 V before irradiation.

Fig. 4. Simulated cluster size for 150 μm thick sensors with $25 \times 100 \mu\text{m}^2$ pixel cells as a function of bias voltage (top). Measured current-voltage curves for Hamamatsu sensors (bottom).

Figure 5 shows the hit efficiency versus bias voltage measured in the DESY testbeam with 4.8 GeV electrons for ROC4Sens sensor modules irradiated to $\Phi_{eq} = 2$ and $4 \times 10^{15} \text{ cm}^{-2}$ (left). The sensors have $25 \times 100 \mu\text{m}^2$ pixel cells and no bias grid. The voltage needed to reach 99% efficiency is shown for the two fluences (right). A high hit efficiency is needed since the IT has only four barrel layers, providing not much redundancy. Extrapolating to fluences up to $8 \times 10^{15} \text{ cm}^{-2}$, the goal is to maintain 99% efficiency with voltages below 800 V.

III. PLANAR SENSORS

The design of efficient, high-voltage stable and radiation hard pixel cells in $50 \times 50 \mu\text{m}^2$, and especially $25 \times 100 \mu\text{m}^2$, is a challenge, taking the design rules of the producers into account. Small single chip pixel sensors with a variety of cell

Fig. 5. Hit efficiency versus bias voltage for an irradiated ROC4Sens sensor module (left). Bias voltage needed for 99% efficiency as a function of fluence (right). The data point at 0 fluence indicates that this n-in-p sensor is already highly efficient at 4V which can be attributed to depletion starting from the front side.

designs have been produced at HPK and were bump bonded at IZM Fraunhofer to RD53A and ROC4Sens readout chips. The assemblies were successfully tested in the laboratory and in testbeams at the CERN SPS, at DESY, and at Fermilab. An important aspect is the biasing scheme, which potentially allows pixel sensors to be tested fully depleted before bump bonding them to readout chips. This can be achieved through a bias dot common to four pixels, at the cost of some signal efficiency when the impinging particle hits the bias dot. The cross section of a $50 \times 50 \mu\text{m}^2$ pixel cell is shown in Fig. 6 (upper). The hit efficiency as a function of position within a cell of four $50 \times 50 \mu\text{m}^2$ pixels with common punch through bias dot is shown in the middle row, for a floating (left) and for a grounded bias dot (right). The tracks are perpendicular to the sensor surface. The pixel cell design is also shown (center). An inefficiency is clearly seen in the area of the bias dot when the bias dot is grounded, i.e. at the same potential as the readout electrode. This inefficiency virtually disappears when the bias dot is left floating. In the lower row, the cluster size as a function of position within the same cell of four pixels is shown for floating (left) and grounded (right) bias grid. The inefficiency is visible for the grounded bias dot as an area in the center with reduced cluster size. These studies will be repeated for irradiated sensor assemblies. If testing before bump bonding is not required, or if a temporary metal grid is used for testing which can later be etched away, a design without bias dot and a p-stop common to four adjacent pixels can be used to further enhance uniformity in charge collection.

The hit efficiency versus the position of the track measured in the DESY testbeam using the EUDET beam telescope [4] is shown in Fig. 7. It is very close to 100 % for the linear and differential front-end sections of the RD53A readout chip, the two sections used at the time of the testbeam. Sensors with individual polysilicon bias resistors were also implemented and tested with the ROC4Sens chip; here the observed loss in signal is under investigation and would require further design iterations to increase the resistivity of the individual bias resistors.

Fig. 6. Cross section of $50 \times 50 \mu\text{m}^2$ pixel cell (upper). Hit efficiency as a function of position within a cell of four $50 \times 50 \mu\text{m}^2$ pixels with common punch through bias dot (middle row), for a floating bias dot (left), cell design (middle), for a grounded bias dot (right). Cluster size as a function of position within a cell of four $50 \times 50 \mu\text{m}^2$ pixels with common punch through bias dot (lower row), for a floating bias dot (left), and for a grounded bias dot (right).

Fig. 7. Cell design for sensor with $25 \times 100 \mu\text{m}^2$ pixel cells for the RD53A chip without bias scheme (left). Hit efficiency for sensor module with this design as a function of track position for the linear (central x values) and differential (right third of the plot) front-end sections (right). The statistical errors are shown as vertical bars unless the efficiency is unity.

Spatial resolution

Three ROC4Sens pixel sensor modules with $25 \times 100 \mu\text{m}^2$ pixels were mounted close together with a common inclination angle of $9^\circ \pm 1^\circ$. Using hits in all three layers, triplet residuals were determined before and after irradiation to $\Phi_{eq} = 2 \times 10^{15} \text{ cm}^{-2}$, Fig. 8. The single plane resolution with multiple scattering unfolded before and after irradiation is $2.3 \mu\text{m}$ and $3.7 \mu\text{m}$, respectively. The spatial resolution for an RD53A-

Fig. 8. Triplet hit residuals in the small pixel direction for three sensors with $25 \times 100 \mu\text{m}^2$ pixels mounted close together and tilted for optimized charge sharing. Before irradiation (left) and after irradiation to $\Phi_{eq} = 2 \times 10^{15} \text{ cm}^{-2}$ (right).

assembly with $50 \times 50 \mu\text{m}^2$ pixel size was determined in the DESY testbeam utilizing a beam telescope, Fig. 9. The resolution unfolded for multiple scattering effects and the pointing resolution of the telescope is shown as a function of inclination angle for the linear and the differential analog front-end section of the RD53A readout chip. For small angles up to the optimal angle at which the resolution is $4.6 \mu\text{m}$, the results for both front-ends agree. The deviation at larger angles is likely due to uncertainties in the ongoing calibration effort.

IV. 3D SENSORS

3D silicon pixel sensors are being studied as an option for the innermost region of the IT, where radiation tolerance is most important. The 3D sensors studied here were produced by Fondazione Bruno Kessler, FBK, Trento [5], [6], using a single-sided process on silicon-silicon wafer bonded wafers. The active thickness of the sensors is $130 \mu\text{m}$, with a total thickness of $200 \mu\text{m}$. The sensors have no bias structure. Ohmic columns are reverse-biased from the backside, while junction columns are kept close to 0 V when connected to the readout chip. A temporary metal layer used for testing is removed before bump bonding. Single chip RD53A sensors with $50 \times 50 \mu\text{m}^2$ and $25 \times 100 \mu\text{m}^2$ pixels were tested before and after irradiation at the CERN PS to a fluence Φ_{eq} between 0.5 and $1 \times 10^{16} \text{ cm}^{-2}$. Figure 10 shows the efficiency for tracks perpendicular to the sensor surface as a function of the position within 2×2 pixel cells for $25 \times 100 \mu\text{m}^2$ (upper plots) and $50 \times 50 \mu\text{m}^2$ (lower plots) pixel sizes before and after irradiation. The 3D-columns and readout electrodes are clearly visible as areas with reduced efficiency. For comparison, the respective cell designs are shown in Fig. 11. Before irradiation, the overall efficiencies are around 97.3% at 3 V for the

Fig. 9. Testbeam setup at DESY with beam telescope (top). Hit residuals versus inclination angle for an RD53A assembly with $50 \times 50 \mu\text{m}^2$ pixel size for two analog front-end sections of the readout chip (bottom).

rectangular pixels and 98.6% at 15 V for the square pixels. After irradiation, efficiencies of around 96.7% at 157 V for the rectangular pixels and 97.5% at 160 V for the square pixels are reached. For inclined tracks, the typical case in the CMS IT, the corresponding efficiencies are in excess of 99 %. This demonstrates that 3D sensors can be operated with high efficiency at half the lifetime fluence for HL-LHC at moderate bias voltages. Tests with even higher fluences will be done in the future. The design of the CMS IT offers the possibility to exchange degraded parts such as the first barrel layer when half the lifetime fluence is reached, should this be necessary.

V. CONCLUSION

CMS will replace its entire tracking detector for the HL-LHC. For the IT, thin planar n-in-p type silicon sensors with pixel sizes of $25 \times 100 \mu\text{m}^2$ or $50 \times 50 \mu\text{m}^2$ will be used, with the option to use 3D sensors for the innermost layer in TBPX and TFPX. Single chip assemblies based on the ROC4Sens R&D readout chip and the RD53A prototype chip have been built and evaluated in test beams at CERN and DESY. Planar sensors with an active thickness of $150 \mu\text{m}$ were tested to $\Phi_{eq} = 4 \times 10^{15} \text{ cm}^{-2}$, which is close to the lifetime fluence for layer 2, and were found to have 99 % hit efficiency for a bias voltage below 400 V. 3D sensors, tested up to half the lifetime fluence of layer 1, $\Phi_{eq} = 1 \times 10^{16} \text{ cm}^{-2}$, showed an efficiency of 97 % for bias voltages around 160 V. Irradiations to higher fluences for planar and 3D sensor assemblies are under way.

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Fig. 10. In-pixel hit efficiency within 2x2 pixel cell for 3D sensors with 25×100 (upper two) and $50 \times 50 \mu\text{m}^2$ pixels (lower two plots). Before irradiation (first and third) and after proton irradiation to a fluence of $\Phi_{eq} = (0.5-1) \times 10^{16} \text{ cm}^{-2}$ (second and fourth plot). The dosimetry has still to be confirmed.

Fig. 11. Pixel cell designs for 3D sensors with $25 \times 100 \mu\text{m}^2$ (left) and $50 \times 50 \mu\text{m}^2$ pixel cells (right). The orange lines mark one cell. The 3D ohmic columns are shown as orange circles, the junction columns are shown in dark blue. The shaded areas around the columns denote polysilicon. The metal layer and bump bond pads are shown in textured light blue.