The Compact Muon Solenoid Experiment

Conference Report

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30 January 2018 (v4, 08 February 2018)

CMS Pixel detector development for the HL-LHC

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Abstract

An upgrade program is underway which will bring the luminosity of the LHC 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 increased radiation hardness for the pixel detector (a non-ionizing fluence of $2 \times 10^{16} \text{ n}_{eq}/\text{cm}^2$ and an ionizing dose of 10 MGy, is expected on the inner pixel layer for 3000 fb^{-1} integrated luminosity). To maintain or even improve the performance of the present system, new technologies have to be fully exploited for the so-called Phase-II 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 thresholds ($\sim 1000 \text{ e}^-$). For the development of the appropriate planar pixel sensor, CMS has recently launched a submission of n^+ -p sensors on 6 inch wafers with an active thickness of $150 \mu\text{m}$ at Hamamatsu. The submission consists of physically thinned, directly bonded and deep diffused wafers with p-stop or p-spray isolation. A variety of sensors with and without biasing scheme is designed to match the different read-out chips (RD53A, ROC4Sens, etc.) and first hybrid modules are assembled at Fraunhofer IZM. In this document, we will present an overview of the Phase II pixel R&D program and report on preliminary results on the HPK submission.

Presented at *HSTD11 11th International Hiroshima Symposium on the Development and Application of Semiconductor Tracking Detectors*

CMS Pixel detector development for the HL-LHC

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Abstract

An upgrade program is underway which will bring the luminosity of the LHC 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 increased radiation hardness for the pixel detector (a non-ionizing fluence of $2 \times 10^{16} \text{ n}_{eq}/\text{cm}^2$ and an ionizing dose of 10 MGy, is expected on the inner pixel layer for 3000 fb^{-1} integrated luminosity). To maintain or even improve the performance of the present system, new technologies have to be fully exploited for the so-called Phase-II 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 thresholds ($\sim 1000 \text{ e}^-$). For the development of the appropriate planar pixel sensor, CMS has recently launched a submission of $\text{n}^+\text{-p}$ sensors on 6 inch wafers with an active thickness of $150 \mu\text{m}$ at Hamamatsu. The submission consists of physically thinned, directly bonded and deep diffused wafers with p-stop or p-spray isolation. A variety of sensors with and without biasing scheme is designed to match the different read-out chips (RD53A, ROC4Sens, etc.) and first hybrid modules are assembled at Fraunhofer IZM. In this document, we will present an overview of the Phase II pixel R&D program and report on preliminary results on the HPK submission.

Keywords: Tracker, Pixel sensors, Test beam, Radiation damage.

1. Introduction

During the Long Shutdown 3 (LS3) of the LHC, the machine will be upgraded to enable instantaneous peak luminosities of $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, or even $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in the ultimate performance scenario. For an expected operation of the HL-LHC of ten years CMS can collect an integrated luminosity of 3000 fb^{-1} . The HL-LHC is expected to run at 14 TeV with a bunch-crossing separation of 25 ns and up to 200 events (pileup) per crossing at the peak luminosity. To maintain or even improve the performance of the present system in this harsh environment, CMS will completely replace the current central tracking system [1]. At the foreseen inner pixel radius of 3 cm, a fluence of particles corresponding to a non-ionizing energy loss (NIEL) of $\Phi = 2.3 \times 10^{16} \text{ n}_{eq}/\text{cm}^2$ and a total ionizing dose (TID) of 12 MGy will be reached after ten years of operation. To cope with these radiation levels a readout chip using 65 nm CMOS technology and an architecture where a group of channels shares digital electronics for buffering, control, and data formatting is being developed within RD53 [2], a joint ATLAS-CMS collaboration. For the development of the appropriate radiation hard pixel sensors CMS has initiated R&D submissions to study 3D and thin planar sensors with pixel sizes of 50×50 and $25 \times 100 \mu\text{m}^2$ produced by different vendors.

Figure 1: Layout of the CMS Inner Tracker for the HL-LHC. Modules consisting of 1×2 readout chips are depicted in green, modules with 2×2 readout chips are drawn in orange. In black the course of the beam pipe and a reference line to indicate $|\eta| = 4$.

2. CMS Inner Tracker Layout

The cross section of a quarter of the baseline Inner Tracker (pixel detector) layout as published in the Tracker Technical Design Report [1] is shown in Fig. 1. The inner tracker consists of a barrel and a forward region. The barrel part (TBPX) is composed of four cylindrical layers extending from $r = 2.9 \text{ cm}$ to $r = 15.7 \text{ cm}$ with a total length of 40 cm. The forward region is split into two sections, the first consisting of eight small double-discs (TFPX) and the second consisting of four large double-discs (TEPX). The number of double-discs derives from the need to extend tracking down to $|\eta| = 4$ to match the physics requirement. To enable the installation of the central part of

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Table 1: Specifications of wafer layout of n⁺-p sensors.

Parameter	Value
Silicon wafer diameter	6 inch (150 mm)
Wafer type	p-type, float zone (FZ)
Crystal orientation	<100>
Resistivity	1-5 k Ω ·cm
Active thickness	150 μ m
Total thickness (not thinned)	200 μ m
Number of RD53A sensors	20
Number of ROC4Sens sensors	39 (p-stop wafer)
Number of PSI46 sensors	10 (p-stop wafer)

the detector with the beampipe in place, clearance is added at the far edge of the detector by introducing a step in the envelope between the pixel detector and the Outer Tracker. To have maximum flexibility and modularity only two types of pixel detector modules are foreseen, namely 1x2 and 2x2 modules (in number of readout chips). The smaller 1x2 modules will be used for the innermost layers and rings, whereas the larger 2x2 modules will be used for the outer radii. The baseline readout chip dimensions are 16.4 mm by 22.0 mm (active area). In total, the pixel detector will have an active surface of approximately 4.9 m² and consist of 4352 modules with 1.947×10^9 pixels.

3. Planar pixel sensor development

As the current 3D submissions and the INFN-FBK program for planar pixel sensors will be documented elsewhere [1], we will limit the following discussion to the first common CMS submission of thin planar pixel sensors at Hamamatsu Photonics K.K. (HPK) [3].

3.1. Overview about the HPK submission

The aim of the HPK submission is to evaluate and optimize design options for small pixel sizes on different materials. The order is for 35 6" p-type float zone wafers with an active thickness of 150 μ m (see Tab.1) and split into:

1. 10 wafers which are thinned down to 150 μ m (FTH150)
2. 20 wafers with an additional 50 μ m handle wafer (FDB150)
3. 5 wafers which are deep-diffused (FDD150)

Each wafer contains a variety of designs of n⁺-p sensors for different readout chips, such as PSI46 resp. PROC600, ROC4Sens (R&D chip from PSI [4]), RD53A, FCP130 (R&D chip from Fermilab) and FE-I4 (mainly for serial power testing) as well as test structures. In case of the FDB150 wafers half of them are with p-stops for the pixel isolation and the other half with p-spray whereas all FTH150 and FDD150 wafer are using p-stop isolation. In Fig. 2 a photo of a HPK wafer with p-stop isolation is shown and the location of sensors for different readout chips is indicated.

In order to be able to test the pixel sensors before bump bonding, a bias scheme is required which does not reduce the charge

Figure 2: Wafer layout of a 6 inch HPK wafer with p-stop isolation.

collection efficiency too much during operation of the sensors. To test this with the RD53A and ROC4Sens chips, which have the same pixel size of $50 \times 50 \mu\text{m}^2$ but different bump-bond patterns (non-staggered vs. staggered), sensors were designed with common punch-through (PT), polysilicon resistors, open p-stop or no bias scheme. The implementation of the needed bias rails were done in a similar way as in [5]. In Fig. 3 the GDSs of some sensor designs for the ROC4Sens with p-stop isolation are shown. Figure 3(c) shows a design with a common punch-through and straight bias rail with a p-stop isolation. In addition, to this design also variants without a gap between bias dot and p-stop¹ and with wiggle like bias rails were implemented. Similar designs were implemented for the polysilicon resistors.

All processed wafers were delivered undiced in April/May 2017 by HPK. Current-voltage (I-V) measurements were made by HPK on all sensors and diodes on the bias ring resp. inner guard ring. The measurements were done in 20 V steps up to 1000 V. The results indicate a general high number of acceptable sensors and high breakdown voltage (> 600 V) for the different sensor design, but also two problematic combinations of sensor design and material. For example on the FDB150 wafers with p-stop isolation the sensors for the ROC4Sens with $100 \times 25 \mu\text{m}^2$ pixel size and common PT have a low yield whereas the same design has a high number of acceptable sensors on the FTH150 and FDD150 wafer. In addition, the current of the sensors of FDD150 is approximately a factor 10 higher compared to sensors of FTH150 and FDB150. However, these I-V and additional C-V measurements on diodes, which, depending on the material, results in full depletion voltages of 55–75 V, show that our specifications with respect to current, breakdown voltage, and resistivity are met.

3.2. ROC4Sens modules

Eight wafers, two from each material type, have been further processed with BCB (benzocyclobutene) for spark protec-

¹A suggestion by Y. Unno Email: yoshinobu.unno@kek.jp

Figure 3: GDSs of example designs ($50 \times 50 \mu\text{m}^2$ cell in the top row and $100 \times 25 \mu\text{m}^2$ cell in the bottom row) for the ROC4Sens with p-stop isolation: a) no bias scheme (R4S50x50-P1) b) open p-stop (R4S50x50-P2) c) common punch-through and straight bias rail (R4S50x50-P3). d) no bias scheme (R4S100x25-P1) e) common punch-through and straight bias rail (R4S100x25-P2). f) routing test, no bias scheme (R4S100x25-P4).

tion and UBM (under bump metalization) for flip chip bonding at Fraunhofer Institut für Zuverlässigkeit und Mikrointegration (IZM) [6]. About 140 ROC4Sens single chip modules have been ordered, of which about 90 are produced. In Fig. 4 a ROC4Sens module glued and wire bonded to a rotated PCB is shown. As can be seen the sensor has on the backside a metallic grid for laser injection and the chip is not thinned down.

Figure 4: ROC4Sens single chip module on a rotated PCB.

As mentioned above, the ROC4Sens is a R&D chip developed at the PSI based on the PSI46 (IBM 250 nm). The chip has 24800 pixels (155 columns x 160 rows) with a pitch of $50 \times 50 \mu\text{m}^2$ and has a total size of $9.8 \times 7.8 \text{ mm}^2$. The chip is simple to operate and can be readout with CMS Pixel-DTB [4].

There are no DACs read out or other programming, no discriminator threshold adjusting or trimming needed and only a small number of signals are required. The full analog pulse height is read out. The chip is suitable for test beams and source measurements with asynchronous hits (no synchronous sampling with external clock). It is expected that the chip is sufficiently radiation hard (5 MGy) and therefore suited for the sensor development for the HL-LHC.

3.3. First test beam results

In Fall 2017 test beam measurements at the beamline 21 of the DESY-II test beam facility [7] using non-irradiated ROC4Sens modules have been performed. DESY-II is an electron/positron synchrotron delivering beams with energies between 1 GeV and 6 GeV using a double conversion beam. At the beamline 21 the EUDET telescope DATURA [8] and a special set-up, called "three-master", for three ROC4Sens pixel modules (see Fig. 5), which was constructed and built at DESY, was used. The "three-master" is essentially a support frame for

Figure 5: Three ROC4Sens modules mounted in the "three-master".

3 planes of pixel modules with a spacing of 20 mm. The planes are tiltable up to 30° without parallax effects. This configuration allows the reconstruction of tracks with a stand-alone DAQ without synchronisation to external devices and is well suited for resolution and efficiency studies.

In Fig. 6 the hit map of a the ROC4Sens module is shown which was used as a third plane in the "three-master". The module consist of a sensor design R4S100x25-P4 (see Fig. 3 f.) from a FTH150 wafer and was biased to a voltage of 120 V. The hit map shows that there are only a few noisy pixel and few bump bond defects. This high quality of flip chip bonding at Fraunhofer IZM is also observed in other modules we have measured.

Figure 6: Hit map of module showing only a few noisy pixel and few bump bond defects. The profile is due to the collimator and/or scintillator.

In Fig. 7 a typical cluster charge distribution together with a fit using a Landau distribution convoluted with a Gaussian is presented. The data are from a module with a sensor design R4S100x20-P2 (see Fig. 3 e.) which has a pixel size of $100 \times 25 \mu\text{m}^2$ and a common PT. The sensor is from a FTH150 wafer and biased at 120 V. The measurement was done with the "three-master" at a beam energy of 5.6 GeV using this module as second plane and with all three module turned by 10° around the $100 \mu\text{m}$ direction. Because an absolute energy calibration is still missing, we performed a gain calibration (pulse height vs. test pulse for every pixel) and scaled the charge to get the most probable value at 11 ke^- . For the offline analysis a threshold of 1.4 ke^- was used and only clusters matched to reconstructed tracks were selected.

Figure 7: Cluster charge distribution of a sensor of $100 \times 25 \mu\text{m}^2$ pixel size and common PT (see figure 3 e.) from a FTH150 wafer biased at 120 V turned by 10° around the $100 \mu\text{m}$ direction. For the fit a Landau convoluted with a Gaussian was used.

In Fig. 8 the calculated triplet residuals for the same module and run as before are shown. The triplet residuals are defined

by $\Delta x = x_B - (x_A + x_C)/2$, where x_B is the x-coordinate in the second plane and x_A and x_C the x-coordinate in the first and second plane in the $25 \mu\text{m}$ direction. For the analysis isolated clusters are used and a cut in cluster charge Q_0 with $8 \text{ ke}^- < Q_0 < 16 \text{ ke}^-$ has been performed to reduce the effect of δ -rays. Performing a Student t fit one obtains a residual width of $4.2 \mu\text{m}$ in the $25 \mu\text{m}$ direction. Unfolding the contributions of the other two planes and multiple scattering the residual width is $2.7 \mu\text{m}$. A further improvement has been achieved by using a PCB with a cutout to reduce the material. First test beam data gives a residual width of $3.05 \mu\text{m}$ from a Student t fit and $2.0 \mu\text{m}$ after unfolding.

Figure 8: Triple residuals of module with a sensor of $100 \times 25 \mu\text{m}^2$ pixel size and common PT (see Fig. 3 e.) from a FTH150 wafer biased at 120 V and turned by 10° . The residual width is $4.2 \mu\text{m}$ in the $25 \mu\text{m}$ direction.

Measurements with the EUDET telescope DATURA and the ROC4Sens as DUT have been performed for the determination of the hit efficiencies and in-depth investigations of the charge collection of the different sensor designs. As an example in Fig. 9 the mean cluster charge vs. track impact point for normal incidence for the sensor designs with $50 \times 50 \mu\text{m}^2$ pixel size, shown in the top row in Fig. 3, is presented. In the same way as in Fig. 3 4×4 pixel cells are shown. All measurements were done at a bias voltage of 120 V and a beam energy of 5.6 GeV. As can be seen the cluster size strongly depends on the design due to different field distributions and diffusion.

3.4. Sparking issues

A know problem for modules with n⁺-p sensors is sparking due to the fact that the readout chips is on ground potential, the sensor edge at the high voltage applied to the backside and the distance between chip and sensor of the order of $25 \mu\text{m}$. To prevent sparking between sensor and chip, there are suggestions to use BCB (benzocyclobutene) on the sensor and/or on

(a)

(b)

(c)

Figure 9: Cluster size vs. track impact point under normal incident for the sensor designs: a) no bias scheme (R4S50x50-P1) b) open p-stop (R4S50x50-P2) c) common punch-through and straight bias rail (R4S50x50-P3). In the same way as in Fig. 3 4x4 pixel cells are shown.

the chip [9] or to use a parylene coating[10] as alternative. All HPK sensor wafer which so far have been processed at Fraunhofer IZM have BCB as a frame from the cut edge to the bias ring on the sensor. For the first 140 ROC4Sens assemblies we have chosen the option without BCB on the chip. Measurements conducted on non-irradiated modules in our lab show sparking (see Fig. 10) at a voltage of ≈ 490 V which is consistent with Paschen's law for air and a gap of $25 \mu\text{m}$ [11]. The microscope photo indicates that the sparks are going from the sensor edge to spy or test pads on the ROC4Sens. To prevent this for the so far assembled modules we will try an additional parylene coating at Fraunhofer IZM.

Figure 10: Sparking between sensor ROC4Sens.

4. Summary and conclusions

For the HL-LHC phase CMS will completely replace its central tracking detector. The new inner tracker consists of barrel, forward and forward extension regions and will have an angular coverage up to $|\eta| = 4$. The requirements on the pixel detector are very demanding in terms of radiation hardness and track density. A readout chip using 65 nm CMOS technology is being developed within RD53. For the development of radiation hard sensors CMS has, among other things, launched an R&D submissions at HPK to study thin fine pitch sensors. First ROC4Sens modules have been assembled with HPK sensors at Fraunhofer IZM and were tested in the DESY-II testbeam. For a sensor with a pixel size of $100 \times 25 \mu\text{m}^2$ and a common punch-through with a turn angle of 10° a resolution of $2 \mu\text{m}$ has been achieved. The next step is the investigation of ROC4Sens modules irradiated at CERN PS with 24 GeV/c protons to a fluence of $2 \times 10^{15} \text{ n}_{eq}/\text{cm}^2$.

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