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Silicon Sensor Prototypes for the Phase II Upgrade of the CMS Tracker

Thomas Bergauer for the CMS Collaboration

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Silicon Sensor Prototypes for the Phase II Upgrade of the CMS Tracker

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Abstract

The CMS Tracker will be completely exchanged in the so called Phase-II upgrade. To preserve and enhance its performance in the High-Luminosity LHC phase, the new tracker will need to cope with very high radiation levels, track densities and pile-ups. In addition, it needs to provide input for the level-1 trigger. In this paper we present the baseline design of the new tracker, with a special emphasis on the two detector module concepts for the outer tracker, the 2S and PS module. The CMS Tracker collaboration designed and procured sensor prototypes from several vendors. These productions are intended for evaluating the production quality of the manufacturers, for providing functional sensors for module prototypes and for concluding the survey towards a suitable silicon base material and sensor design. Here we provide first results of the macro-pixel-light sensor for the PS module and of full-scale strip sensor prototypes for the 2S module concept, both on 6- and 8-inch wafers.

Keywords: CMS tracker, Phase II upgrade, silicon sensors

1. The High-Luminosity LHC

The current schedule of the Large Hadron Collider (LHC) at CERN calls for a series of data-taking periods, interrupted by so-called "long shutdowns". Long Shutdown 1 (LS1) took place recently between 2013 and 2015 with the aim to ensure safe and reliable LHC operation at center-of-mass energies of 13–14 TeV. In LS2, planned for mid-2018-2019, the injector chain will be improved and upgraded to deliver bunches with very high intensity and low emittance. The experiments will perform some upgrades to their detector systems, thus this period is also called Phase-1 upgrade. It is expected that the peak luminosity will exceed the nominal value by a factor of two, providing an integrated luminosity of over 300 fb^{-1} by the year 2023. This will also indicate the end-of-life of most of the detectors of the Compact Myon Solenoid (CMS) experiment, which was designed to withstand up to this level of radiation, corresponding a rough lifetime of 10 years.

The exploitation of the full potential of the Large Hadron Collider (LHC) of CERN is one goal of the European strategy on particle physics [1]. Therefore, it is planned to exchange significant parts of the CMS experiment during LS3, currently scheduled between 2023 and 2025. This is called Phase-II upgrade. One of the major topics there is to completely re-build the Tracker of CMS to cope with $5 \times 10^{34}\ \text{s}^{-1}\text{cm}^{-2}$ instantaneous luminosity and up to 150 collisions per bunch crossing (pile-up). The new tracker should withstand a radiation damage caused by a total integrated luminosity of 3000 fb^{-1}.

2. Phase II Upgrade of the CMS Tracker

To cope with the requirements of the HL-LHC, the new tracker must have an increased granularity, while having less material in the active volume to reduce the material budget (Fig. 1).

2.1. Trigger Module Concept

The selection of interesting physics events by the level-1 trigger becomes extremely challenging at

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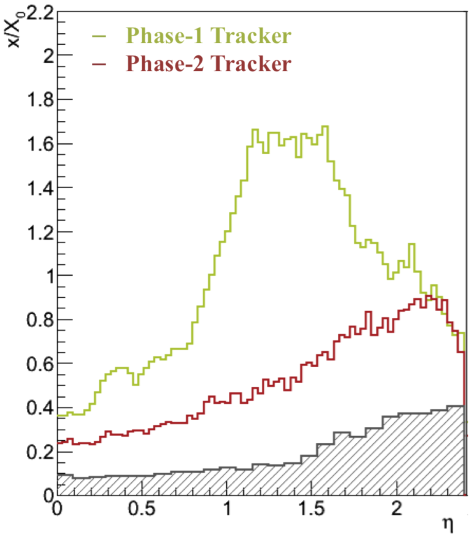

Figure 1: Material Budget of the current (Phase-1) and the baseline layout of the Phase-2 Tracker vs the pseudorapidity η. The expected contribution of the pixel detector to be upgraded during LS2 is provisionally used also for the new tracker (hashed histogram).

high luminosity, not only because of the rate increase, but also because selection algorithms become inefficient at high pileup. In order to preserve and possibly enhance the trigger performance of CMS, tracking information must contribute to the trigger decision. This concept is working on hardware level utilizing detector modules consisting of two closely spaced silicon sensors. By combining the hit information from these two planes one can estimate the transverse momentum p_T locally in each detector module, as shown in Fig. 2. The front-end ASICs correlate the signals collected

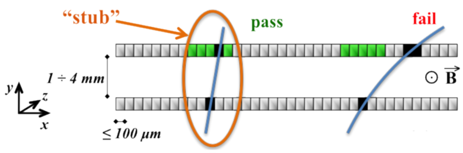

Figure 2: Two closely spaced sensors are used for local determination of p_T on module level.

in the two sensors, and select pairs that form so-called "stubs" compatible with particles above the chosen p_T threshold, which will be sent to the level-1-trigger. The strong magnetic field of CMS allows to use this concept in the entire radial range above $R \approx 20$ cm. Two module types which follow this concept are under development.

2.1.1. 2S Module Design

"2S" modules are composed of two superimposed strip sensors, mounted with the strips parallel to each another. Figure 3 shows an exploded view of such a module with a description of the components. In the baseline design, the sensors are

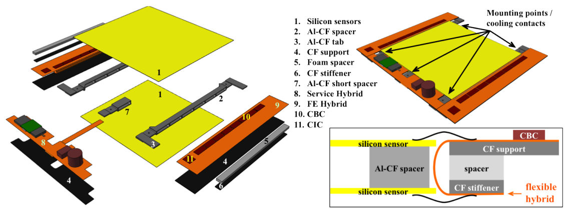

Figure 3: Exploded view of a 2S module comprising two strip sensors, showing front-end (FE) hybrids and Al-carbon fiber (CF) support structure.

optimized to fill the area of 6-inch wafers, therefore having a size of 10×10 cm^2. The strip length is half of the sensor length. Thus, wire bonds at opposite ends of the sensors provide the connectivity to the readout hybrid. On each side 8 *CMS Binary Chip* (CBC) readout ASICs are located. A CIC concentrator chip feeds the data to the "service hybrid", which carries the Gigabit Transceiver (GBT), an optical converter and a DC/DC converter that provides power to the module electronics.

2.1.2. PS Module Design

"PS" modules (Fig.4) are composed of two sensors of approximately 5×10 cm^2, one segmented into strips (called PS-s), and the other segmented into "macro-pixels" of size 100 $\mu m \times 1.5$ mm and therefore called PS-p sensor. The connection to the 16 Macro Pixel ASICs (MPA) of each PS-p sensor is realized using the commercially available C4 bump-bonding technology. As for the 2S modules, wire bonds provide the connection to the PS-s sensors, which are read out using the SSA chip.

3. Tracker Layout Options for Phase II

The layout of the Outer Tracker has been the subject of extensive studies and detailed modelling, exploring several variants, including geometries with barrel layers only, and geometries with different numbers of barrel layers, and/or different numbers and size of end-cap disks [2].

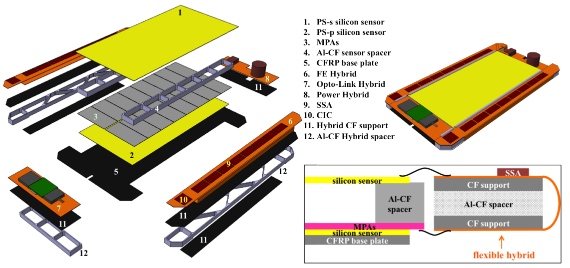

Figure 4: Exploded view of a PS module comprising a strip and a pixel sensor.

3.1. *Baseline Layout*

The version shown in Fig. 5 has been adopted as the baseline design, as it provides efficient use of the silicon sensors while providing good tracking performance. It consists of 15,508 detector modules

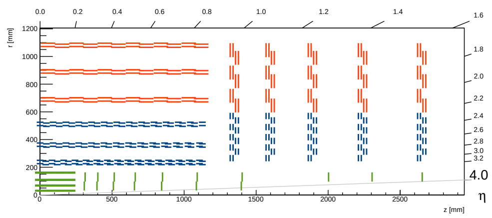

Figure 5: Baseline layout of the Phase-2 Tracker showing pixel layers (green), PS module layers (blue) and 2S module layers (red).

with a total active surface of 218 m^2, 47.8 million strips and 218 million macro-pixels. The 7,084 PS modules covering an active area of 60 m^2 are arranged in the radial range between 20 cm and 60 cm from the interaction point, while the 8,424 2S modules further outside contribute with 150 m^2 to the total active surface. The pixel sensors (shown in green in Fig. 5) extend the coverage up to $\eta \leq 4$.

3.2. *Tilted Barrel Layout*

To reduce the number of PS modules while maintaining the same geometrical coverage, an alternative layout with tilted geometry for the *Tracker Barrel with PS modules* (TBPS) is being studied. In this layout, shown in Figure 6, the modules closest to the center are parallel to the beam while those nearer to the *Tracker End-Cap Double Disks* (TEDD) are at tilt angles ranging from 35 to 75 degrees. This layout has been optimized minimizing both cost and material in the tracking volume.

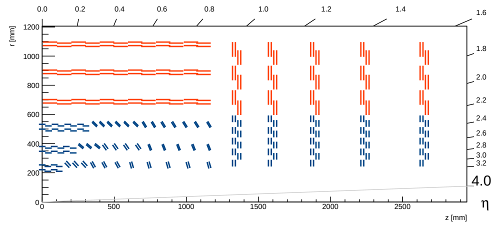

Figure 6: Layout option of the Phase-2 Tracker with tilted PS modules (blue).

3.3. *Layout with 8-inch Sensors*

The possibility of producing the silicon sensors on 8-inch wafers (rather than 6-inch) is also being pursued in the interest of potential cost savings. In this layout option, the 2S modules are split into 2S_short and 2S_long modules, respectively. The 2S_long modules will take advantage of the larger area available on 8-inch wafers and thus use 10×15 cm^2 large sensors. This module type will be deployed in the two outermost layers of the tracker (Fig.7). For occupancy reasons, the innermost 2S layer need to be equipped with modules with shorter strips. For this, the 2S_short modules utilize sensors of 10×7.5 cm^2. Two of those sensors can be accommodated onto one 8-inch wafer.

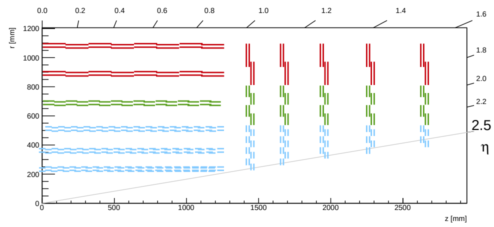

Figure 7: Layout of the Phase-2 Tracker using sensors from 8-inch wafers using 2S_short modules (in green) and 2S_long modules (red). The light blue lines represent PS modules.

4. Radiation Tolerant Sensors

The expected particle fluences that must be tolerated during the HL-LHC phase by the tracker are up to 10^{15} n_{eq} cm^{-2}. A comprehensive program has been carried out to identify suitable silicon materials [3]. Measurements on the charge collection of 300 μm thick silicon confirmed earlier studies [4] that strip sensors with collection of holes for signal generation have greater degradation than sensors with collection of electrons for signal generation (Fig.8).

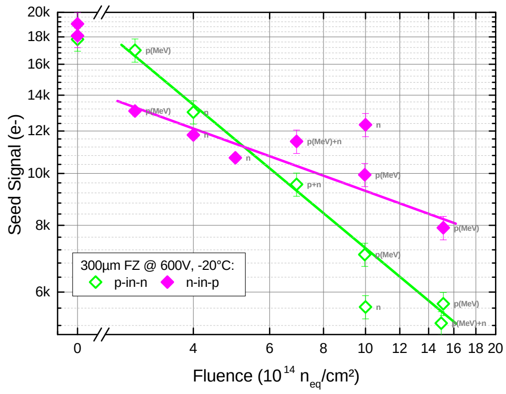

Figure 8: Seed strip vs. fluence for 600 V biasing at −20 C after short annealing (50 h to 250 h) at room temperature, for float-zone (FZ) sensors with thicknesses of 300 μm. Lines are drawn to guide the eye.

In addition, irradiated sensors with n-type bulk have shown non-Gaussian noise, resulting in an irreducible rate of fake hits [3]. This phenomenon, also called Random Ghost Hits (RGH), was also observed on p-type sensors with a too high p-stop concentration [5].

5. Sensor Prototypes

The CMS tracker collaboration designed and procured prototype sensors for both PS and 2S module concepts.

5.1. Sensors for MaPSA-light

The focus for the PS module prototypes is on the pixel part, since it is more complicated and requires more R&D. The full-size PS pixel (PS-p) sensor will have an area of 10×5 cm^2. It will consist of macro pixels of size 100 μm $\times$ 1446 μm. It will be bump-bonded to 16 MPA (Macro Pixel ASIC) chips, each capable of reading out 1920 pixels. A scaled-down version of the MPA chip, which can handle 16×3 pixels only, is called MPA-light. Six of these MPA-light chips are foreseen to be bump-bonded onto a PS-p-light sensor. This assembly is called Macro Pixel Sub Assembly (MaPSA)-light and is shown in Figure 9. The PS-p-light sensors consist of 288 long pixel of the same dimensions as the pixel cell of the readout chip. They are manufactured by CIS on p-type float-zone (FZ) silicon of 4-inch wafers with a thickness of 200 μm and a resistivity between $4 - 8$kΩ cm as a DC-process. A first batch was

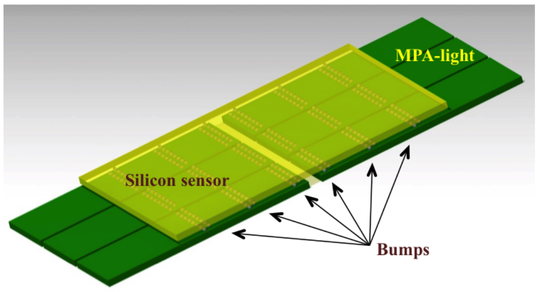

Figure 9: Schematic drawing of the MaPSA-light assembly comprising a PS-p-light-Sensor and six MPA-light chips.

delivered in March 2015, followed by three further batches of higher quality later this year. The sensors were qualified and maintain a high inter-strip resistance after an irradiation of 1×10^{15} n_{eq} cm^{-2}.

5.2. 2S Sensors from 6-inch Wafers

The sensors for the standard 2S modules (baseline design) have been designed by CMS and were produced by Hamamatsu Photonics (HPK) on 6-inch p-substrate FZ wafers with a resistivity of $3-8$kΩ cm and a physical thickness of 320 μm. The active thickness has been reduced to 240 μm by the deep diffusion technique. Fifteen wafers have been delivered with p-stop and five wafers with p-spray strip isolation technique, respectively. In addition, twenty wafers of *magnetic Czrochalsky* (mCz) substrate have been ordered but are not yet delivered. The wafer layout is shown in Figure 10. It con-

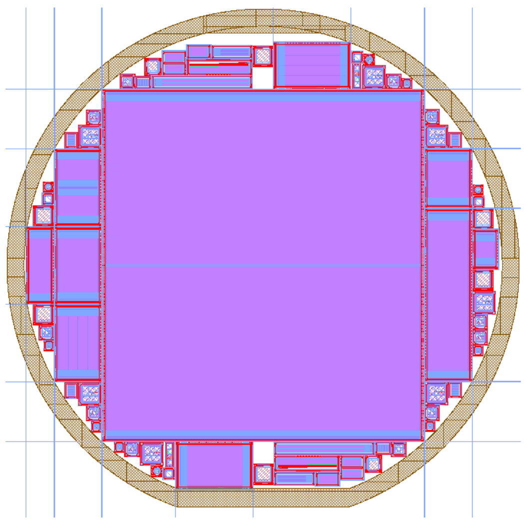

Figure 10: Schematic drawing of the 6-inch layout containing the full-size 2S sensor prototypes.

tains the main sensor with an approximate size of 10×10 cm^2 with a strip pitch of 90 μm and a strip length of 5 cm in the wafer center. The total number of strips is 2032 where each strip is coupled to the bias line using a poly-silicon resistor. The main sensor is surrounded by several mini-sensors, diodes, MOS, GCD, Van-der-Pauw, SIMS and sheet structures to fill the available area on the wafer.

The strip tests performed by HPK showed 5 pinholes out of 15 sensors (30,480 strips in total), which corresponds to 0.16 per mille. The measurements have been cross-checked by CMS on a sample basis. Figure 11 shows the results of current and $1/C^2$ vs. voltage scans of three sample sensors. The latter

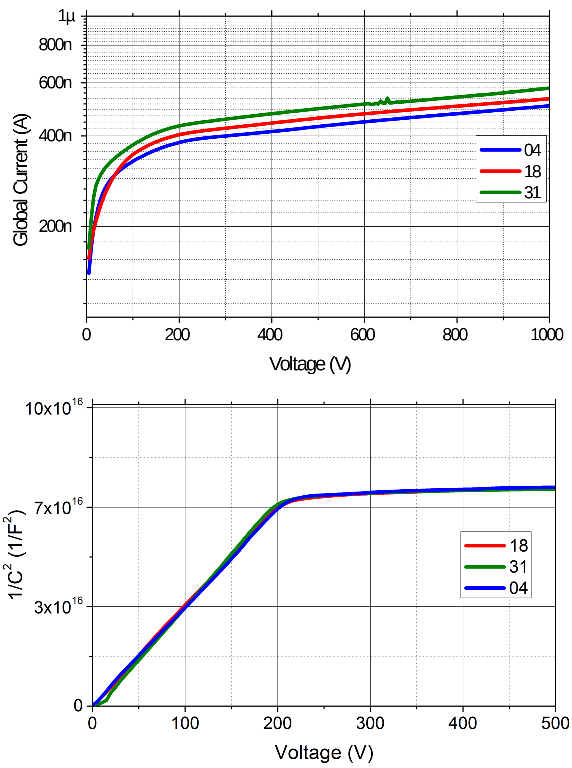

Figure 11: Current vs. voltage (top) and $1/C^2$ vs. voltage (bottom) behavior of three HPK 2S sensors.

ones result in a full depletion voltage slightly above 200 V, which corresponds to a resistivity of slightly below the specific minimum of 3 $k\Omega$ cm. The dark current is perfectly stable up to 1000 V (where the measurement ended) with currents below 6 nA per cm^2 at 1000 V. The sensors are now being used to build full-scale 2S modules for assembly studies, beam tests and irradiations.

5.3. 2S_long Sensors from 8-inch Wafers

To follow the developments of the chip industries, an effort started to increase the wafer size available for the production of silicon strip sensors beyond 6 inch. The first strip sensors on 8-inch wafers were produced by Infineon in autumn 2015, following a year-long collaboration [6]. A picture of the full wafer is shown in fig. 12. It shows a large 2S_long

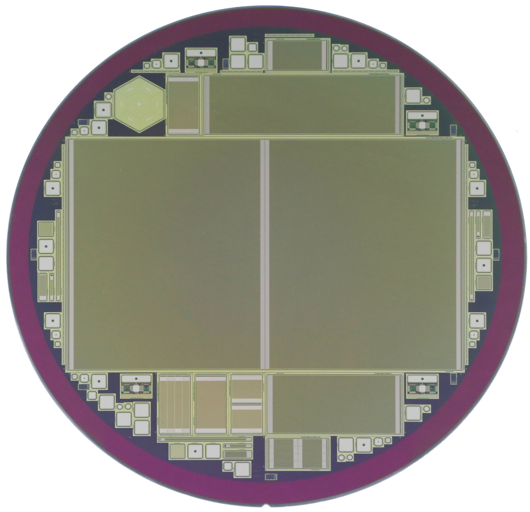

Figure 12: Photo on one of the 8-inch wafers (processed at Infineon) with the 2S_long sensor in the center.

sensor in the center, surrounded by a lot of mini sensors and test structures. The main sensor is an elongated version of the standard 2S sensor, thus having an active area of roughly 10×15 cm^2 with 7.5 cm long strips. The wafers are p-substrate FZ material with 7 kΩ cm resistivity. The sensor has a physical thickness of 200 μm. Similar to HPK, p-stop and p-spray strip isolation was used. The first batch consists of 25 wafers, from which five have been already characterized. Figure 13 shows the results of both current and $1/C^2$ vs. voltage scans of these five sensors. The capacitance behaves according to the expectations and confirms the resistivity of the base material very well. For the IV behavior, the p-spray wafer shows an unusual shape of the IV curve. For the other sensors, all with p-stop strip isolation technique, the dose of the p-stop implantation was varied. Therefore, different breakthrough behavior is observed. First strip-by-strip measurements have not shown any shorts of each strip's built-in capacitor, a failure usually called "pinhole".

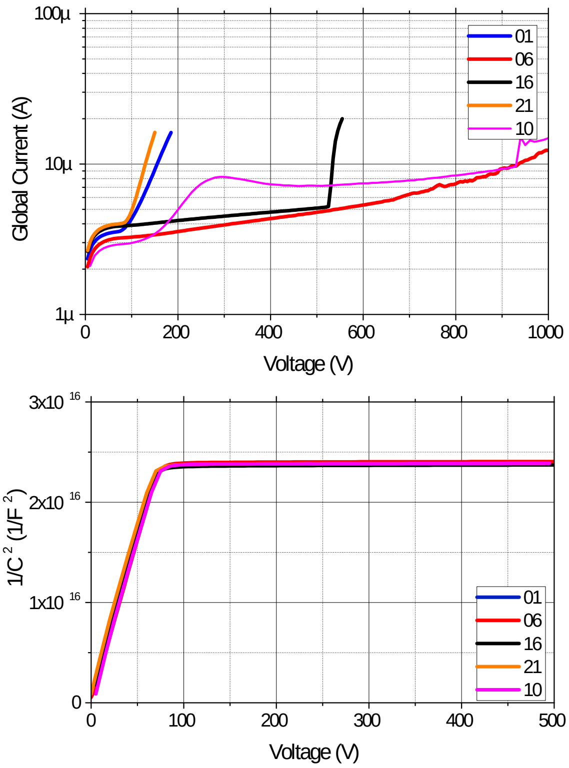

Figure 13: IV (left) and $1/C^2$ vs. voltage curves for five 2S_long sensors produced by Infineon on 8" wafers with $200\mu m$ physical thickness. Strip isolation is done by p-spray (wafer #10) and by p-stops (all others).

6. Summary

A completely new CMS tracker is necessary for the High-Luminosity LHC phase, scheduled after the Long Shutdown 3 in 2025. This tracker will need to have a superior radiation hardness to survive 3000fb^{-1} of integrated luminosity. Moreover, a higher granularity of the detector elements will be necessary because of the higher track density and pile-ups. In addition, the tracker needs to contribute to the level-1-trigger by providing "stubs", which is a local estimation of track momenta. CMS addresses this problem by detector modules which are equipped with two silicon sensors: the PS modules in the inner and the 2S modules in the outer regions, respectively.

A baseline layout of the tracker has been presented showing the arrangement of these detector modules in six barrel layers and five endcap layers. An optimized layout exists where the PS modules are tilted to always point perpendicular to the interaction point. Another layout variant becomes important when silicon sensors from 8-inch wafers are being used, increasing the number of different module types from two to three (PS, 2S_short, 2S_long). The R&D on radiation hardness results in a baseline for the silicon material which favors p-substrate with 200 μm thickness.

For the PS module concept, the focus is on the macro-pixel sub-assemblies, where DC-coupled macro-pixel sensors have been procured, which are going to be bump-bonded onto MPA-light ASIC chips. For the 2S module concept, full-size sensors have been designed and were produced in both 6- and 8-inch versions. While the first ones were procured from HPK, the latter ones have been produced in collaboration with Infineon.

Acknowledgments

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