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Exploring the quality of latest sensor prototypes for the CMS Tracker Phase II Upgrade

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ABSTRACT

The luminosity of the LHC will be increased by a factor of five to seven after the third long shutdown (LS3) scheduled in the mid of the next decade. The significant increase in luminosity along with the limitations of the current Tracker require a complete renewal of the CMS Outer Tracker, the Tracker Phase-2 Upgrade, during the LS3. New types of modules called PS and 2S modules are foreseen offering enhanced functionality and radiation hardness. Milestones in sensor R&D for the 2S modules as well as first characterization results are presented. AC-coupled silicon strip sensors of two vendors, produced on 6-inch as well as on 8-inch wafers, are considered which both are in n-on-p technology. Global as well as single strip parameters were measured providing insights into the quality of the sensors.

1. Introduction

The current CMS Tracker will be operational until LS3 up to an integrated luminosity of 300 fb^{-1}. Beyond LS3, the performance of the Tracker would significantly decrease mainly due to radiation damage causing an increase in leakage current which cannot be compensated by an appropriate temperature decrease of the cooling system anymore [1]. This fact alone makes a replacement of the Tracker during LS3 compulsory. For the high luminosity period after LS3, an integrated luminosity of up to 3000 fb^{-1} in total and fluences of up to 1.5×10^{15} n_{eq} cm^{-2} (Fig. 1) are expected which pose several challenges to the new Tracker in terms of radiation hardness and pile-up.

In particular, the new modules must withstand ~10 years of high luminosity data taking which makes more radiation hard sensors one of the most important aspects of the Tracker Upgrade. An estimated pile-up of 140 collisions per bunch crossing in average, three times more than currently observed, requires a higher granularity of the Phase II Tracker to keep the occupancy below 1% [1]. The resulting large amount of data in combination with bandwidth limitations and the compliance with the L1 trigger upgrade represents another major issue for the upgrade. To overcome this issue, the modules for the Phase II Upgrade need to provide additional functionality as explained in the subsequent section.

2. Module concepts

2.1. Trigger capabilities

The design of the new modules allows to distinguish between high and low transverse momenta (p_T) of incident particles on module level and therefore contributing to the L1 trigger decision at a bunch crossing rate of 40 MHz. The p_T discrimination is achieved by using two stacked and closely separated silicon sensors. If a particle is passing through the sensors, the hit position on the first and second sensor is correlated giving information on the particle's p_T. High p_T particles will only be slightly deflected by the magnetic field of CMS and will hit both sensors nearly on the same position (such an event is called "stub") whereas low p_T particles will be deflected more resulting in considerable different hit positions (Fig. 2). Depending on the window size ("stub window") where for the second hit is searched, specific transverse momenta can be discriminated. The whole procedure is called stub finding logic and is implemented in the new read-out chip of the modules. The read-out chip is called CMS binary chip (CBC) providing binary data and the above described p_T discrimination.

2.2. PS and 2S modules

Two types of modules called PS and 2S modules are foreseen for the CMS Tracker Upgrade. The PS module incorporates one macro pixel sensor and one strip sensor which are stacked and closely separated. The 2S module follows the same concept of stacked sensors but incorporates two identical silicon strip sensors with parallel strip orientation. The distance between the sensors

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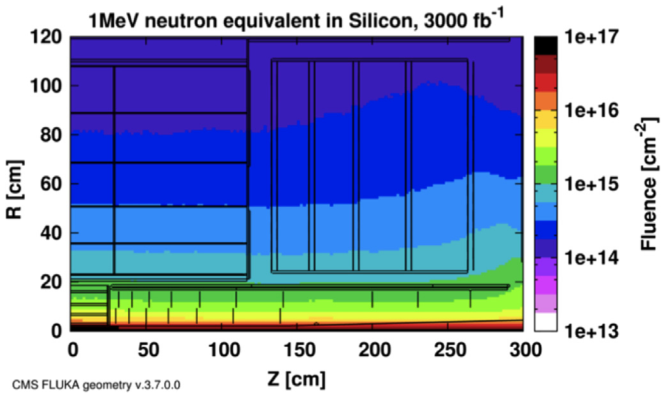

Fig. 1. One quarter of the CMS Tracker showing particle fluences in $n_{eq}\,cm^{-2}$ for different regions corresponding to an integrated luminosity of 3000 fb^{-1} [1].

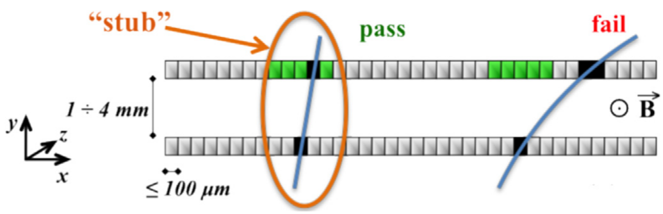

Fig. 2. Illustrated stub finding logic showing accepted and rejected particle curvatures [1].

will be 1.8–4 mm depending on where they are located inside the Tracker. Generally, the PS modules will be closer to the interaction point due to the required higher granularity and better z-resolution there.

Fig. 3 shows an exploded view of a 2S module. Each front end (FE) hybrid hosts 8 CBCs which and is wire bonded to the strips of the sensors (the strips are segmented at the center, Section 3.2). The data of the CBCs are fed by a concentrator chip to the service hybrid which transmits the data via a multi-gigabit transceiver. The spacing of the sensors is defined by aluminum carbon fiber (Al-CF) spacers.

3. Silicon strip sensors for 2S modules

The 2S modules for the Tracker Upgrade will incorporate sensors very different to the currently used ones. In particular, they will have p-type bulk material showing a better performance concerning charge collection after irradiation [2]. Furthermore, non gaussian noise was observed for p-on-n sensors causing random fake hits [1]. Besides the change of the polarity of the base material, thinner sensors are preferred due to a reduced leakage current and material budget and a lower trapping probability after high irradiation. In addition, a better annealing behavior was observed for thinner sensors [1].

3.1. 2S prototype sensors of two manufacturers

In total, 45 float-zone p-type base material wafers with a crystal orientation of <100> were ordered at two different manufacturers, Hamamatsu Photonics K.K. (HPK) and Infineon Technologies AG (IFX). In contrast to HPK, IFX sh. HPK produced 20 6-inch wafers with 2S sensors having the baseline design. IFX produced 25 8-inch wafers with an elongated version of 2S sensors called "2S long" representing the worlds first AC-coupled silicon strip sensors produced on 8-inch wafers [3]. The concept of 2S long sensors is currently under evaluation for the application in the outer regions of the Tracker which could provide cost advantages.

Fig. 4 shows the 6-inch wafer layout of HPK together with the 8-inch wafer layout of IFX. Besides the main sensors, both wafers feature a variety of smaller sensors used for irradiation purposes and p-stop geometry studies. Furthermore, different kinds of test structures are implemented to investigate the process quality.

3.2. Basic Sensor Properties

HPK processed 320 μm thick wafers with a resistivity of 3 kΩ cm. The active thickness is confined to 240 μm using the deep diffusion technique where the backside implant is deeply diffused into the bulk enabling a smaller active area. Sensors of IFX are produced on 200 μm thick wafers (physical and active thickness) with a resistivity of 7 kΩ cm.

Both 2S and 2S long are AC-coupled and biased via polysilicon resistors. Due to the oxide charge induced n-type inversion layer, a p-stop respectively p-spray layer serves for strip separation. Each strip spans over half of the length of the sensor. Both sensor types have 2032 strips with a width to pitch ratio of 0.25. The basic physical dimensions of the 2S and 2S long sensors are shown in Table 1.

4. Electrical sensor characterization

The prototype sensors of HPK and IFX were extensively characterized providing insights into their overall quality. In particular, 15 out of 25 2S long sensors of IFX were electrically characterized. The other sensors of IFX were held back for prototype module construction and more detailed investigations at the manufacturer and in the laboratory. Results of only three 2S sensors of HPK are shown in the following. Measurements of the remaining sensors of HPK are currently ongoing. All measurements were performed at 23°C and below 30 % relative humidity.

4.1. Global parameters

The measured current–voltage characteristics (*IV*) and capacitance–voltage characteristics (*CV*) of sensors of HPK can be found in [4]. The sensors exhibit a full depletion voltage of ~200 V, are stable up to 1 kV and show very low dark currents in general.

Figs. 5 and 6 show the IV and CV behavior for 15 2S long sensors of IFX. The CV curves are well overlapping and indicate a full depletion voltage of ~70 V which is, as for HPK, in agreement to the specified resistivity and thickness. However, the global IV characteristics are very different. Most of the sensors show a breakthrough right after 100 V and draw significantly more current than sensors of HPK.

4.2. Single strip parameters

Four major single strip parameters were measured on sensors of HPK and IFX. The single strip current I_{strip}, the polysilicon resistance R_{poly}, the coupling capacitance C_{ac} and the current through the dielectric layer I_{diel}.

Fig. 7 shows the measured single strip currents per cm strip length. Sensors of both vendors exhibit currents below 2 nA/cm fulfilling the preliminary CMS specifications.[1]

Fig. 8 shows the measured polysilicon resistances. According to the specifications R_{poly} values of (1.5 ± 0.3) MΩ are required. Sensors of HPK exhibit values within this range whereat the measured values for sensors of IFX are in general too low. The individual peaks result from different R_{poly} implantation doses which can now be used to choose more suitable implantation

[1] These specifications might change for a later series production.

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