Silicon sensor development for the CMS tracker upgrade



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# Silicon sensor development for the CMS tracker upgrade

**The CMS Tracker collaboration**

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ABSTRACT: CMS started a campaign to identify the future silicon sensor technology baseline of the new tracker for the high-luminosity phase of LHC. We ordered a large variety of 6 inch wafers in different thicknesses and technologies at producer Hamamatsu. Thicknesses ranging from 50 microns to 300 microns are explored on Floatzone, Magnetic Czochralski and Epitaxial Silicon both in n-in-p and p-in-n versions. P-stop and p-spray are explored as isolation technologies for the n-in-p type sensors as well as the feasibility of double metal routing on 6 inch wafers. Each wafer contains many different structures to answer different questions, e.g. geometry, Lorentz angle, radiation tolerance, annealing behavior or read-out schemes. Dedicated process test-structures, as well as diodes, mini-sensors, long and very short strip sensors and real pixel sensors have been designed for this evaluation. This contribution provides an overview of the campaign and summarizes interesting measurements performed so far.

KEYWORDS: Particle tracking detectors; Si microstrip and pad detectors; Radiation-hard detectors; Materials for solid-state detectors



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## 1 Introduction

The future High Luminosity LHC will feature new preconditions for silicon sensors such as a ten-fold increase in luminosity, dramatically increased track density and an increased radiation field, especially for inner tracker layers. Therefore it is substantial that future sensors will be very radiation hard and have high granularity. Also a reduced material budget as well as a feasible mass production process are required for a large-scale silicon tracker. The CMS Tracker Collaboration has ordered a large number of 6 inch wafers at renowned producer Hamamatsu Photonics (HPK) to investigate possible sensor technologies and materials. Within this campaign, the sensors will be irradiated to different fluences corresponding to different radii in the tracker.

### 1.1 The wafer

The wafer has been packed with a variety of structures [2], each intended for a different purpose. There are test structures to qualify and monitor the quality of the production process and determine operating parameters as well as mini sensors for beam tests and source measurements. These allow for the actual assembly of modules and therefore the investigation of the influence of geometry and materials on resolution, noise and signal-to-noise ratio. Material properties and response to irradiation are investigated with different diodes. A detailed overview of the different structures can be found in figure 1.

### 1.2 The materials

Previous work done by RD48 and RD50 at CERN has shown that silicon substrates with a high oxygen content show a higher degree of radiation tolerance. The natural concentration is higher for some production processes whilst for some others it can be increased artificially. Therefore this campaign features different materials with high oxygen concentration:

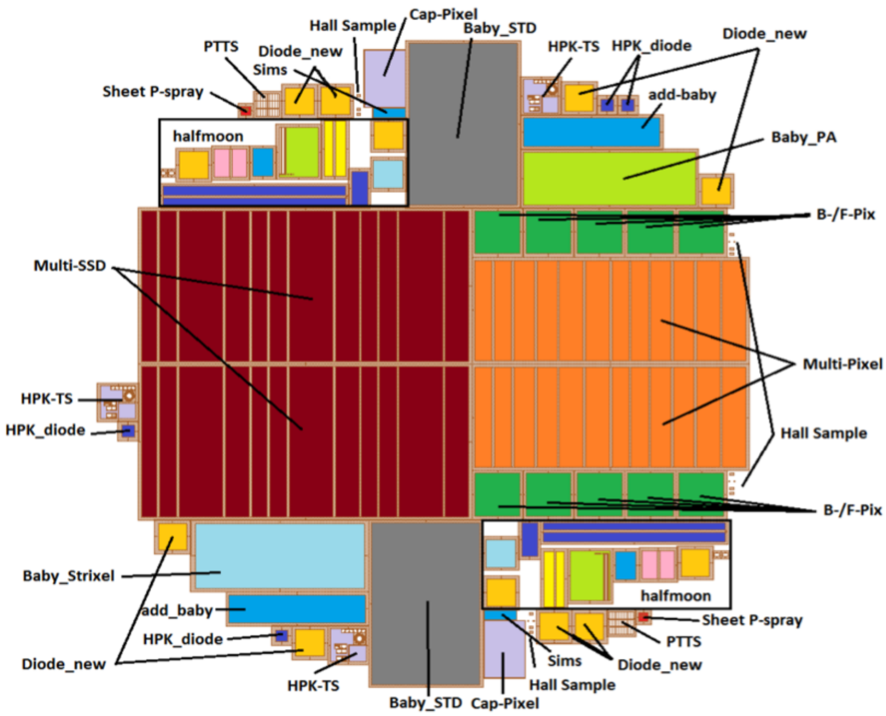


**Figure 1**. The HPK campaign Wafer.

- *FZ - Floatzone Silicon* which is the standard process.
- *MCZ - Magnetic Czochralski Silicon* where the crystal is pulled out of a melt.
- *Epi - Epitaxial Silicon* is CVD[1] grown on an oxygen-enriched carrier substrate.

The increased radiation environment in the HL-LHC, which will reach a peak luminosity of $10^{35} cm^{-2} s^{-1}$ or $3000\, fb^{-1}$ in 10 years, will require thinner sensors to reduce the required bias voltage. To achieve this, wafers with a deep-diffused backplane implant and physically thinned wafers are part of the campaign. Known material like $320 \mu m$ FZ material is used as reference. Additionally, electron readout devices (P-type) show reduced charge trapping after irradiation and therefore they are investigated with two different insulation technologies, namely p-stop and p-spray. Some wafers are processed with a second metal layer to study signal routing options like on-sensor pitch adapters. For an overview of all materials and other wafer options see table 1.

## 2 Testing

In order to understand the sensor properties and their influence on the performance fully, a variety of tests have to be performed. Among them are electrical tests to validate the functionality, determine parameters like the full depletion voltage and study the performance of the pieces as well as tests with particles and readout systems to study the impact of geometry and material on spatial resolution and S/N.

[1] Chemical vapor deposition.



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**Table 1**. List of materials for the HPK campaign — all p-bulk materials exist with p-stop and p-spray insulation. There are six wafers per type.

| | N-FZ | P-FZ | N-MCZ | P-MCZ | N-EPI | P-EPI |
|---|---|---|---|---|---|---|
| 320$\mu m$ | • | • | | | | |
| 200$\mu m$ deep diffusion | • | • | | | | |
| 200$\mu m$ physical | • | • | • | • | | |
| 120$\mu m$ deep diffusion | • | • | | | | |
| 120$\mu m$ physical | • | • | | | | |
| 100$\mu m$ epitaxial | | | | | • | • |
| 50$\mu m$ epitaxial | | | | | • | • |
| 200$\mu m$ double metal | • | • | | | | |

### 2.1 Qualification

Electrical tests are performed on test structures, diodes and sensors. These include current and various capacitance- and resistance scans which yield information on material properties, the production process quality and operating parameters like the full depletion voltage on minisensors. Other than that, measurements of the charge collection efficiency (CCE) (figure 2), which measures the injected versus the integrated collected charge, and trapping time (TCT), which is a time resolved signal, are performed. Another parameter which is of great importance for HEP experiments is the measurement of the Lorentz angle which is done on a dedicated minisensor. These measurements have to be repeated after each irradiation step to monitor and quantify the shift of the full depletion voltage, dark current and performance as response to radiation damage. Additionally they have to be carried out in a cold environment to suppress annealing effects, prevent thermal runaway and reproduce operating conditions.

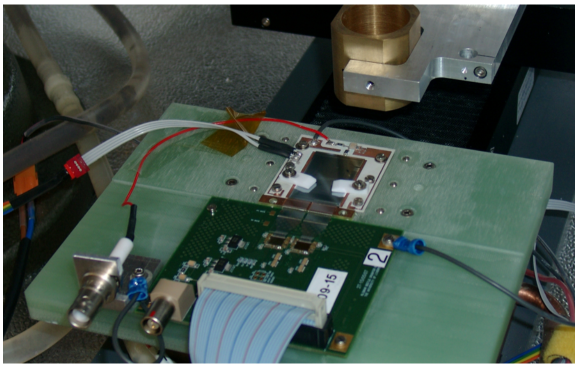


**Figure 2**. Setup for CCE measurement at KIT Karlsruhe.

### 2.2 Source and beamtests

Some detector properties like the spatial resolution and signal-to-noise ratio depend strongly on the geometry and the material and thus have to be measured, using an actual readout system as in a large scale experiment. The sensors are therefore assembled in modules and are equipped with CMS APV 25 [1] readout chips and electronics. In case of the HPK campaign, these are mostly dedicated multi-geometry minisensors allowing for the investigation of various strip pitch- and width ratios in combination with different thicknesses and materials. These modules are then exposed to particles, either from a radioactive source — which allows the determination of the signal, noise and signal-to-noise ratio — or a high energetic particle beam that, in conjunction

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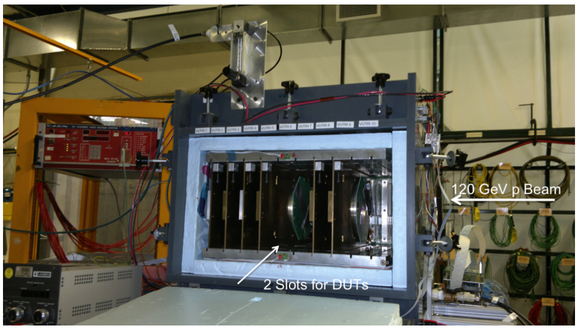


**Figure 3**. Silicon Beam Telescope at FNAL testbeam, March 2011

**Table 2**. Irradiation steps for the HPK campaign.

| Step | Radius [cm] | Fluence $[n_{eq}/cm^2]$ | Comment |
|---|---|---|---|
| 1 | 40 | $3*10^{14}$ | |
| 2 | 20 | $1*10^{15}$ | inner Si-strip layer |
| 3 | 15 | $1.5*10^{15}$ | |
| 4 | 10 | $3*10^{15}$ | |
| 5 | 5 | $1.3*10^{16}$ | inner pixel layer |

with a beam telescope (figure 3), allows for the measurement of particle tracks and therefore the calculation of the spatial resolution of a specific sensor.

## 3 Irradiation

A very important part of this campaign is to find a radiation-hard silicon substrate that can serve as a technological baseline for the future, upgraded CMS tracker.

To achieve this, a set of structures from the HPK wafer undergoes five different irradiation steps (table 2) to investigate the impact of proton-, neutron- and mixed irradiation. These steps correspond to different radii around the interaction point and to the estimated fluences these tracker layers will see with HL-LHC luminosity [2]. Irradiated detectors will be tested electrically and in a beam test while the microscopic impact of the radiation- and annealing studies will be qualified on diodes. The sequence of irradiation can be seen in figure 4.

## 4 First results

So far, some of the structures have been shipped, received and measured by the participating institutions. Electrical tests have shown some interesting behavior of certain materials and processes. The backplane implant of $200\mu m$ wafers for example has been done using a so-called deep diffusion process where the doping atoms are diffused deeply into the wafer using thermal treatment, to reduce the active volume. Although this might turn out as a cheaper alternative for mass production of detectors, it yields some difficulties. Since the doping profile does not show a very sharp step,

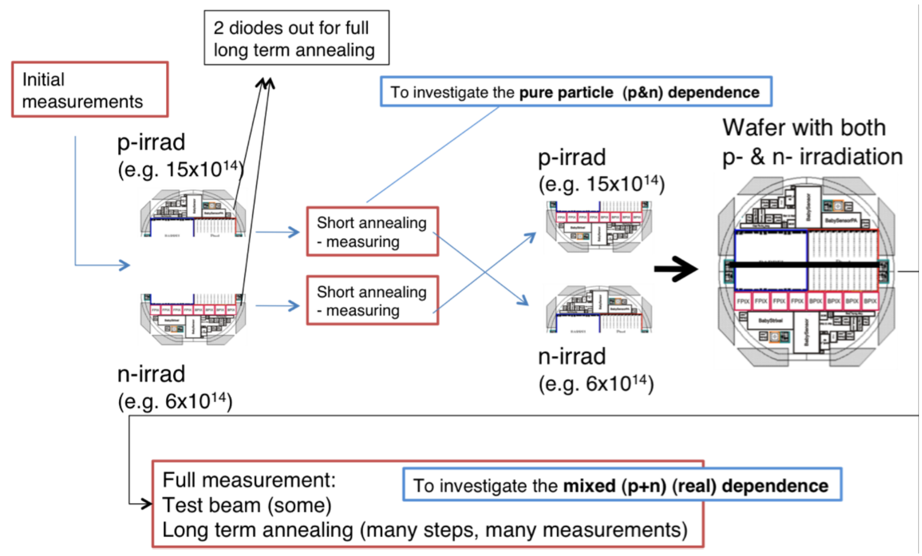


**Figure 4**. Irradiation sequence for the HPK campaign.

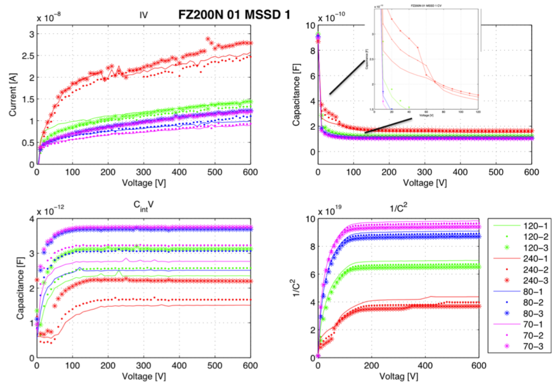


**Figure 5**. Data set of Multi-geometry strip sensor validation. Clockwise: dark-current, backplane capacitance, interstrip capacitance, $\frac{1}{C_{\text{back}}^2}$. The colors and symbols represent the 12 regions of the sensor.

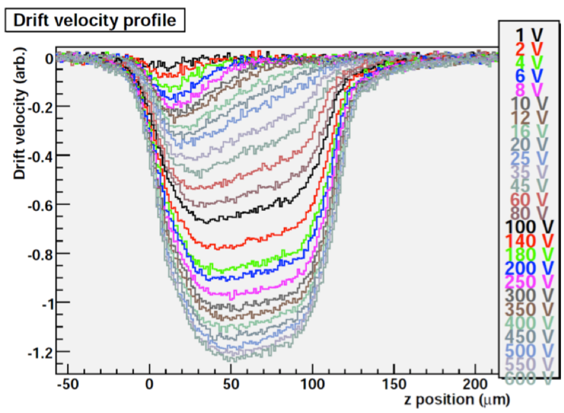


**Figure 6**. Drift velocity profile (el. Field) obtained with Edge-TCT measurement on a 120 $\mu m$ BabySTD Stripsensor. Here z is the coordinate perpendicular to the sensor plane

the limits (or thickness) of the active zone are not that well defined which makes it hard to extract or define the full depletion voltage. Some additional kinks in the overall detector capacitance (figure 5) appear, which might be a geometric effect of very large-pitch regions that first deplete to the backplane, before they fully deplete sideways between the strips.

Figure 6 shows a drift velocity profile of a 120$\mu m$ thick BabySTD sensor obtained with an Edge-TCT setup. Here, a laser mounted on a moving stage injects charge from the side orthogonal to the detector plane at various depths. The time resolved signal as a function of voltage is proportional to the drift velocity which allows to measure a depth profile of the electric field inside the sensor material. This is a useful tool to understand doping profiles and charge collection in the sensor, especially after irradiation.

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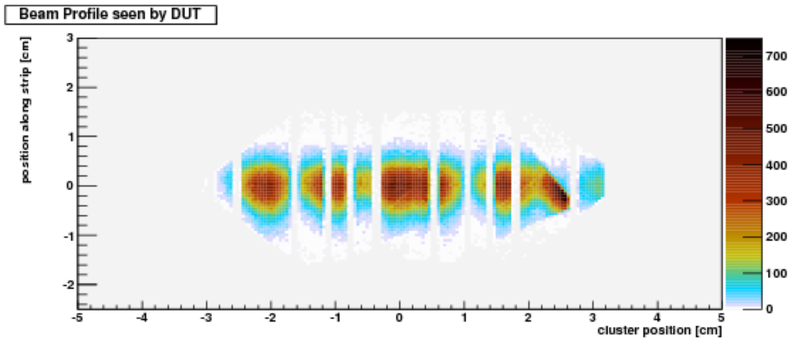


**Figure 7**. Beam profile from a position scan as seen by a Multi-geometry strip DUT at the March 2011 beamtest at FNAL.

Some standard floatzone multi-geometry strip- and multi-geometry pixel detectors in various thicknesses and doping schemes have been put in a beam test at FNAL in March 2011. The data analysis is continuing. Figure 7 shows the beam profile obtained from a position scan as seen by a multi-geometry strip sensor (FZ200N) as 2D histogram. The different regions and their borders can be distinguished. Detailed studies on the various geometries have to follow. Another beam test with the first irradiated detectors is scheduled for September 2011.

## 5 Outlook

For the near future a variety of tests and irradiations are scheduled. Among them is the source testing of multi-strip and multi-pixel sensors with the CMS APV25 readout system [1], the full electrical qualification of structures after proton-, neutron- and mixed irradiation to assess the impact of radiation damage on the various materials and some annealing studies on diodes. So far, only the irradiation step to the lowest fluence has been carried out, four more are waiting to be done at the proton cyclotron in Karlsruhe and the TRIGA Mk.2 reactor in Ljubljana. The first structures with a second metal layer for signal routing on the sensor have been delivered and distributed between the participating institutions.

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