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Silicon Sensor Developments for the CMS Tracker Upgrade

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Abstract

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Silicon Sensor Developments for the CMS Tracker Upgrade

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ABSTRACT: Preparing for the high-luminosity phase of LHC the CMS Tracker collaboration has started a campaign to identify the future planar silicon sensor technology baseline for a new Tracker. A variety of 6 inch wafers have been ordered in different thicknesses and technologies at HPK. Thicknesses ranging from 50 μm to 300 μm are explored on float-zone, magnetic Czochralski and epitaxial material both in n-in-p and p-in-n versions. p-stop and p-spray are explored as insulation technology for the n-in-p type sensors as well as the feasibility of double metal routing on 6 inch wafers. To explore the limits of the technologies many different structures have been designed to answer different questions, e.g. geometry, Lorentz angle, radiation tolerance, annealing behavior, read-out schemes.

This contribution provides an overview of the individual structures and their characteristics and summarizes measurements done on small strip sensors before and after irradiations.

KEYWORDS: CMS Tracker Upgrade; silicon sensors; radiation hardness.

Contents

1. Introduction	1
2. Radiation environment	2
3. Materials	2
4. Test-structures	3
4.1 Radiation hardness	4
4.2 Sensor design	4
4.3 Process qualification	5
5. Characterization of mini strip sensors	5
5.1 Before irradiation	5
5.2 After irradiation	6
6. Outlook	8

1. Introduction

The Large Hadron Collider (LHC) has started operation with a very steep ramp-up in luminosity. This allows to expect that the LHC will meet its design goal of $10^{34} \text{ s}^{-1} \text{ cm}^{-2}$ soon. Upgrades in the accelerator chain will allow to increase the luminosity further to $5 \cdot 10^{34} \text{ s}^{-1} \text{ cm}^{-2}$ (High Luminosity LHC or HL-LHC), which will exceed the instantaneous and integrated luminosity which some of the sub-detectors were designed for. One of the affected sub-detectors at CMS is the Tracker. The current version consists of about 200 m^2 of silicon strip sensors in the outer volume and 1 m^2 of silicon pixel sensors close to the interaction point. This choice of planar silicon sensors as sensitive elements of the Tracker will be kept as baseline for the upgraded Tracker (the technology choice for the most inner layer(s) of the pixel detector is still open). With the presented campaign we will have a comprehensive study on the limitations of the different silicon base materials and layout choices [2]. The new silicon sensors have to withstand the harsh radiation environment (up to $2 \cdot 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$) and guarantee good separation of tracks at the tenfold higher particle densities at the HL-LHC. Using thinner sensors and/or integrated pitch-adapters would allow to reduce the material of the sensor modules and help to keep the material budget of the Tracker low.

The CMS Tracker collaboration has purchased several planar silicon wafers from one supplier (Hamamatsu Photonics K.K.), who has demonstrated to be able to deliver the high quality and quantity we need for a huge tracking detector as in CMS. For best comparability it is important that the different wafers are processed at one manufacturer using one mask design. At the moment 14 institutes are involved in the measurements, which are performed before irradiation, after pure particle (neutrons or protons) damage and after mixed irradiation followed by investigations on the annealing behavior.

Figure 1. Simulated particle fluence distributions for the central ($z=0$ cm) and end-cap ($z=250$ cm) region. Data from S. Müller [6].

Table 1. Summary of the foreseen particle fluences.

Radius	Protons / $10^{14} \text{ n}_{\text{eq}}\text{cm}^2$	Neutrons / $10^{14} \text{ n}_{\text{eq}}\text{cm}^2$	Total / $10^{14} \text{ n}_{\text{eq}}\text{cm}^2$	Ratio p/n
40cm	3	4	7	0.75
20cm	10	5	15	2.0
15cm	15	6	21	2.5
10cm	30	7	37	4.3
5cm	130	10	140	13

2. Radiation environment

Figure 1 shows a simulated fluence distribution for an integrated luminosity of 3000 fb^{-1} for the current CMS Tracker layout. The radial dependence of neutral and charged hadron fluences differs significantly, which leads to a variation of the ratio of charged to neutral hadron vs. radius. It was found (e.g. in [3], [4], [5]) that mixed irradiations lead to different effects in different materials. Therefore we need to probe these effects on our materials in a consistent way. Since we cannot survey the conditions in the entire Tracker volume we picked some representative points as summarized in Tab. 1. Irradiations are performed with 24 MeV protons at ZAG¹, Germany, and reactor neutrons at Ljubljana, Slovenia, and are mainly funded by AIDA².

3. Materials

One goal of this campaign is to probe the limitations of the known silicon materials:

¹<http://www.zyklotron-ag.de>

²<http://aida.web.cern.ch>

Float-zone Best known material, which was first available in the high quality (high resistance) we need for detector material. With n-type bulk it serves as reference to compare to the current sensor installations.

Magnetic Czochralski This growth technique results in a high oxygen concentration in the silicon, which was shown to be beneficial in terms of radiation hardness by RD48³ and RD50⁴. See also [3].

Epitaxial This method allows to produce very thin (25 µm-100 µm) active sensors by chemical vapor deposition of silicon on a carrier wafer.

These materials are available as n-type (p-in-n) as was used in the current Tracker and as p-type (n-in-p) with electron readout, which shows reduced trapping effects at high irradiation (e.g. [4]). The n-type strip implants need insulation, which is realized in two processes:

p-spray moderate homogeneous doping of segmented side with $\sim 10^{12}$ ions/cm²

p-stop additional implanted p-type strips between the n-type read-out strips

At very high fluences charge carriers are being trapped before they can reach the segmented side and get lost during the integration time of the read-out electronic. This means that the charge collection distance drops below 320 µm and the benefit of thick sensors, in which particles can generate more charge carriers, is lost. Therefore thinner sensors are preferred since they also have lower full depletion voltages. To investigate the properties of thin sensors we have ordered various thicknesses. The float-zone material is available in 320 µm and 200 µm physical thickness, 120 µm on carrier wafer and 320 µm thick with a reduction of active thickness (to 200 µm and 120 µm) by *deep diffusion* of the backside doping. The magnetic Czochralski material is physically 200 µm thick and the epitaxial wafers come in 50 µm, 75 µm and 100 µm versions.

The *deep diffusion* process allows to produce thin sensors at lower costs compared to the thinning process or wafer bonding. The active thickness is reduced and therefore the depletion voltage. The physical thickness is still 320 µm, which allows easier handling than with thinner wafers, but a potential benefit for the material budget with thinner sensors would be abandoned. Since the sensor mass is only about 1/3 of the module mass the benefit would be small anyway. We will investigate if this process is a reliable alternative to the known processes during this campaign.

For more advanced read-out schemes a second metal layer, separated by about 1.3 µm oxide on top of the standard processed wafer, has been implemented on 200 µm wafers (n- and p-type). We realized different pitch-adaptor layouts and routings to investigate coupling effects.

4. Test-structures

The qualification process for our materials requires the use of various test-structures (figure 2) to answer individual questions:

³<http://rd48.web.cern.ch/rd48/>

⁴<http://rd50.web.cern.ch/rd50/>

Figure 2. Overview of the wafer mask with labellings of the main test-structures used in this campaign.

4.1 Radiation hardness

Main criteria in terms of operation are Charge Collection (CC) and leakage current as function of applied bias voltage. These two are intensively measured on **diodes** and **mini-sensors** together with the full depletion voltage from the capacitance-voltage (CV) characteristic and microscopic measurements with Thermally Stimulated Current (TSC) and Transient Current Technique (TCT). In addition, the strip parameters are characterized on the mini-sensors.

The evaluation of the sensor properties is done after pure proton, pure neutron and mixed irradiation followed by measurements at several defined annealing steps.

4.2 Sensor design

Strip capacitance is the main source for electronic noise, which could only be superseded by shot noise from leakage current at very high fluences. Therefore this parameter is studied in detail on **multi-geometry strip** sensors [7], which have 12 regions with different strip pitches (70µm, 80µm, 120µm, 240µm) and width to pitch ratios (0.15, 0.2, 0.3). The inter-strip, back-plane and total capacitance is measured as already described in [8], but now also on thin wafers and irradiated to higher fluences.

To gain experience with long pixel devices (pixel length 1.25/2.5 mm) a **multi-geometry pixel** sensor was designed, which implements both punch through and polysilicon bias resistors and different strip pitches (80µm, 100µm, 120µm).

For most of the Tracker volume we plan to use large ($\sim 10 \times 10 \text{ cm}^2$) strip sensors with a two- to four-fold segmentation along the strips. A first implementation of this so called ‘**strixel**’ sensor (labeled ‘Baby_Strixel’ in figure 2) also features the possibility to read out the inner strips ‘conven-

tionally’ at the edges of the sensor by routing lines, which run between the outer strips (for details see [9] and [10]). This would allow to avoid placing the hybrid including the read-out chips on top of the sensor, for which operability still needs to be investigated. Another possible application could be the strip- p_T -module as introduced in [11] featuring further segmentation along the strips. A strip- p_T -module comprises two strip sensors on top of each other with the strips of both being connected to one read-out chip, which correlates the hits of both. Hits at the same positions on both sensors indicate high- p_T tracks, since they are not strongly bent in the 3.8 T magnetic field of CMS. This allows to filter out the low momentum tracks and send high- p_T track information to the first level trigger at achievable data rate [12].

As mentioned above, we need to reduce the material budget in the tracking system. One contribution can be the integration of the pitch-adaptor (PA), which is needed for easy and reliable wire-bonding converting the about 80 μm pitch of the strips to about 45 μm pitch of the read-out chip pads. Up to now the PA was processed with aluminum on glass and glued on the hybrid. This additional glass substrate can be saved by implementing the PA in the silicon sensor itself. One layout of this **mini-sensor with integrated PA** was realized on the first metal (‘Baby_PA’, see also [9], [10]) and several others on the ‘Baby_Std’ of the second metal wafers.

Real size **pixel sensors**, which fit on the CMS pixel read-out chip (PSI46) footprint, are designed with variations in pixel size and punch-through biasing.

4.3 Process qualification

Very important for monitoring the process quality are the **standardized test-structures**, which were developed over years and will be put on all wafer layouts we are going to produce. On small dedicated structures all process relevant parameters are accessible and can easily be measured using micro probe cards and switching matrices [13].

5. Characterization of mini strip sensors

There are two types of mini sensors on the wafer: the so called ‘Baby_Std’ has 256 strips at 80 μm pitch and 3.3 cm strip length; the smaller one is called ‘Baby_Add’, has 64 strips at the same pitch and 2.6 cm strip length. The larger version will undergo pure neutron and pure proton irradiations as well as mixed irradiation and seven defined annealing points. Before and after each step the ‘Baby_Std’ is completely characterized (measurements of IV, CV, strip parameters, charge collection). The small one is dedicated to Lorentz Angle measurements and was mixed irradiated with a reduced characterization program.

5.1 Before irradiation

Figure 3 shows strip mean values for different strip parameters on some of the wafer materials. As can be deduced from the small error bars, most of the strip parameters are very uniform over one sensor. The inter-strip resistances are very high and at the limit of the measurement accuracy. The stated values are more lower limits than actual values.

The difference of the materials are very small for the coupling capacitance. Inter-strip capacitance is about 10% higher for the 320 μm thick sensors compared to the 200 μm ones. The bias resistance shows some variations between 1.4 and 2.4 $\text{M}\Omega$, where the magnetic Czochralski n-type has

Figure 3. Mean (over 256 strips of one sensor) values of the strip parameters measured at 600 V at 20°C. Legend in figure 3(a) holds for all plots. The label codes the material (float-zone: FZ; magnetic Czochralski: MCz), the thickness in μm and the doping type (n-type: N; p-type with p-stop: P; p-type with p-spray: Y).

significantly higher values than the other materials, but still in an acceptable range. The leakage current shows the strongest differences between the materials: 320 μm wafers have the lowest leakage current. Thin FZ sensors show up to 20 times higher currents due to defects introduced during the deep diffusion process. MCz sensors have even higher currents, which might be related to the thinning process. We will compare these measurements to physically 200 μm thick FZ sensors, which have not been delivered yet. We also see the tendency that p-type sensors have higher strip leakage currents. The current through the dielectric (used to detect pinholes, which are shorts between read-out aluminium strip and strip implant; we apply 10 V and the limit is $I_{diel} < 100 \text{ pA}$) is at a low level of around 1 pA. The higher value of FZ320P is due to few outliers.

Overall the quality of the delivered sensors is excellent with few process related peculiarities, which will be watched during the evaluation process.

5.2 After irradiation

The large mini-sensors have just undergone the first irradiation step together with all the other structures and measurement data is not available yet.

We have irradiated the small mini-sensors ('Baby_Add') made from FZ material with neutrons and protons and measured IV, CV and strip parameters on sample basis. In figure 4 we present the full depletion voltages as extracted from CV-curves. One can observe the strong increase in full depletion voltage (U_{fd}) with fluence. The thick sensors quickly rise above 1000 V, while the thin devices show lower U_{fd} due to the higher electric fields. The open symbols represent the measurements

Figure 4. Full depletion voltages and total leakage currents vs. fluence. The first points at ‘1e+14’ represents the measurements before irradiation! After each irradiation step and before the measurements a 10 min at 60 °C annealing was performed, which explains the lower values after the second irradiation (open symbols). As expected, the thinner materials has lower full depletion voltages. The label codes the material (float-zone: FZ; magnetic Czochralski: MCz), the thickness in μm and the doping type (n-type: N; p-type with p-stop: P; p-type with p-spray: Y).

after the second irradiation with protons. The additional annealing of 10 min at 60 °C before the measurement reduces U_{fd} thus the curves are below the curves after neutron irradiation only. We also observe that this p-type material has a steeper slope likely to be assigned to the missing type inversion in the already acceptor dominated p-type silicon. Next step is a systematic study of the charge collection of these irradiated sensors.

The total leakage current in figure 4(d) was measured with guard-ring connected to ground and normalized to the active volume (area: 26.5 mm × 5.55 mm; thickness: 320/200/120 μm). There is no systematic difference between the different materials visible (FZ320 material at very high fluences could not be fully depleted and therefore the leakage current was measured at 1000 V). The average slope of all materials is about $\alpha = (1.3 \pm 0.13) \cdot 10^{-18} \text{ A/cm}$. This was compared to the hardness factor α from [14], which after an annealing of 20 min at 60 °C yields about $5 \cdot 10^{-17} \text{ A/cm}$ at 20 °C;

Table 2. Strip parameters before and after irradiation for a 320 μm p-type sensor with p-spray strip insulation at a bias voltage of 600V. Values before irradiation are from a Baby_Std, averaged over 256 strips; after irradiation they are from a Baby_Add, averaged over about 10 strips. Values are normalized to strip lengths.

Fluence p/n ratio	0 $n_{\text{eq}}/\text{cm}^2$ -	$6.6 \cdot 10^{14} n_{\text{eq}}/\text{cm}^2$ 2.6/4	$3.8 \cdot 10^{15} n_{\text{eq}}/\text{cm}^2$ 30/8
Sample Temperature	FZ320Y_01_Bst_1 20 °C	FZ320Y_01_Badd_1 -10 °C	FZ320Y_03_Badd_2 -10 °C
Bias resistance	$1.68 \pm 0.01 \text{ M}\Omega$	$1.9 \pm 0.01 \text{ M}\Omega$	$2.1 \pm 0.05 \text{ M}\Omega$
Coupling capacitance	$27.1 \pm 0.1 \text{ pF/cm}$	$27.5 \pm 0.1 \text{ pF/cm}$	$27.8 \pm 0.1 \text{ pF/cm}$
Inter-strip capacitance	$462 \pm 4 \text{ fF/cm}$	$445 \pm 31 \text{ fF/cm}$	$439 \pm 18 \text{ fF/cm}$
Inter-strip resistance	$>100 \text{ G}\Omega\text{cm}$	$>150 \text{ M}\Omega\text{cm}$	$>50 \text{ M}\Omega\text{cm}$
Leakage current	$42 \pm 1 \text{ nA/cm}$	$445 \pm 10 \text{ nA/cm}$	$1800 \pm 23 \text{ nA/cm}$
Current through dielectric	$370 \pm 490 \text{ fA/cm}$	$940 \pm 430 \text{ fA/cm}$	$1460 \pm 600 \text{ fA/cm}$

scaled to -20 °C using [15] it results in $\alpha = 0.84 \cdot 10^{-18} \text{ A/cm}$. The parametrization in [14] was derived from measurements with diodes up to a fluence of $1 \cdot 10^{15} n_{\text{eq}}/\text{cm}^2$. Our measurements on these strip sensors show a 50% higher leakage current than expected from the diode measurements. The origin of this deviation is under investigation. Surface and oxide/silicon interface damage generates extra current, which has to be quantified. Errors in the estimation of fluence are within 15% and cannot account for the total excess current.

Table 2 summarizes mean strip parameters measured on mini-sensors before and after irradiation to the given fluences. We observe a slight increase of the bias resistance and no change in coupling and inter-strip capacitance within the measurement accuracy. The leakage current increases as described before. This also affects the measurement accuracy of the inter-strip resistance. Therefore the lower measurement limits drop and we can only state lower limits. The current through the dielectric also shows a slight increase with fluence but stays at a very low level of below 2 pA/cm. This quick look at the strip parameters did not show any surprise and demonstrate the good quality of the processed sensors. This is a good basis for a comparative study of the materials.

6. Outlook

Sensor quality after first characterizations looks excellent! Currently, the first irradiation for R=40cm has been performed and characterizations are ongoing. Beam tests are being prepared for irradiated multi-geometry strip sensors and sensors with integrated pitch-adaptor on first and second metal layer. Lorentz Angle measurements on FZ devices have been performed at the Institut für Experimentelle Kernphysik together with the Institut für Technische Physik (both at KIT) and are being analyzed. Device simulations are being conducted to complement the measurements.

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