The Compact Muon Solenoid Experiment

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Silicon Sensor Developments for the CMS Tracker Upgrade

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Abstract

As the high luminosity phase of the LHC is approaching, the CMS collaboration started research for the future silicon sensor baseline for the CMS Tracker phase II upgrade. Wafers of various materials (float-zone, magnetic czochralski and epitaxial), thicknesses from $320\mu\text{m}$ down to $50\mu\text{m}$ and n-bulk or p-bulk doping have been ordered at one manufacturer, HPK, for good comparison. Alongside, the feasibility of processing sensors with double metal routing on 6" wafers is explored. Different structures answer different questions covering aspects from radiation hardness to layout issues in this evaluation. A mixed irradiation program with protons and neutrons probes radiation hardness representing a mixture of charged and neutral hadrons expected in the CMS tracker after an integrated luminosity of 3000fb^{-1} at several radii. This contribution gives an overview of the first proton irradiated diodes. Furthermore, a sensor with integrated pitch adapter on a second metal layer is characterised and presented for the first time.

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SILICON SENSOR DEVELOPMENTS FOR THE CMS TRACKER UPGRADE

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As the high luminosity phase of the LHC is approaching, the CMS collaboration started research for the future silicon sensor baseline for the CMS Tracker phase II upgrade. Wafers of various materials (Float-zone, Magnetic Czochralski and Epitaxial), thicknesses from $320\mu\text{m}$ down to $50\mu\text{m}$ and n-bulk or p-bulk doping have been ordered at one manufacturer, HPK, for good comparison. Alongside, the feasibility of processing sensors with double metal routing on 6" wafers is explored. Different structures answer different questions covering aspects from radiation hardness to layout issues in this evaluation. A mixed irradiation program with protons and neutrons probes radiation hardness representing a mixture of charged and neutral hadrons expected in the CMS tracker after an integrated luminosity of 3000fb^{-1} at several radii. This contribution gives an overview of the first proton irradiated diodes. Furthermore, a sensor with integrated pitch adapter on a second metal layer is characterised and presented for the first time.

Keywords: CMS; Tracker Upgrade; Silicon Sensors; Radiation hardness

1. Campaign overview

The LHC at CERN will be upgraded to the high luminosity LHC after 2020. The CMS Tracker therefore has to deal with a harsher radiation environment. More radiation damage is introduced in the silicon sensors which leads to higher leakage current, higher depletion voltage and lower signal to noise. In addition, more proton interactions produce more tracks and lead to a higher occupancy. The CMS Collaboration started a campaign to identify the future silicon sensor technology baseline for the phase II upgrade of the CMS tracker. To find irradiation hard material, a large irradiation program has been set up for the materials of interest. The mixed irradiations with protons and neutrons represent the radiation environment

of charged and neutral hadrons with different ratios at an integrated luminosity of 3000fb^{-1} at five radii inside the CMS Tracker.¹ To reduce the material budget in the tracker, sensors with new readout designs have been developed.

1.1. *Choice of materials*

The silicon base material is one of the important parameters for radiation hardness of silicon sensors. In this campaign three different processes for growing sensor grade silicon are compared: Float-zone (FZ), Magnetic Czochralski (MCz) and Epitaxial (Epi) grown material. All materials are available as n-bulk and p-bulk versions. The n-type strip implants of p-bulk sensors require additional isolation which is done with two different techniques, also under investigation in this campaign. The p-spray method is a homogeneous p-doping of lower concentration all over the strip side of the sensor. P-stop on the other hand is a p-type strip implant with a higher doping concentration between the n-type readout strips.² In addition, wafers with a second metal layer were ordered. Six wafers of each material and bulk doping together with the double metal wafers sum up to 158 wafers in total.

This contribution covers deep diffused FZ with a thickness of $320\mu\text{m}$ and $200\mu\text{m}$ as well as MCz at $200\mu\text{m}$. Thinner material is not foreseen for outer radii in the tracker. The double metal sensor under investigation is FZ $200\mu\text{m}$ thick.

1.2. *Deep diffusion material*

An advantage of thinner sensors is the lower depletion voltage compared to thicker sensors. After irradiation also trapping of charge carriers is reduced due to the reduced thickness and a higher electrical field. A reduction of the active thickness can be achieved with deep diffusion: a high concentration of dopants is diffused deep into the wafer. This leads to a smooth change of doping concentration compared to wafer bonding, but the process is cheaper. In the left side of figure 1 a fitted doping profile used for the CV simulation of $320\mu\text{m}$ and $120\mu\text{m}$ thick FZ diodes can be seen, which leads to a good agreement between simulation and measurement (fig. 1 right).

2. Irradiated structures: Diodes

Diodes provide a good insight into the material itself. To identify radiation hard material for the future CMS Tracker, current (IV) and capacitance

Fig. 1. Deep diffusion doping profiles for 320 μm , 200 μm and 120 μm n-type diodes (*left*). *Right*: Simulation of diodes' capacitance-voltage curve with shown doping profiles.

(CV) as function of bias voltage as well as charge collection and TCT^a measurements are performed. Irradiations of the diodes presented here are all performed with 24 MeV protons from the Cyclotron in Karlsruhe (ZAG).

IV is used to determine the current related damage parameter $\alpha = \frac{\Delta I}{F \cdot V}$ with $\Delta I = I_{irrad} - I_0$ where I_{irrad} is the current after irradiation and I_0 is the current before irradiation. F is the fluence in 1 MeV neutron equivalent and V is the active volume of the diode. For the leakage current the value at 20% over depletion was taken. For diodes irradiated to $1.1 \cdot 10^{14} n_{eq} cm^{-2}$ α is below the expected³ value of $5 - 5.5 \cdot 10^{-17} A/cm$ after an annealing of ten minutes at 60°C. Diodes irradiated to $3.0 \cdot 10^{14} n_{eq} cm^{-2}$ lie above the expected value with $(6.0 \pm 0.3) \cdot 10^{-17} A/cm$ (fig.2). The error bars include a temperature uncertainty of 0.5°C. However, the current of diodes with larger fluence was measured at 0°C and scaled to 20°C while the current of the other diodes was measured directly at 20°C. For the current scaling, an activation energy of $E_a = 1.21 eV$ was used.⁴ Errors on the irradiated fluence and the activation energy, which was not measured for these samples so far, are not included here.

The depletion voltage (fig. 2 *right*) of the irradiated diodes was taken from the $1/C^2$ vs. voltage plot. All n-type diodes show type inversion after irradiation which is seen in TCT measurements. p-type diodes show increasing depletion voltage after irradiation, FZ increasing slightly more than MCz. No difference between diodes with p-spray(Y) and p-stop(P) is observed.

^aTransient Current Technique

Fig. 2. *Left:* Current related damage parameter for two diodes per material. *Right:* Depletion voltage of diodes after irradiation with 24MeV protons.

3. New designs: Double metal sensor

An idea to save material in the tracker is to implement the pitch adapter, used to connect to the readout with wirebonds, directly on the sensor. The corresponding test structure, which is called **Baby Pitch Adapter (BPA)**⁵, adapts the pitch of the readout on the first metal layer. The **Double Metal Pitch Adapter sensor (DMPA)** with a second metal layer advances this idea by implementing the routing of aluminum lines on a second metal layer separated from the first metal layer by a $1.3\mu\text{m}$ thick oxide. It was shown that processing a second metal layer on 6" wafers is working. The electrical characterization of the FZ 200 μm DMPA showed comparable results with respect to a baby standard sensor looking at interstrip resistance, bias resistance, strip leakage current, pinhole measurement and coupling capacitance. The interstrip capacitance however increases towards the middle of the pitch adapter, where the pads on the second metal layer lay directly over neighbouring strips of the first metal layer peaking at an increase of 50%. An increased capacitance leads to higher noise on affected strips.

Fig. 3. Cluster (black circles) and seed (blue squares) signal (*left*) and signal to noise (*right*) for the FZ 200 μm double metal sensor.

The signal measurements were done with an ALiBaVa⁶ setup and a ⁹⁰Sr source. The source's spot was positioned over the region of the pitch adapter. The collected signal (see fig. 3 *left*) is at its maximum of 17000 electrons for a 200 μ m thick sensor and is flat over the sensor. The signal to noise ratio (fig. 3 *right*) is good with a value of 17 over the sensor. Only 7 strips show an increased cluster noise of about 25% in the inner region of the pitch adapter from strip 65 upwards, which leads to a drop in the signal to noise ratio and arises from a higher interstrip capacitance. Yet, in other regions (especially till strip 64) the pitch adapter on the second metal layer has no effect on the signal to noise ratio and is working flawlessly.

Compared to a FZ 320 μ m BPA⁵, which shows a drop in the signal to noise ratio in the pad region (strip 27 upwards), the signal to noise for the FZ 200 μ m DMPA is 13% to 70% (pad region) higher and almost flat over the sensor.

4. Conclusions and outlook

Two first irradiations with protons have been performed and a first evaluation of depletion voltage and leakage current scaling with fluence was done. The double metal sensor with integrated pitch adapter was analyzed and performed better than a sensor with pitch adapter on the first metal layer.

In the coming months, more irradiations on the structures will be performed. The operability of an irradiated double metal sensor with integrated pitch adapter will be investigated as well.

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