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Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

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Bernhard Lutzer for the CMS Collaboration

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These TS consist of different microelectronic devices like diodes, resistors or MOS structures. They enable the extraction of parameters which are not accessible in a silicon detector and allow the assessment of the quality of the sensors which are produced on the same wafer. The TS have been irradiated with protons and neutrons to emulate the radiation damage caused by the particle fluence inside the CMS tracker after 10 years of operation. This contribution will present measurements of non-irradiated and irradiated test structures at different fluencies. The changes of the properties of the microelectronic devices will be discussed as well as the design of the TS.

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Characterization of Irradiated Test Structures for the CMS Tracker Upgrade

Bernhard Lutzer
on behalf of the CMS collaboration^a

^a*Institute of High Energy Physics (HEPHY) of the Austrian Academy of Sciences, Vienna, Austria*

Abstract

The CMS collaboration is currently conducting a campaign to identify radiation-hard materials for an upgrade of the CMS tracker. This upgrade is needed to be able to cope with the higher radiation background of the future HL-LHC; additionally the performance of the current tracker will be significantly degraded at the time of the upgrade, requiring a replacement anyhow. Several different test structures (TSs) and sensors have been designed for a 6 inch wafer layout. These wafers were produced by an industrial supplier (Hamamatsu Photonics K.K.) and differ by their bulk material (Float Zone, Magnetic Czochralski and CVD-Epi), thickness (from 50 μm to 320 μm) and N-P-type doping. These TSs consist of different microelectronic devices as for instance diodes, resistors or MOS structures. They enable the extraction of parameters which are not accessible in a silicon detector and allow the assessment of the quality of the sensors produced on the same wafer. The TSs have been irradiated with protons and neutrons to emulate the radiation damage caused by the particle fluence inside the future CMS tracker after 10 years of operation. This contribution will present measurements of non-irradiated and irradiated test structures at different fluencies. The changes of the properties of the microelectronic devices will be discussed as well as the design of the TSs.

Keywords: Silicon stripsensor, Test structures, Irradiation, CMS, Tracker

1. Introduction and motivation

The current Compact Muon Solenoid (CMS) tracker at the Large Hadron Collider (LHC) has to withstand high levels of radiation due to the high luminosity of the LHC of up to $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. This harsh radiation environment leads to a degradation of the silicon tracking sensor performance. Effects on the sensor are e.g. a change of the bulk resistivity following by an increase of the full depletion voltage, or a change of the coupling capacitance. It has been estimated that the detector performance will be insufficient after 500 fb^{-1} of delivered luminosity¹ [1]. Thus, a replacement of the current tracker will be required.

Additionally, an upgrade of the LHC is scheduled for 2022. At this upgrade, called HL-LHC, it is planned to achieve an integrated luminosity of up to 3000 fb^{-1} during its lifetime. Consequently, even higher radiation hardness requirements are imposed on the upgraded tracker. Furthermore, a higher granularity of the sensors is needed to account for the higher detector occupancy in the future.

In order to meet these requirements demanded in the future, the HPK²-campaign aims to define the future tracker sensor baseline.

2. The HPK-campaign

At first, a common wafer layout has been designed. The layout, shown in figure 1, features different structures such as test-structures, baby sensors or MSSDs. Each of these structures consists of sub-structures. They are used to investigate different aspects of the future tracker baseline [2], e.g. the choice of wafer material or sensor layouts. This article focuses on the two test-structures (TSs) which are highlighted with red rectangles in figure 1.

2.1. Wafer types

A set of possible wafer types to choose the new baseline from has been ordered from HPK. Only one manufacturer was chosen to ensure comparability of the measurement results.

The ordered material types are Float Zone (**FZ**), Magnetic-Czochralski (**MCZ**) and CVD-Epitaxy (**Epi**) silicon. For each type, P-strip implant in N-bulk material (**N**) and N-strip in P-bulk were produced. N-in-P-bulk types need strip isolation structures to avoid low interstrip resistances due to inversion layers. These are p-stop (**P**) and p-spray (**Y**). Moreover, a set of thicknesses (e.g. **320**, **200** and **120** μm for FZ material) has been chosen to account for different positions in the upgraded tracker, see section 2.2.

Additionally, wafers with a second metal layer have been designed to investigate the possibility of integrated pitch adapters. In total, the campaign is evaluating 21 different combinations of material type and thickness with a total sum of 156 wafers. Table 1 gives an overview of the ordered wafer types. In the

Email addresses: bernhard@lutzer.eu (Bernhard Lutzer on behalf of the CMS collaboration), <http://www.hephy.at> (Bernhard Lutzer on behalf of the CMS collaboration)

¹This is about the equivalent of 10 years of operation.

²Hamamatsu Photonics K.K.

Figure 1: Wafer layout.

Bulk type	FZ			MCZ	Epi	
	320	200	120		100	50
N	x	x	x	x	x	x
P (p-stop)	x	x	x	x	x	x
Y (p-spray)	x	x	x	x	x	x
N+2 nd -metal	-	x	-	-	-	-
P+2 nd -metal	-	x	-	-	-	-
Y+2 nd -metal	-	x	-	-	-	-

Table 1: Table of bulk materials, thickness in μm .

current CMS tracker Float Zone P-in-N silicon with 320 μm thickness is used.

Some of the delivered wafers differed from the order. A study of the delivered material showed for example that deep diffusion instead of wafer bonding wafers have been delivered [3].

All wafers were diced into the respective structures (TSs, MSSDs, etc.) and distributed among the responsible institutes. Thus, each institute has the same set of available wafers types which allows a holistic comparison and triggers an intensive institutional cooperation.

2.2. Irradiation plan

In order to investigate the radiation hardness of the different materials irradiation studies are performed. Most structures are irradiated with protons and neutrons at different fluences. The irradiation sites are TRIGA Mark II scientific reactor in Ljubljana, Slovenia and cyclotron in Karlsruhe, Germany. Each fluence corresponds to a radius inside the future CMS tracker. These radii (or distances from the interaction point) were derived from FLUKA simulations, see figure 2. Table 2 gives an overview of the fluences used for the irradiation campaign.

Previous research suggested an optimal thickness of the sensor depending on the location inside the tracker. An active

Figure 2: Expected fluences for the HL-LHC dependent on the radius from the interaction point [2].

thickness larger than 200 μm is sensible for 40 cm and 20 cm radius. The respective active thickness for 10 cm and 5 cm should be less than 200 μm [4].

Radius	Proton Φ_{eq}	Neutron Φ_{eq}	Total Φ_{eq}
40 cm	$3 \cdot 10^{14}$	$4 \cdot 10^{14}$	$7 \cdot 10^{14}$
20 cm	$1 \cdot 10^{15}$	$5 \cdot 10^{14}$	$1.5 \cdot 10^{15}$
10 cm	$3 \cdot 10^{15}$	$7 \cdot 10^{14}$	$3.7 \cdot 10^{15}$
5 cm	$1.3 \cdot 10^{16}$	$1 \cdot 10^{15}$	$1.4 \cdot 10^{16}$

Table 2: Campaign irradiation plan, fluences measured in $[\text{cm}^{-2}]$. Bold red fluences are already done, crossed out fluences are skipped, other ones are scheduled.

The total equivalent fluence in the rightmost column of table 2 represents both, one irradiation with neutrons and one with protons on one structure. This step is also called mixed irradiation. The separate proton and neutron steps at 20 cm in table 2 have been left out. Thus, only results of the total fluence at 20 cm are shown subsequently.

Complementary, our institute conducted irradiation studies with the TRIGA Mark II reactor of the Institute of Atomic and Subatomic Physics of the Technical University of Vienna with lower neutron fluences than those of the HPK-campaign.

3. Measurement types

A test structure, shown in figure 3, contains several sub-structures like diodes, MOS capacitors or resistors [5]. Their first use was to monitor the process quality during the production of several thousand silicon sensors of the current CMS tracker. This undertaking proved very successful [6].

Now each test structure is characterized before and after irradiation to determine the change of detector properties, e.g. the full depletion voltage of diodes³. A comparison of those measurements allows to assess the radiation hardness of different

³The full depletion voltages of diodes and sensors are related.

Figure 3: A picture of a test-structure with a scale.

wafer types. Table 3 shows the characterized parameters with the measurement type and the structure which is used therefor.

The motivation for using test-structures is that they allow the extraction of additional information about the process quality. For instance, the measurement of the dielectric breakdown voltage on a sensor is not possible without destruction.

Parameter	Meas.	Structure
Dark Current	IV	Diode
Depletion Voltage	CV	Diode
Flatband Voltage	CV	MOS
Dielec. Breakdown Volt.	IV	C_{CAP}
Oxide Thickness	C	C_{CAP}
Interstrip Capacitance	CV	C_{INT}
Interstrip Resistance	R	R_{INT}
Poly & Alu Resistance	R	R_{sheet}
Via Resistance	R	R_{Via}

Table 3: Parameters, structures and measurement types on a TS. I is the current, V the voltage, C the capacitance and R the resistance.

4. Results

This section presents an overview of test structures measurements. All samples have been annealed for 10 minutes at $T=60^\circ\text{C}$. The measurements have been performed at a temperature of $T=-20^\circ\text{C}$ and in a low humidity atmosphere. With the exception of those in section 4.1, all results are of the HPK campaign.

4.1. $C(V)$ -curves of irradiated MOS capacitors

Due to the high fluences used in HPK irradiation campaign the MOS characteristics changed crucially. In order to understand this behaviour, smaller fluence steps were necessary. Therefore, our institute performed complementary irradiations at the reactor in Vienna. Figure 4 shows the same $C(V)$ -plot in different zoom steps. Each curve represents a different irradiation fluence between 10^{11} and 10^{14} cm^{-2} as noted in the plot legend.

A fluence depending transition behaviour of the $C(V)$ -curve with different effects can be observed. The capacitance drop decreases with increasing fluences while the flat band voltage shows only minor deviations.

Figure 4: Dielectric breakdown voltage, legend states the fluence measured in neq cm^{-2} . Increasing fluences correspond to decreasing capacitances.

This can be explained with an increasing bulk resistivity and minor changes of the fixed oxide charges.

4.2. Flat band voltage before irradiation

Figure 5 shows the flat band voltages of MOS capacitors before irradiation. This value is an important parameter regarding the oxide process quality. The behaviour of the $C(V)$ -curves of MOS capacitors, discussed in 4.1, suggests that only unirradiated measurements make sense. The flat band voltage is homogeneous between N and P materials, but not dependent on the bulk material or the thickness (for N/P). V_{fb} of N and P are generally low which is desired for a high process quality.

4.3. Sheet resistances

Different structures have been designed to evaluate the sheet resistance quality. The fluence dependent sheet resistivities can be found in figure 6. The n^+ -implant resistance shows a minor decrease with irradiation while the polysilicon resistance plot seems not to be dependent on the irradiation fluence. The only distinctive feature are higher values for the MCZ200N TSs. The aluminum resistance is hardly influenced by the irradiation. This measurement has proven to be quite difficult and will be replaced by a four-wire method in the future.

4.4. Interstrip resistance

The method used obtaining the interstrip resistance is only possible on test-structures. In contrast to sensors, the R_{INT} -structure consists of isolated strips without bias resistors. Hence, an easy characterization of the pure interstrip resistance

Figure 5: Flat band voltages of unirradiated MOS capacitors.

Figure 7: Interstrip resistance for 80 μm pitch.

Figure 6: Resistivities vs. fluence.

Figure 8: Interstrip resistance for 120 μm pitch.

is possible. Figures 7 and 8 show the interstrip resistance for the different materials. A sharp decrease of the resistance can be found after irradiation. This can be explained by modifications of the bulk and implant resistivity.

4.5. Interstrip capacitance

The interstrip capacitance is shown in figure 9. One can see a major increase after the first irradiation step. Afterwards, a saturation can be observed for higher fluences.

4.6. Coupling capacitance and dielectric breakdown voltage

The coupling capacitance (figure 10) and the dielectric breakdown voltage (figure 11) are parameters of the oxide quality. Those are measured on the C_{AC} -structure.

The generally high breakdown voltages point to a high quality oxide. The coupling capacitances do not show a trend depending on the fluence.

5. Summary and Outlook

These first irradiation results show that as expected some parameters change with irradiation while others remain mostly stable. The hugest difference before and after irradiation can be found for the interstrip resistance, where the value changes over several orders of magnitude. While the values at the 20 cm

Figure 9: Interstrip capacitances vs. fluence.

Figure 10: Coupling Capacitance vs. fluence.

fluence step of R_{int} are still fine, it is not yet clear if this will be the same for the highest fluences. The interstrip capacitance increases slightly, but shows a saturation for higher fluences while the n^+ -implant resistivity decreases slightly.

The poly silicon and aluminium sheet resistances, the coupling capacitance and the dielectric breakdown voltage do not seem to be dependent on the fluence.

The $C(V)$ -curves of irradiated MOS capacitors showed interesting behaviours which could lead to further investigations in this area.

About the half of the irradiation steps of table 2 have been already made. The next irradiation steps with protons and neu-

Figure 11: Dielectric breakdown voltage.

trons are currently undergoing and will be analysed soon. The new irradiation steps with higher fluences will show which materials are able to withstand the highest fluences and are therefore suitable for the production of the new CMS tracker which should be in operation in 2022. Complementary, our institute is currently scheduling new irradiations at the scientific reactor in Vienna to enhance the experience at lower fluences.

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