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P-stop isolation study of irradiated n-in-p type silicon strip sensors for harsh radiation environments

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ABSTRACT

In order to determine the most radiation hard silicon sensors for the CMS Experiment after the Phase II Upgrade in 2023 a comprehensive study of silicon sensors after a fluence of up to $1.5 \times 10^{15}\,n_{eq}/cm^2$ corresponding to 3000 fb^{-1} after the HL-LHC era has been carried out. The results led to the decision that the future Outer Tracker ($20\,cm < R < 110\,cm$) of CMS will consist of n-in-p type sensors. This technology is more radiation hard but also the manufacturing is more challenging compared to p-in-n type sensors due to additional process steps in order to suppress the accumulation of electrons between the readout strips. One possible isolation technique of adjacent strips is the p-stop structure which is a p-type material implantation with a certain pattern for each individual strip. However, electrical breakdown and charge collection studies indicate that the process parameters of the p-stop structure have to be carefully calibrated in order to achieve a sufficient strip isolation but simultaneously high breakdown voltages. Therefore a study of the isolation characteristics with four different silicon sensor manufacturers has been executed in order to determine the most suitable p-stop parameters for the harsh radiation environment during HL-LHC. Several p-stop doping concentrations, doping depths and different p-stop pattern have been realized and experiments before and after irradiation with protons and neutrons have been performed and compared to T-CAD simulation studies with Synopsys Sentaurus. The measurements combine the electrical characteristics measured with a semi-automatic probestation with Sr90 signal measurements and analogue readout. Furthermore, some samples have been investigated with the help of a cosmic telescope with high resolution allowing charge collection studies of MIPs penetrating the sensor between two strips.

1. Introduction

Increasing demands for more radiation hard silicon detectors for high energy physics experiments at the LHC at CERN in Geneva require detailed studies of different sensor technologies based on silicon. Several studies towards more radiation hard detectors have been carried out with the result that the n-in-p technology is more radiation hard compared to the p-in-n type, considering the efficiency of charge collection [1–6]. Therefore, more detailed studies of the n-in-p detectors have been started in order to optimize their overall performance with respect to low noise and leakage current but simultaneously high charge collection efficiency. Several wafer submissions with different vendors to semiconductor industry have been performed. All wafer layouts included specific test structures and test sensors which should ensure the comparability of measurements and allow a comprehensive conclusion on the n-in-p type technology. One of the key interests of n-in-p type detectors is the necessary isolation of n-strips due to the accumulation of electrons beneath the sensor surface. The attractive potential for negative charges is generated by the positive charges in the silicon dioxide which even increases with increasing fluence. In the past, three different techniques of isolation layer have been developed for the n-in-p type technology, the p-spray, which is a uniform layer covering the whole wafer, p-stop which is a individual pattern for each strip or pixel, and the combination of both. However, electrical breakdown and charge collection studies indicate that the process parameters of the p-stop structure have to be carefully calibrated in order to achieve a sufficient strip isolation and high interstrip resistance, but simultaneously high breakdown voltages. Several investigations among different experiments did not allow to conclude on whether the p-spray or the p-stop technique is more suitable to ensure sufficient strip isolation after very high fluence. Furthermore the processing and its quality of the isolation structure is strongly related to the manufacturer. There are indications that the calculation of the p-spray implantation dose and energy is more challenging compared to the p-stop [7]. In the study presented, the p-stop technique is investigated in detail.

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2. Radiation level

During the long shutdown three, starting at around 2024, the LHC accelerator will be upgraded to deliver higher luminosity. As a consequence the CMS Tracker has to be fully replaced in order to cope with the harsh environment. The new tracker will be composed of a pixel detector with a range of up to $r < 20$ cm and an Outer Tracker covering the regions $20\ \mathrm{cm} < r < 110\ \mathrm{cm}$. Strip and macropixel sensors at the inner radii of the Outer Tracker will face a hadron fluence of up to $1.5 \times 10^{15}\ n_{eq}\ \mathrm{cm}^{-2}$ after the target integrated luminosity of about 3000 fb^{-1} over 10 years of operation. As a consequence, irradiation studies have been performed with protons and neutrons with the maximum fluence of $\Phi = 2 \times 10^{15}\ n_{eqcm^{-2}}$. The neutron irradiation took place at the TRIGA Mark II reactor in Ljubljana [8] whereas 23 MeV protons have been chosen for the irradiation with charged hadrons at the ZAG in Karlsruhe [9]. The irradiations have been done in several steps covering the range from $\Phi = 1 \times 10^{14}\ n_{eq}\mathrm{cm}^{-2}$ to $\Phi = 2 \times 10^{15}\ n_{eqcm^{-2}}$.

3. Silicon sensors: n-in-p technology

Fig. 1 shows an image section taken from the GDS[1] file, which has been used for the sensor production. The pitch (p) of the sensors in this study is either 80 μm or 90 μm. The $n+$ implants for the strips are 18 μm for the 80 μm pith and 20 μm for the 90 μm pitch resulting in a width-to-pitch ratio of 0.22 for all sensors in this study. Key properties of the isolation technique under study are the p-stop doping concentration and the p-stop pattern. The latter means the p-stop to strip implant distance (PS) of each individual p-stop implantation. The width of the p-stop is kept constant for all sensors to 6 μm. The aluminum overhang varies for the sensors between 4.5 μm and 6.5 μm.

Besides these parameters, the specifications for the production were comparable. The substrate is float-zone silicon with ⟨100⟩ crystal orientation and a resistivity of 4 kΩ cm to 10 kΩ cm. The physical thickness varies for the different submissions between 200 μm and 320 μm.

P-stop characteristics

The tested strip detectors in this study mainly differ in the p-stop isolation characteristics. Sensors from four different vendors and with five different doping concentrations and doping depths have been produced and investigated. An overview of all p-stop parameters is given in Table 1. The depth is defined as the depth below the bulk surface where the doping concentration reaches the bulk concentration, (Fig. 2). These values have been used for the T-CAD simulation as input parameters. The values are mainly derived from discussions with the process engineers. ToF-SIMS[2] measurements of the doping profiles are scheduled. Hereby, the composition of the surface is investigated using the sputtering of primary ions and analysis of the ejected secondary ions.

4. Experiments and simulation

The sensors have been qualified before and after irradiation. The measurements included the electrical qualification in a probe station and signal measurements with the ALiBaVa[3] [10] setup as well as T-CAD simulation studies with the Synopsys Sentaurus tool [11].

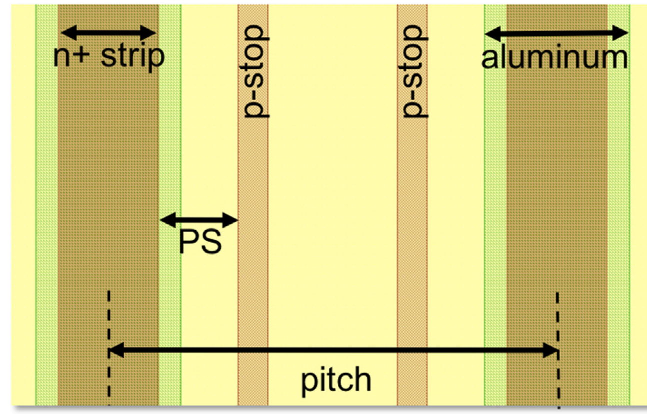

Fig. 1. Scheme of two strips of a n-in-p type sensor with p-stop isolation technique extracted from a GDS file which has been used for the photolitographic masks.

Table 1
P-stop doping profile parameters of the sensors in this study.

Variant	Peak conc. (cm^{-3})	Doping depth (μm)	Implant dose (cm^{-2})
V1	1×10^{16}	2.2	9×10^{11}
V2	9×10^{16}	2.7	8×10^{12}
V3	$< < 1 \times 10^{16}$	<2.0	$< < 1 \times 10^{11}$
V4	1×10^{16}	1.5	7×10^{11}
V5	1×10^{16}	2.5	9×10^{11}
V6	1×10^{17}	2.5	8×10^{12}

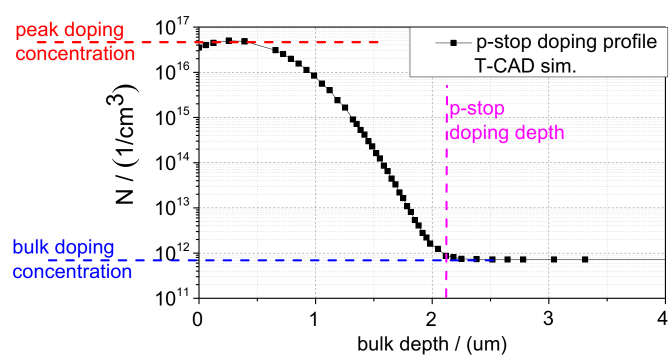

Fig. 2. Exemplary doping profile used for the T-CAD simulations.

4.1. Electrical qualification

The sensors have been measured in order to investigate the isolation structure which should not affect the sensor characteristics significantly. In particular, the breakdown voltage (V_{BD}) needs to be high because voltages up to 900 V might be reached towards the end of the sensor lifetime. As the p-stop doping concentration affects the electric field strength, the implant dose must be as low as possible. On the other hand, the interstrip resistance (R_{int}) requires a certain minimum of implant dose in order to ensure the minimum R_{int} of approximately 50 MΩ even after an integrated luminosity of 3000 fb^{-1}.

Probe needles have been used to apply the bias voltage (V_{bias}) for IV characteristics. In addition, a low voltage ramp in $\Delta = 0.2$ V steps up to 1 V between two adjacent strips has been applied. With the ohmic law, the R_{int} can be calculated.

[1] Graphical design station – data format of IC layout files
[2] Time-of-flight secondary ion mass spectroscopy.
[3] A Liverpool Barcelona Valencia.