PROCEEDINGS OF SCIENCE

Passive CMOS Strips Sensors - Characterisation, Simulation and Test Beam Results

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In the passive CMOS Strips Project, strip sensors were designed by a collaboration of German institutes and produced at LFoundry in 150 nm technology. Up to five individual reticles were connected by stitching at the foundry in order to obtain the typical strip lengths required for the LHC Phase-II upgrade of ATLAS or CMS trackers. The sensors were tested in a probe station and characterised with a Sr90-source as well as laser-based edge- and top-TCT systems. At last, detector modules were constructed from several sensors and thoroughly studied in a test beam campaign at DESY. All of these measurements were performed before and after irradiation. Sensors were also simulated using Sentaurus TCAD and the charge collection characteristics were studied using Allpix^2. We provide an overview of simulation results, summarise the laboratory measurements and present the test beam results for irradiated and unirradiated passive CMOS strip sensors.

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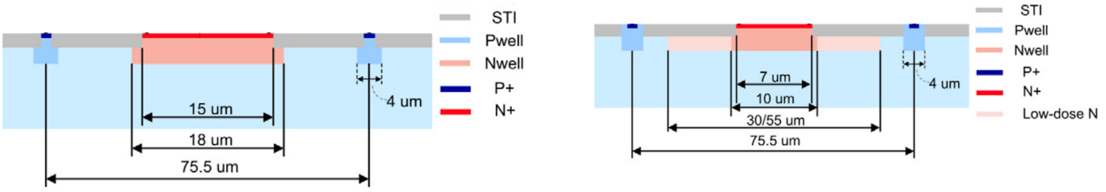
1. Passive CMOS Strip Sensors

CMOS strip sensors offer a cost-effective alternative to strip sensors currently used for the upgrades of high-energy experiments. Moreover, there will be a need for large area radiation hard tracking detectors for the future experiments. CMOS silicon strip sensors fabricated with a possible integration of read-out electronics in the silicon bulk are a promising candidate to take a part in the future of high-energy physics.
The passive CMOS strip sensors were fabricated in LFoundry [1] in a 150 nm process and a reticle size of 1 cm^2. Sensors were made in two different lengths of strips - 2.1 and 4.1 cm. In order to achieve the desired lengths, sensors had to be stitched. Therefore, there are up to five stitches in each sensor. Sensors were diced from a p-type FZ eight inch wafer with a resistivity of 3 - 5 kΩ·cm, they have a nominal active thickness of (150 ± 10) μm and a strip pitch of 75.5 μm.
Each individual sensor includes three different designs - *regular, low dose 30* and *low dose 55*. The designs are sketched in Figure 1. The *regular* has a 15 μm wide strip n^+-implant. The *low dose* designs introduce an additional low-doped n-implant and a MIM capacitor. The low-doped n-implant comes in two widths (30 and 55 μm) and is placed below the high-doped n-implant that for the *low dose* designs is only 7 μm wide.



(a) *Regular* design

(b) *Low dose 30/55* design

Figure 1: Sketch of the CMOS strip implant designs [2].

2. TCAD Simulation

Electrical characteristics of CMOS strip sensors were investigated in detail using the Sentaurus TCAD [3] simulation software. The simulated structures describe a 1 μm long 2D strip segment. The structures were obtained using the Sentaurus TCAD process module as the whole fabrication process was simulated. Simulations use typical models and default values for most parameters.

In Figure 2 it is shown that for unirradiated sensors the simulations accurately predict the magnitude of leakage current and the shape of its dependence on bias voltage. Simulations were performed with nominal values of parameters for the physics models that were implemented aiming at the prediction of a general trend rather than fitting the individual curves. In this respect the overall agreement between simulation and measurements can be considered good enough.

The simulations of unirradiated sensors also provide a detailed look on the electric fields, see Figure 3. While for the *regular* design the electric field is higher right below the strip, the *low*

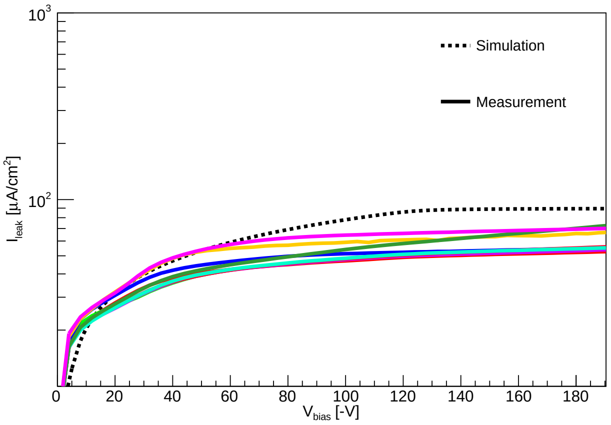


Figure 2: Comparison of measured and simulated $I - V$ curves of CMOS strip sensors before irradiation.

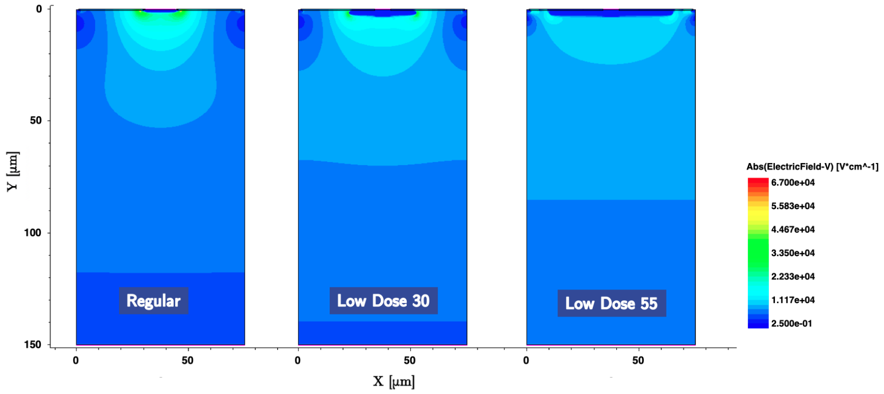


Figure 3: Electric field of a one strip structure at 100 V for the different designs - *regular, low dose 30* and *low dose 55*.

dose 30 and *low dose 55* show lower electric field values below the strip [4]. As an effect of the additional low-doped n-implant for the *low dose 30* and *low dose 55* design, the region of higher electric field below the strip spreads through a larger part of the silicon bulk in comparison to the *regular* design.

3. Measurements of Irradiated Sensors

The CMOS strip sensors underwent a neutron irradiation campaign at the TRIGA Mark II Reactor in Ljubljana. The samples studied were irradiated to fluences ranging from $1{\cdot}10^{14}$ n_{eq}/cm^2 to $1{\cdot}10^{15}$ n_{eq}/cm^2. Two types of sensors were irradiated - short (SH) with a strip length of 2.1 cm, and long (L) with a strip length of 4.1 cm. The *I-V* characteristics were measured using a cold setup at a temperature of -30 ± 1 °C.

The measured currents were normalised to 20 °C using the Chilingarov formula [5] and to evaluate the measured data the geometric current damage constant α^* [6] was calculated based on

$$\alpha^* = \frac{I}{V \cdot \Phi}$$

where I corresponds to the leakage current after annealing (60 °C for 80 minutes) at full depletion at the temperature of 20 °C, V is the geometric volume of the bulk, and Φ is corresponding fluence. Figure 4 shows the measured I-V characteristics of irradiated sensors before annealing at -30 °C for fluences $1{\cdot}10^{14}$, $3{\cdot}10^{14}$ and $1{\cdot}10^{15}$ n_{eq}/cm^2 respectively. An increase in leakage current with increasing fluence can be clearly observed. Also the leakage current is lower for the short structures in comparison to the long ones as expected. Comparing the designs we can see that the *regular* seems to be more radiation hard as the I-Vs are a bit more uniform and the leakage current is lower than for *low dose* designs.

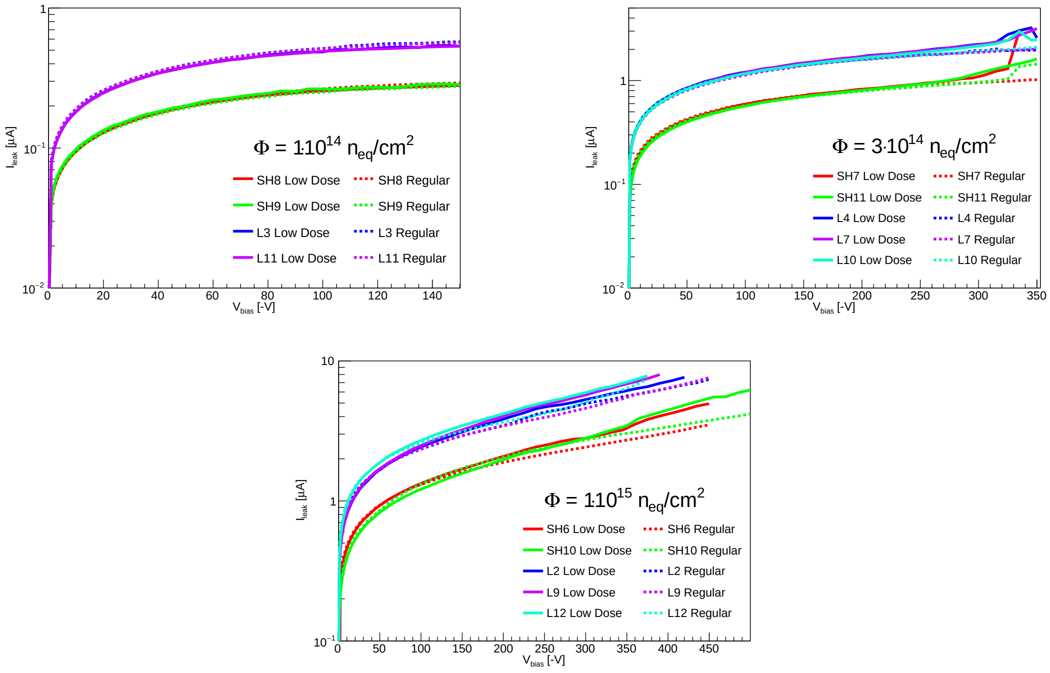


Figure 4: Measured leakage currents for neutron irradiated CMOS strip sensors at -30 °C.

Radiation hardness of the sensors under the study can also be evaluated based on the calculation of the radiation damage constant α^*, plotted in Figure 5. An increase in radiation hardness constant can be observed with irradiation. Comparing α^* values for the lowest and highest fluences, there is an increase of ≈ 25 % with irradiation.

4. Test Beam Results

Several test beam campaigns were performed in 2022 and 2023 at the DESY-II test beam facility exploiting the 3.4 and 4.2 GeV electron beam line to characterise the CMOS strip sensors in terms

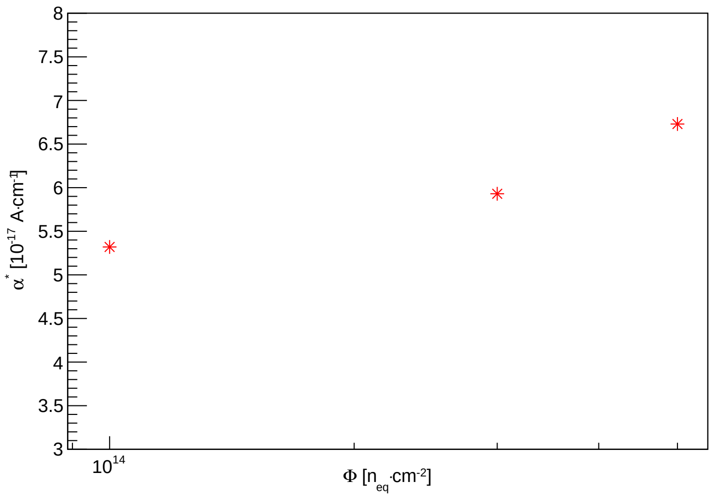


Figure 5: Dependence of the current damage constant α^* on the neutron fluence.

of their spatial resolution and hit detection efficiency [7]. During the test beam campaigns all three designs were investigated before irradiation and after irradiation, using both neutrons and protons.

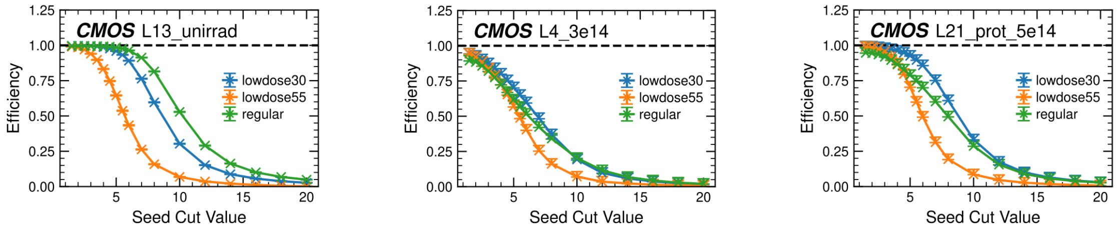


Figure 6: Efficiencies of *regular*, *low dose 30* and *low dose 55* designs as a function of seed cut value for unirradiated, neutron irradiated $\Phi = 3{\cdot}10^{14}$ $n_{eq}{\cdot}cm^{-2}$ and proton irradiated $\Phi = 5{\cdot}10^{14}$ $n_{eq}{\cdot}cm^{-2}$ sensors respectively.

Figure 6 shows the dependence of efficiency on the seed cut value. If the signal to noise ratio of a strip in an event is above the seed cut value, this strip is counted as a hit.
We observe a clear deterioration in efficiency after irradiation as expected. The unirradiated sensors follow a s-curve shape with a plateau close to one for lower and medium signal/noise cut values, for higher seed cut values it steeply decreases and then slowly declines towards zero for high signal/noise values. The previously mentioned plateau disappears after irradiation as the efficiency decreases. The decrease in efficiency after proton irradiation is lower than after neutron irradiation.

5. Conclusions

A detailed look into the characteristics of passive CMOS strip sensors was provided by TCAD simulations and by the comparison of simulation results to the laboratory measurements. Before irradiation, the agreement between simulated and experimental characteristics is very good and the electric fields show clear differences between each sensor design - *regular*, *low dose 30* and *low dose 55*.

After neutron irradiation we observe an increase in measured leakage current as expected. A closer look on sensors' behaviour after irradiation was provided by the calculation of the radiation damage constant α^*. Radiation damage constant values showed a consistent behavior for all the investigated doses.

Test beam results show deterioration in efficiency after irradiation as expected. The deterioration in efficiency is lower after proton irradiation than after neutron irradiation to the same equivalent fluence.

6. Acknowledgements

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