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

Martin Printz for the CMS Collaboration

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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.

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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 $1.5 \times 10^{15}$ $\text{n}_{\text{eq}}/\text{cm}^2$ 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.

Keywords: Radiation hardness, Silicon detector, Strip isolation technology, p-stop parameter

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; 2; 3). 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 power 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 layer 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. Three different techniques of isolation layer have been developed, the p-spray, which is a uniform layer covering the whole wafer, p-stop which is an 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 tech-
nique is more suitable to ensure sufficient strip isolation after very high fluence. There are indications that the calculation of the p-spray implantation dose and energy is more challenging compared to the p-stop (4). In the study presented, the p-stop technique is investigated in detail.

2. Radiation level

During the long shutdown 3, 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 be compatible with the increasing radiation level and further demands, which are not discussed here. Basically, the new tracker will be composed of a pixel detector with a range of up to \( r < 20 \text{ cm} \) and an Outer Tracker covering the regions \( 20 \text{ cm} < r < 110 \text{ cm} \). Strip and macropixel sensors at the inner radii of the Outer Tracker will face a hadron fluence of up to \( 1 \times 10^{15} \text{n}_{eq}\text{cm}^{-2} \) after the target integrated luminosity of about \( 3000 \text{ fb}^{-1} \) over 10 years of operation. As a consequence, irradiation studies have been performed with protons and neutrons with the maximum fluence of \( \Phi = 2 \times 10^{15} \text{n}_{eq}\text{cm}^{-2} \). The neutron irradiation took place at the TRIGA Mark II reactor in Ljubljana (5) whereas 23 MeV protons have been chosen for the irradiation with charged hadrons at the ZAG in Karlsruhe (6). The irradiations have been done in several steps covering the range from \( \Phi = 1 \times 10^{14} \text{n}_{eq}\text{cm}^{-2} \) to \( \Phi = 2 \times 10^{15} \text{n}_{eq}\text{cm}^{-2} \).

3. Silicon sensors: n-in-p technology

Figure 1 shows an image section taken from the GDS file, which has been used for the sensor production. The pitch (p) of the sensors in this study is either \( 80 \mu\text{m} \) or \( 90 \mu\text{m} \). The n+ implants for the strips are \( 18 \mu\text{m} \) and \( 20 \mu\text{m} \) 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 \( 6 \mu\text{m} \). The aluminum overhang varies for the sensors between \( 4.5 \mu\text{m} \) and \( 6.5 \mu\text{m} \). Besides these parameters, the specifications for the production were comparable. The substrate is float-zone silicon with \(<100>\) crystal orientation and a resistivity of \( 4 \text{k}\Omega\text{cm} \) to \( 10 \text{k}\Omega\text{cm} \). The physical thickness varies for the different submissions between \( 200 \mu\text{m} \) and \( 320 \mu\text{m} \).

<table>
<thead>
<tr>
<th>Variant</th>
<th>peak conc. (cm(^{-2}))</th>
<th>doping depth ((\mu\text{m}))</th>
<th>implant dose ((\text{cm}^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>(1 \times 10^{16})</td>
<td>2.2</td>
<td>(9 \times 10^{11})</td>
</tr>
<tr>
<td>V2</td>
<td>(9 \times 10^{16})</td>
<td>2.7</td>
<td>(8 \times 10^{12})</td>
</tr>
<tr>
<td>V3</td>
<td>(&lt;1 \times 10^{16})</td>
<td>&lt;2.0</td>
<td>(&lt;1 \times 10^{11})</td>
</tr>
<tr>
<td>V4</td>
<td>(1 \times 10^{16})</td>
<td>1.5</td>
<td>(7 \times 10^{11})</td>
</tr>
<tr>
<td>V5</td>
<td>(1 \times 10^{16})</td>
<td>2.5</td>
<td>(9 \times 10^{11})</td>
</tr>
<tr>
<td>V6</td>
<td>(1 \times 10^{17})</td>
<td>2.5</td>
<td>(8 \times 10^{12})</td>
</tr>
</tbody>
</table>

\(^1\text{Graphical Design Station - data format of IC layout files}\)

\(^2\text{Time-of-Flight Secondary Ion Mass Spectroscopy}\)
The sensors have been measured in order to investigate the isolation structure, which independent of the irradiation dose should not affect the sensor characteristics in a significant way. In particular, the breakdown voltage ($V_{BD}$) needs to be higher than 900V which could 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 calculated as low as possible in order to achieve such high breakdown voltages. 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 a very high fluence of $\Phi = 2 \times 10^{15} \text{cm}^{-2}$ corresponding to 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 0.2 V steps to 1 V between two adjacent strips has been applied. Due to the ohmic law, the $R_{int}$ can be calculated with the measured current.

4.2. Signal measurements

The signal of the sensors has been measured with the analogue Beetle chip within the ALiBaVa setup. Calibration, clustering and signal/noise have been calculated. The analogue chip allows detailed analysis of the signal distribution and the noise behavior with and without an external source. Beta electrons from a Sr90 source have been used to generate the signal. A scintillator below the sensor provides the trigger information.

4.3. T-CAD simulation

Complementary to the measurements, T-CAD simulations with the Synopsys Sentaurus software package have been performed. The simulations have been tuned in order to reproduce the experimental data, and subsequent predictions of new sensor geometries and parameters have been investigated. As simulations of unirradiated devices can be started with the internal physics models of Sentaurus, radiation damage has to be implemented by adding additional energy levels and cross sections into the bandgap. Within a huge measurement campaign (9) of silicon sensors for the CMS Phase II Upgrade, several T-CAD damage models based on measurements have been developed, which are able to reproduce data up to a fluence of $\Phi = 1.5 \times 10^{15} \text{cm}^{-2}$ with great agreement (10). Table 2 shows the model used in this study. This is an effective two-defect damage model for proton irradiation, the neutron model has not been used. All variants but the variant V1 have been irradiated with 23 MeV protons. V1 samples received a mixed irradiation of protons and neutrons. From the simulations, the maximum electric field strength and the charge collection depending on the sensor parameter and fluence of the samples have been extracted.

5. Combined results from measurement and simulation

As mentioned before, the focus of this study was to find the optimum p-stop doping concentration and depth. Therefore, the samples have been electrically qualified and investigated regarding their charge collection before and after irradiation for comparison.

5.1. Electrical qualification

One of the key parameter of n-in-p type sensors is the interstrip resistance $R_{int}$. Measurements for all variants have been performed before and after irradiation. For comparison the $R_{int}$ values are normalized to 1 cm strip length and plotted in Figure 3.

The specification of $R_{int} > 50 \text{ MΩ}$ mentioned in section 4.1 is valid independent of the irradiation as long as the minimal projected surface concentration is in the order of $9 \times 10^{11} \text{ cm}^{-2}$. It is noticeable that the projected surface concentration of V3 with less than $1 \times 10^{11} \text{ cm}^{-2}$ has been chosen too low leading to values for the interstrip resistance of a few tens of kΩ which would significantly affect the position resolution of the sensor in a negative way. The increase of the $R_{int}$ for the low

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Table 2: Effective two-defect damage model for proton irradiation of silicon sensors for T = 253 K. $E_C$ and $E_V$ are the edge energies of the conduction and valence band. $\sigma_e$ and $\sigma_h$ are the cross sections for electrons and holes. $\Phi$ is the fluence.

<table>
<thead>
<tr>
<th>Defect</th>
<th>Energy (eV)</th>
<th>$\sigma_e$ (cm$^{-2}$)</th>
<th>$\sigma_h$ (cm$^{-2}$)</th>
<th>Concentration (cm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptor</td>
<td>$E_C = 0.525$</td>
<td>$1.2 \times 10^{-14}$</td>
<td>$1.2 \times 10^{-14}$</td>
<td>$1.55 \times \Phi$</td>
</tr>
<tr>
<td>Donor</td>
<td>$E_V + 0.48$</td>
<td>$1.2 \times 10^{-14}$</td>
<td>$1.2 \times 10^{-14}$</td>
<td>$1.395 \times \Phi$</td>
</tr>
</tbody>
</table>

Figure 3: Interstrip resistance for the different variants as a function of the fluence.

concentration values after proton irradiation can be explained by the increase of the negative space charge towards the surface due to the ionization of acceptor traps. The resulting negative space charge repels the electrons at the surface and avoids the buildup of an accumulation layer. More detailed studies of this effect are ongoing. The variants V2 and V6 with comparably high projected surface concentration of about $8 \times 10^{12}$ cm$^{-2}$ do not show any suspicious effects considering the $R_{int}$. The value is sufficient and ensures independent of the fluence a sufficient interstrip isolation.

5.2. Signal measurements

After the electrical qualification, the samples have been bonded to the ALiBaVa Beetle readout chip and the noise and signal distribution generated by passing Sr90 beta electrons have been analyzed. Generally the noise signal of silicon sensors shows gaussian behavior. Hence, a signal is detected when the noise contribution exceeds five sigma of the gaussian noise (hit interpretation if signal $\geq 5\sigma$), (Figure 4). Depending on the p-stop isolation parameter, random ghost hits are observed which are defined for pedestal runs by counting all signals with $\geq 5\sigma$ of the gaussian fit width and divided by the number of strips and recorded events. These unexpected random ghost hits have been observed within a huge measurement campaign for p-in-n type sensors only, in which the n-in-p type sensors have been of the variant 1 in the study presented. A random ghost hit occupancy of 1% and higher was defined as bad. The occurrence strongly depends on the fluence, the bias voltage and the particle type of the irradiation. A detailed summary on this effect is described in (11).

Random ghost hits have now also been observed in this study for n-in-p type sensors depending on the p-stop doping profile. The most probable values (MPV) of the signal during the measurements for all variants are plotted in Figure 5 as a function of the fluence without annealing and for a bias voltage of $V_{bias} = -600$V. Measurements with random ghost hits are indicated by the RGH label. It can be seen that the occurrence of RGHs is just observed for the variants V2 and V6,
which have a comparably high p-stop doping concentration of about $1 \times 10^{17}$ cm$^{-3}$. High random ghost hit rate (>1%) is observed already at relatively low fluence of $\Phi = 4 \times 10^{14}$ neq/cm$^{-2}$ for neutron irradiation. This can be explained by taking the surface damage into account. Damage of the silicon dioxide at the sensor surface is introduced less by neutrons compared to protons which deposit energy by ionization. As a consequence, the positive charge of the silicon dioxide does not increase significantly, leading to higher peak electric field strength in the bulk compared to proton irradiated samples (11).

T-CAD studies indicate that the electric field strength can even exceed $3 \times 10^5$ Vcm$^{-1}$, which is the breakdown voltage of a pn junction in silicon. A section from the T-CAD simulation of sample V2 in Figure 6 shows high electric fields occurring directly at the p-stop edges and exceeding $3 \times 10^5$ Vcm$^{-1}$. The values for the electric field have been extracted 0.5 µm beneath the surface and plotted as a function of the position between the strips in Figure 7. With this observation, the RGH rate in n-in-p type samples can now be explained.

The physics model for the avalanche effect starts to generate charges for electric fields in the range between $1.75 \times 10^5$ Vcm$^{-1}$ and $6 \times 10^5$ Vcm$^{-1}$ (blue line in Figure 7) after the van Overstraetende Man model (12). These avalanche electrons are then detected with the readout electronics and wrongly interpreted as charges generated by ionizing energy loss from traversing particles. Simultaneously, simulations of variants V1, V3, V4 and V5 with moderate p-stop doping concentrations do not indicate a generation of avalanche electrons at all due to lower maximum electric field strengths.

Furthermore, no significant effect of the p-stop doping depth has been observed, neither in the electrical qualification nor in the AlIBaVu measurement. Hence, considering the experimental data, no clear recommendation on the p-stop depth can be expressed whereas a peak p-stop doping concentration of $1 \times 10^{16}$ cm$^{-3}$ seems to be sufficient with respect to good microstrip isolation and breakdown voltage. Also the charge collection efficiency (CCE) seems to be independent of the p-stop process characteristics. For a more detailed CCE study, the samples have to be measured during test beam conditions with a telescope in order to achieve a substrip resolution of the hits.

The successful reproduction by simulation of experimental data has been proven in (10) and (13). Therefore, the model in Table 2 has been used for a scan of the electric field strength in a sensor as a function of the
fluence and the p-stop doping concentration. The result is shown in Figure 8. The outcome is very well comparable to the measurements, meaning that the expected high electric field strengths of 1.75 \times 10^5 \text{ Vcm}^{-1} and higher are reached when the p-stop doping concentration reaches at least the minimum of 2 – 3 \times 10^{16} \text{ cm}^{-3}. The doping depth for the numerical analysis was constantly 2 \mu m and comparable to the depth of the variants in this study. Combining results from the electrical qualification, signal measurements and T-CAD studies, the doping concentration of 1 \times 10^{16} \text{ cm}^{-3} and a doping depth of around 2 \mu m seems to be the most appropriate considering the strip isolation and low random ghost hit rate, respectively low electric field strengths.

The same procedure has been performed for a fixed p-stop doping concentration but varying the p-stop to strip implant distance (PS), (Figure 1). The maximum electric field strengths in the bulk have been extracted from simulations with constant sensor geometry and parameters but the PS.

Considering the signal, no indications on optimal PS values are given for both measurement and simulation, Figure 9. On the other hand, Figure 10 shows slightly higher electric fields when the p-stop is close to the strip n+ implant. In this case, the electric field is more concentrated between p-stop and strip in comparison to a wider distance between the two implants. This is especially of interest for the photolithographic mask designers who with a wide PS do not have to design special and complex routing of the p-stop around the sensor AC pads.

6. Conclusion

The future CMS silicon outer tracker will use n-in-p type sensors. Critical detector parameters like the pitch and strip implant width and concentration are fixed and do not need any further investigations towards radiation hard silicon sensors for HL-LHC lifetime. The necessary strip isolation by implantation of group III elements, however, needs to be carefully calculated in order to ensure a sufficient interstrip isolation without negative impacts on the sensor performance. In this study, sensors with different p-stop isolation parameters have been investigated for their radiation hardness in dependence on the p-stop doping concentration and depth. Interestingly, no significant differences of the variants in the electrical qualification have been observed, whereas undesired random ghost hits occurred after irradiation for high p-stop doping concentrations.
The combination of data and T-CAD studies clearly prefers doping concentrations of around $1 \times 10^{16}$ cm$^{-3}$, while the p-stop doping depth does not show significant influence. The distance between the floating p-stop and grounded strip implants is favored to be wide, or rather the p-stop implants should be placed in the center between adjacent strips. Further studies, especially beam tests with substrip resolution, are scheduled.

7. Acknowledgement

We would like to thank the engineers from CNM Barcelona and CiS in Dresden for sharing some of the process parameters which have been used for the T-CAD simulations.

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