PROCEEDINGS OF SCIENCE

Impact of low-dose electron irradiation on the charge collection of n^+p silicon strip sensors

Robert Klanner[*†]
Institute of Experimental Physics, University of Hamburg, Germany
E-mail: Robert.Klanner@desy.de

Joachim Erfle, Eckhart Fretwurst, Erika Garutti, Christian Henkel, Alexandra Junkes, Sergej Schuwalow, Joern Schwandt, and Georg Steinbrueck
Institute of Experimental Physics, University of Hamburg, Germany

The response of n^+p silicon strip sensors to electrons from a ^{90}Sr source was measured using the ALiBaVa read-out system. The measurements were performed over a period of several weeks, during which several operating conditions were varied. The sensors were fabricated by Hamamatsu on 200 µm thick float-zone and magnetic-Czochralski silicon. Their pitch is 80 µm, and both p-stop and p-spray isolation of the p^+ strips were studied. The electrons from the ^{90}Sr source were collimated to a spot with a full-width-at-half maximum of 2 mm at the sensor surface, and the dose rate in the SiO_2 at the maximum was about 0.6 mGy/s. The dose in the SiO_2 at the end of the measurements was about 500 Gy. Significant changes in the charge collection and charge sharing were observed as function of ^{90}Sr irradiation dose. Annealing studies, with temperatures up to 80°C and annealing times of 18 hours, show that the changes can only be partially annealed. The observations are qualitatively explained with the help of TCAD simulations in which the effects of radiation damage in SiO_2 have been included. The relevance of the measurements for the design and use of p^+n strip sensors in different radiation environments is discussed.

Technology and Instrumentation in Particle Physics 2014,
2-6 June, 2014
Amsterdam, the Netherlands

*Speaker.
†for the CMS Tracker Collaboration

PoS(TIPP2014)040

1. Introduction

Today, segmented silicon detectors with a spatial resolution of approximately 10 μm are used in precision tracking detectors closest to the interaction point of most collider experiments. They contribute to practically all physics analyses and were essential for the discovery of the Higgs boson and many other beautiful results from the four large-scale LHC experiments. As amply reported at TIPP 14, they have demonstrated an extraordinary performance with respect to precision, efficiency and reliability. The High-Luminosity LHC upgrade, HL-LHC, poses further challenges with respect to track density and radiation exposure: for an anticipated integrated luminosity of 3 000 fb^{-1}, hadron fluences of up to 10^{16} neq/cm^2 (1 MeV equivalent neutrons) are expected, causing radiation damage of the silicon crystal and ionization doses of several MGy resulting in surface damage in the insulating layers of the sensors. Whereas silicon-bulk damage has been studied extensively, only limited knowledge of surface damage on high-ohmic silicon [1] and its interplay with bulk damage is available.

In this contribution the effects of low-dose irradiation on the charge collection properties of n^+p strip sensors, when using electrons from a 100 MBq ^{90}Sr source, are studied, and the relevance of the results for the HL-LHC upgrade are discussed. This paper is the summary version of a more complete one that will be published shortly. More details on the measurements, on the results and their interpretation can also be found Refs. [2, 3].

2. Experimental set-up and sensors investigated

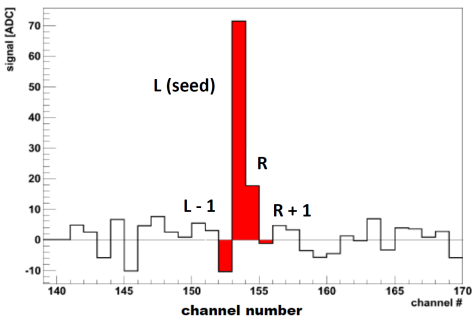
Two different types of *Baby add* n^+p test sensors from the CMS-HPK Campaign [4], one with p-spray and one with p-stop implants, have been investigated. The sensors were built on 200 μm float-zone (FZ) silicon with a B doping of $3.7 \cdot 10^{12}$ cm^{-3} and an oxygen concentration of about $5 \cdot 10^{16}$ cm^{-3}, as well as on magnetic-Czochralski (MCz) silicon with similar bulk doping, but with a one order of magnitude higher oxygen concentration. The 64 *AC*-coupled readout strips have a length of 25 mm, a pitch of 80 μm, and are made up of 19 μm wide p^+ implants separated from the Al strips by 250 nm SiO_2 and 50 nm Si_3N_4. The Al overlaps the 650 nm thick SiO_2 layers, which cover the region between the strips, by 5 μm, and the entire sensor, with the exception of the bond pads, is covered by an additional 500 nm of SiO_2 for passivation. The p-spray implantation was $5 \cdot 10^{10}$ cm^{-2}. The p^+ stops, two 4 μm wide p^+ implants at 6 μm distance, have a doping of $2 \cdot 10^{11}$ cm^{-2}.

For the measurements a 100 MBq ^{90}Sr source, placed in a copper collimator and mounted on a computer controlled x-y translation table was used to irradiate the silicon sensor. The temperature of the sensor could be adjusted between $-30\,^\circ$C and $+80\,^\circ$C. The sensor was read out by ALiBaVa [5], a multi-channel readout system for silicon strip sensors with 25 ns integration time. Two plastic scintillators, placed 58 and 62 mm from the source, provided the trigger signal from electrons that have traversed the silicon sensor and deposited energy in both scintillators. The energy distribution of the electrons and photons and the spatial distribution of the energy-loss rate in the SiO_2 layer on the surface of the sensor is estimated using Monte Carlo simulation. The dose-rate distribution is circular with a diameter at full-width-half-maximum of 2 mm and a value at the maximum of 50 Gy/d. The non-ionizing energy-loss (NIEL) rate, relevant for radiation damage in the silicon bulk, corresponds to about 10^8 neq /(cm^2·d). The simulated energy-loss distribution of the trigger electrons in the silicon sensor is similar to a Landau distribution for minimum-ionizing-particles (mip), with a most-probable-value (mpv) of 56 keV, compared to 54 keV for mips. The angular spread of the trigger electrons is about ± 100 mrad.

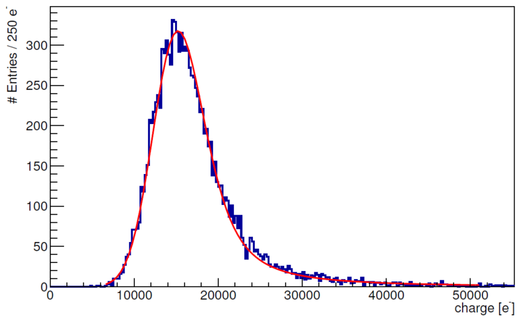
In this paper we report results from a non-hadron-irradiated *p*-spray, a non-hadron-irradiated *p*-stop, and a *p*-stop sensor irradiated by $15 \cdot 10^{14}$ neq/cm^2 23 GeV protons and $6 \cdot 10^{14}$ neq/cm^2 reactor neutrons, which is equivalent to the radiation field at the HL-LHC 15 cm from the beams after an integrated luminosity of 3 000 fb^{-1} [6, 7]. The corresponding ionizing dose in SiO_2 is about 0.75 MGy. Most of the measurements presented here were performed at $-20\,^\circ$C, the temperature at which it is planned to operate the silicon sensors at the HL-LHC.

3. Analysis

In the off-line analysis events are selected if the trigger signal was in phase within ± 5 ns with the 40 MHz ALiBaVa clock. Fig. 1a shows the pulse heights (PH) versus strip number after pedestal and common mode subtraction [2] for a typical event. The strip with the biggest PH is called the seed, its biggest neighbour defines the region of the passage of the electron, and together with the 2 next-to-next neighbours are the 4 strips used in the analysis of an event. They are labeled *L*-1, *L*, *R*, and *R*+1. Fig. 1b shows the distribution of the sum of the pulse heights of the four strips, PH(4-cluster), in units of electron charges, e, for 5 000 events measured using a non-irradiated sensor after pedestal and common-mode subtraction. As expected from the simulation, the distribution can be fitted by the convolution of a Landau distribution with a Gaussian, which is shown as the solid line. In the further analysis however, we will use the median of the pulse-height distributions, as for individual strips they cannot be described by the convolution of Landau and Gaussian distributions. The noise, with a root-mean-square (rms) value of about 810 e, allows a good separation of the electron signal which has an mpv of about 17 000 e. After hadron irradiation the rms noise increased to about 950 e.



(a)

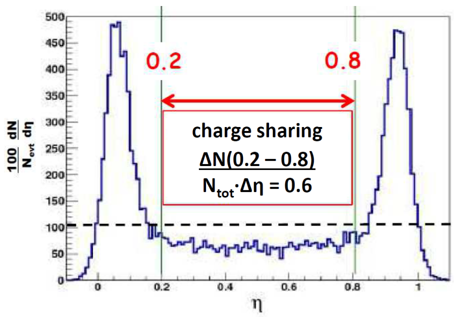


(b)

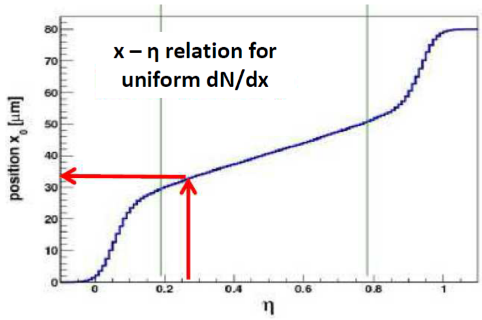
Figure 1: (a) Pulse height vs. strip number for a typical event, explaining the naming of the strips in a 4-strip cluster. (b) Distribution of the pulse-height sum for the 4 strips of a cluster for the non-irradiated sensor after pedestal and common-mode subtraction. The continuous curve represents the fit to the data by a Landau distribution convoluted with a Gaussian.

The analysis uses the variable $\eta = PH(R)/(PH(R)+PH(L))$, introduced in Ref. [8]. $PH(L)$ is the pulse height in strip L, and $PH(R)$ in strip R. The η-distribution allows the investigation of the electric field distribution and the charge sharing and charge collection of segmented sensors.

In an n^+p sensor the back plane is at negative potential and the electric field points from the n^+ implants to the back plane. If all field stream lines originate at the n^+ implants of the readout strips, the readout noise is zero, the particles traverse the sensor with normal incidence and charge diffusion can be ignored, then the event distribution dN/dη will be the sum of two δ-functions, one at $\eta = 0$ and the other at $\eta = 1$. Electronic cross talk shifts the positions of the δ-functions inwards, and noise causes a broadening and a further inward shift. Diffusion, which broadens the charge distribution arriving at the readout strips by about $\pm 4\,\mu$m, results in some charge sharing, and an angular spread of the traversing particles further increases charge sharing. If some field stream lines originate at the Si-SiO_2 interface, charge sharing will increase further, and the dN/dη distribution in between the peaks at low and high η values will be populated. The more field lines originate at the Si-SiO_2 interface, the more events will appear in the central η region.



(a)



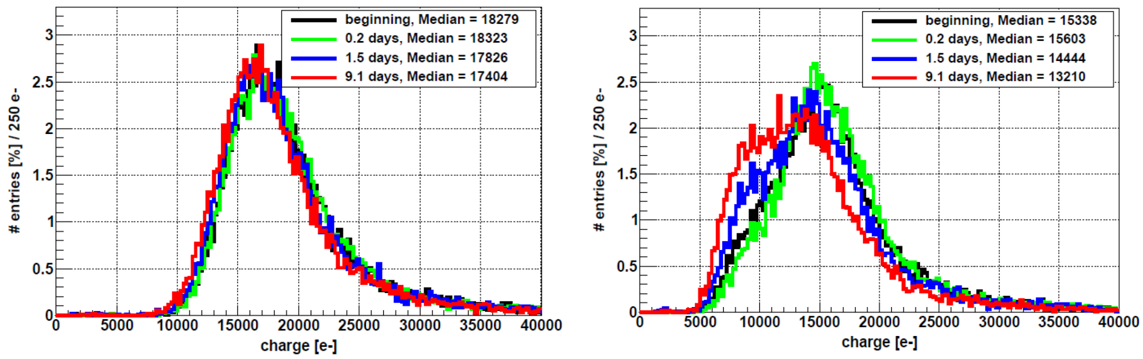
(b)

Figure 2: (a) Example for a differential distribution $(100/N_{evt})\cdot\mathrm{d}N/\mathrm{d}\eta$. (b) Cumulative η distribution, which relates η and the distance of the particle passage from the center of strip L.

Fig. 2a shows the distribution $(\mathrm{d}N/\mathrm{d}\eta)\cdot(100/N_{evt})$ measured for the non-hadron-irradiated p-stop sensor biased at 600 V after 2 days of β source measurement, which corresponds to a dose of 100 Gy. N_{evt} is the number of events. The value found in the central η region is about 60, which is significantly higher than 15−20 which is expected from the angular spread of ± 100 mrad. To characterize charge sharing we use the quantity CS [%], defined as 100 times the fraction of events between $\eta = 0.2$ and 0.8 divided by the width of interval $\Delta\eta = 0.6$. Thus CS gives the percentage of charge sharing compared to 100 % charge sharing. In addition, η allows the determination of the position of the traversing particle relative to the center of strip L as discussed in Ref. [8] and shown in Fig. 2b.

4. Results

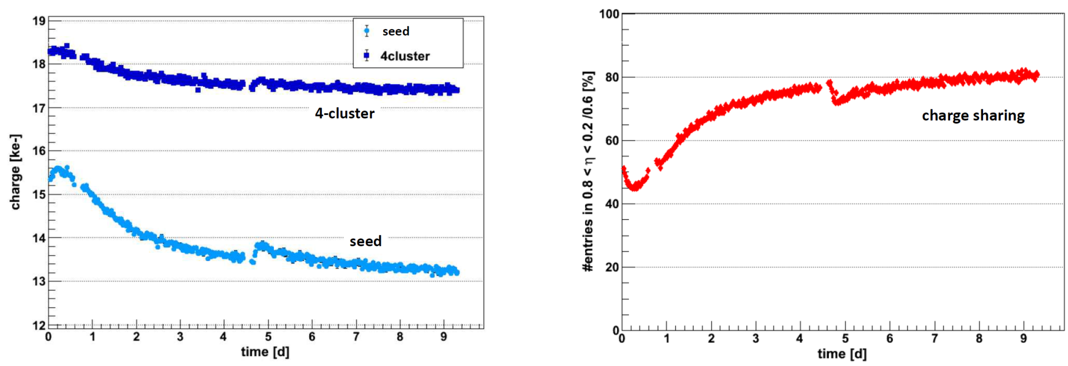
We first present results for the two non-hadron-irradiated sensors and then for the hadron-irradiated p-stop sensor. An explanation and discussion of the observations with the help of Synopsys-TCAD simulations which include surface charges at the Si-SiO_2 interface are given in Sect. 5.



(a) (b)

Figure 3: (a) PH(4-cluster) distributions for the non-irradiated p-stop sensor after exposure to β doses of 0 Gy (start of measurements), 10 Gy (after 0.2 days), 75 Gy (after 1.5 days), and 500 Gy (after 9.1 days). (b) The corresponding PH(seed) distributions.

Fig. 3a shows the pulse-height distributions of the 4-strip clusters, PH(4-cluster), and Fig. 3b the corresponding pulse-height distribution for the seed clusters, PH(seed), for the non-irradiated p-stop sensor fabricated on magnetic-Czochralski material, measured 0, 0.2, 1.5 and 9.1 days after the start of the measurements with the β source. The corresponding doses in the SiO_2 are 0, 10, 75 and 500 Gy. For PH(4-cluster) we observe Landau distributions with dose-dependent changes of the median of $+0.25, -2.5$ and -4.8 %, respectively. Significantly larger changes are observed for PH(seed): the median changes by $+1.7, -5.8$ and -14.0 %, respectively. In addition, the shape changes: the approximately triangular distribution with a maximum around 15 000 e changes to a distribution that is nearly flat between 7 500 and 15 000 e.



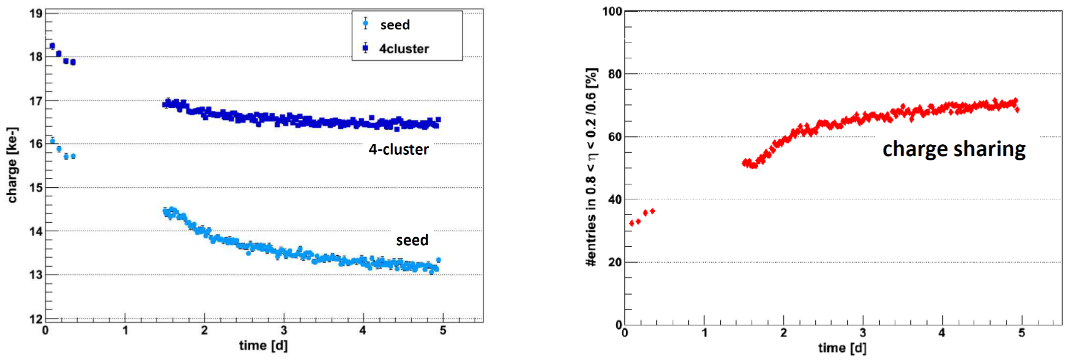
(a) (b)

Figure 4: (a) Median of the PH(4-cluster) and PH(seed) distributions for the non-irradiated p-stop sensor as function of the measurement time with the β source. The initial dose is 0 Gy, and the dose after 9.1 days 450 Gy. (b) Same as (a) for the charge sharing, *CS*, defined in text.

Fig. 4a shows the time dependence of the median of the PH(4-cluster) and PH(seed) distributions, and Fig. 4b of the charge sharing, *CS*, defined in Sect. 3. As a function of measurement time, the dose in the SiO_2 increases from 0 to about 500 Gy. For PH(4-cluster) we observe a constant value up to about 0.4 days, and then a steady decrease by about 5 %. For PH(seed) a much larger decrease by 15 % after an initial short term increase by 3 % is observed. *CS* is initially 52 %, 45 % at 0.3 days, and then steadily increases to 80 %. At 4.5 days the β source was put in the park position, and a calibration of the electronics and a voltage scan for pedestal and noise determination between 0 and 1000 V was performed. This is seen as a gap and a step in the time dependence.

A source scan along the strips on which the source had been centered for 9.5 days shows that the decrease in PH(4-cluster) and in PH(seed) is limited to the region where the source had been positioned and that outside this region no effects of the irradiation are observed.

To investigate a possible dose-rate dependence, measurements were performed with a 38 MBq source at a position, which had not been exposed to the β source before. It was found that, within the accuracy of the measurements, the results only depend on dose and not on the dose-rate.



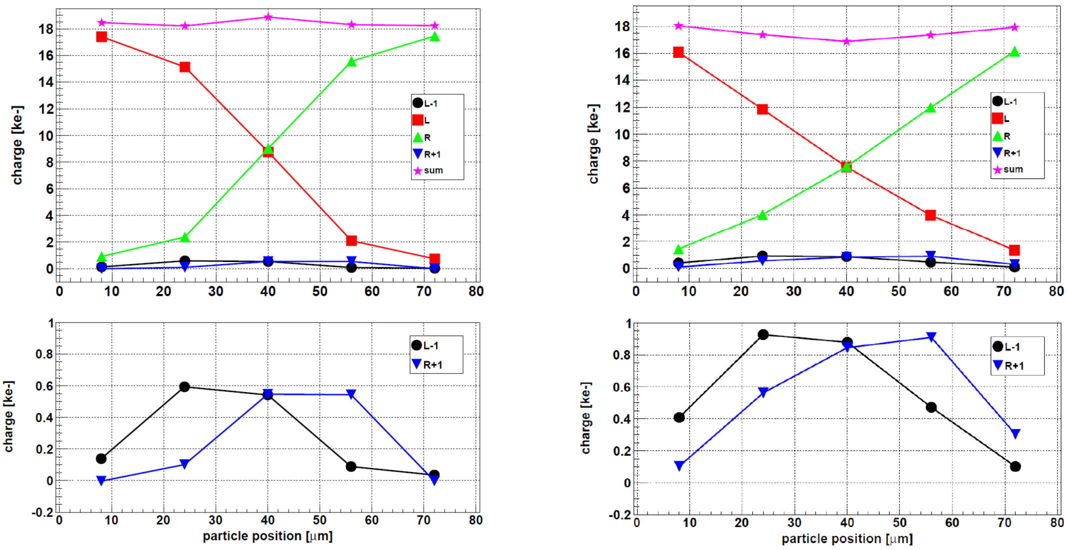
(a) (b)

Figure 5: (a) Median of the PH(4-cluster) and PH(seed) distributions for the non-irradiated *p*-spray sensor as function of the measurement time with the β source. The initial dose is 0 Gy and the dose after 5 days 250 Gy. Between 0.4 and 1.4 days the measurement was interrupted because of a problem with the nitrogen flow, required for avoiding ice on the sensor. During that time the sensor was exposed to the β source. (b) The corresponding time dependence for the charge sharing.

Fig. 5 shows the time dependence of the medians of PH(4-cluster) and PH(seed), and of the charge sharing, *CS*, for the non-irradiated *p*-spray sensor built on float-zone material. Data between 0.3 and 1.5 days are missing, as during this time the nitrogen flow was interrupted and the sensor was covered by an ice layer. Qualitatively the results are similar to the ones from the non-irradiated *p*-stop sensor: the median of PH(4-cluster) decreases by about 10 %, PH(seed) by 20 %, and *CS* increases from 30 % to 75 %. We note, however, that the initial short time change observed for the *p*-stop sensor, is absent for the *p*-spray sensor.

Next, the annealing behaviour was investigated for the *p*-stop sensor fabricated on magnetic-Czochralski silicon after a dose of about 800 Gy from the β source. The annealing temperatures chosen were -20, 20, 40, 60 and 80°C with typical annealing times of $18-24$ h. Only small changes were observed for PH(4-cluster): the biggest change was a decrease by about 3 % for annealing at 80 °C, which, however, quickly recovers after a few hours of exposure to the β source. The changes for PH(seed) are larger: a decrease by 3 % for 24 h at 60 °C and by 6 % for 18 h at 80 °C, which again recover quickly after irradiation with the β source. The charge sharing *CS* also shows significant changes: annealing increases the value of *CS*, which then decreases quickly after the sensor is irradiated again. After a long-term exposure of 3 days, the steady-state values shown in Fig. 4 at 9 days, are approached. It is clear that the observed behaviour is quite complex.

For the hadron-irradiated p-stop sensor fabricated on float-zone silicon measured at $-20\,^\circ$C at a voltage of 1000 V, we find the median of PH(4-cluster) to be 12.8 %, whilst that of PH(seed) is 11.2 % and that of CS is 16 % at the beginning of the measurements with the β source. PH(4-cluster) decreases by about 3 % during the 7.5 days of the measurement, which correspond to a β dose in the SiO_2 of 375 Gy. PH(4-cluster) steadily decreases by about 3 %, PH(seed) decreases by about 5 % and CS increases to 19 %. We conclude that for the irradiated sensor the effects are significantly smaller than for the non-irradiated sensors.



(a) (b)

Figure 6: Distribution of the medians of the pulse heights in the individual readout strips and PH(4-cluster) as function of track position for the p-stop sensor after a dose in the SiO_2 from the β source of (a) 10 Gy and (b) 500 Gy. The bottom plots show PH(L-1) and PH(R+1) with an expanded y scale.

As discussed in Sect. 3, the measured value of η allows the estimation of the distance, x, of the particle passage from the centre of the readout strip L and thus the investigation of the position dependence of the charge collection. Fig. 6 shows for the non-hadron-irradiated p-stop sensor fabricated on magnetic-Czochralski silicon PH(4-cluster), PH(L-1), PH(L), PH(R) and PH(R+1) as function of x for β source dose values of 10 and 500 Gy. Comparing the distributions we notice for the 500 Gy data in the region between the readout strips a decrease of PH(4-cluster) by about 12 % and an increase of the pulse induced in strips L-1 and R+1 from about 3 % to 5 %.

5. Discussion of the results

In this section we will give a qualitative explanation of the observations reported in Sect. 4. Significant changes of the charge collection are already observed after 0.2 days, when the ionizing dose in the SiO_2 at the maximum of the distribution is 10 Gy and NIEL, the non-ionizing energy loss, is $2 \cdot 10^7$ neq/cm^2. Given such a low NIEL value, bulk damage is excluded as an explanation, and charge build-up in the insulators and surface damage have to be considered.

The main effects of ionizing radiation in SiO_2 are the accumulation of positive oxide charges and the formation of interface traps at or close to the Si-SiO_2 interface [1, 9, 10].

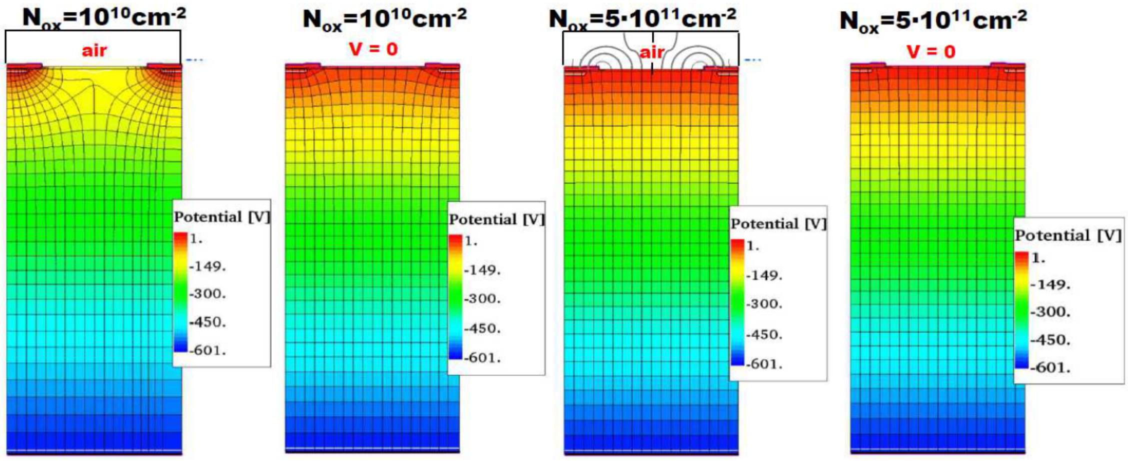


Figure 7: Simulated potential and electric field stream lines for a *p*-spray sensor with a *p*-spray doping of $2.5 \cdot 10^{11}$ cm^{-2} and oxide-charge densities of 10^{10} and $5 \cdot 10^{11}$ cm^{-2}, for the different surface boundary conditions discussed in the text.

In order to understand the influence of oxide charges and of the sensor-surface boundary conditions on the electric field in the sensor, a number of simulations using SYNOPSYS TCAD were carried out. The results are shown in Fig. 7, which shows the electric field stream lines and the potential for a sensor of thickness 200 µm, bias voltage of 600 V, bulk *p*-doping of $3.7 \cdot 10^{11}$ cm^{-3} and *p*-spray implant of $5 \cdot 10^{10}$ cm^{-2}. For the two simulations on the left side an oxide-charge density of $N_{ox} = 10^{10}$ cm^{-2} was assumed, and for the two simulations on the right side $N_{ox} = 5 \cdot 10^{11}$ cm^{-2} was assumed. Two different boundary conditions at the strip side were used: either a potential of 0 V on a plane at 500 µm distance from the sensor surface and zero charges on the sensor surface (denoted *air*), or a potential of 0 V on the sensor surface (denoted V= 0).

We note, that for the simulation with $N_{ox} = 10^{10}$ cm^{-2}, in particular for the *air* boundary condition, most field stream lines originate at the readout strips. Thus for a particle at normal incidence, practically all generated electrons will reach a single readout strip, and apart from a small effect due to charge diffusion, there will be no charge division.

For the simulation with $N_{ox} = 5 \cdot 10^{11}$ cm^{-2} the field distribution is very different, resembling the field of a pad diode. The reason is that the *p*-spray implant of $2.5 \cdot 10^{11}$ cm^{-2} is overcompensated by the charge density N_{ox}, resulting in an approximately constant potential at the Si-SiO_2 interface and thus in a small electric-field component parallel to the interface. Therefore electrons, which reach the Si-SiO_2 interface within the typical charge collection time of a few nanoseconds, will drift to the read-out strips on a much longer time scale. If this time scale is long compared to the integration time of the readout electronics, which was about 25 ns, the electrons are effectively trapped at the Si-SiO_2 interface, and signals will be recorded not only on strips L and R, but also on strips L-1 and R+1, as seen in Fig. 2, and even on strips beyond.

6. Summary and Outlook

It is observed that a dose from a β source as low as 10 Gy significantly influences the charge collection and charge sharing in segmented n^+p sensors. This can be explained by the build up of positive charges in the oxide layers, which can overcompensate the p-implants used to isolate the n^+-implants of the segmented electrodes. The effects are significantly smaller for sensors after hadron irradiation. Annealing effects are observed. However, the effects are small. The study shows the importance of taking both bulk and surface damage into account when designing silicon sensors for a high-radiation environment like for the HL-LHC.

The impact of changes in charge sharing and charge losses on the performance of silicon sensors with high spatial resolution depends very much on the type and performance of the readout electronics. For analogue readout with good signal-to-noise-ratio (S/N), charge sharing can be used to achieve an optimum spatial resolution. If the S/N is poor and a relatively high threshold has to be set, reaching high detection efficiencies will be difficult. For a strip sensor with 80 μm pitch the pulse height of the seed strip is frequently smaller than 50 % of the most probable value (mpv) of the cluster pulse-height distribution. Therefore to reach high efficiencies, the pulse-height threshold has to be below 0.4 mpv. If the pulse-height threshold is set at 3 times the variance of the noise, a S/N value of at least 7.5 is required. If binary readout is used, the setting of the threshold requires a careful optimization with respect to noise hits, efficiency, cluster size and position resolution.

References

[1] J. Zhang, I. Pintilie, E. Fretwurst, R. Klanner, H. Perrey and J. Schwandt, *Study of radiation damage induced by 12 kev X-rays in MOS structures built on high-resistivity n-type silicon*, Journal of Synchrotron Radiation 19 (3): 340−346, 2012.

[2] J. Erfle, *Irradiation study of different silicon materials for the CMS tracker upgrade*, PhD thesis, University of Hamburg, DESY-THESIS-2014-010, 2014.

[3] C. Henkel, *Charge losses in silicon strip sensors after in-situ irradiation with a β source*, BSc thesis, University of Hamburg, 2014, unpublished.

[4] A. Dierlamm for the CMS Tracker Collaboration, *Characterisation of silicon sensor materials and designs for the CMS Tracker Upgrade*, PoS (Vertex 2012) 016.

[5] R. Marco-Hernandez, *A portable readout system for microstrip silicon sensors*, Nuclear Instruments and Methods in Physics Research A 623(1): 207−209, 2010.

[6] S. Müller, *The Beam Condition Monitor 2 and the Radiation Environment of the CMS Detector at the LHC*, Note: CMS-TS-2010-042 (2010).

[7] I. Dawson, *Radiation background simulation and verification at the LHC: Examples from the ATLAS experiment and its upgrades*, PoS (Vertex 2012) 015.

[8] E. Belau, et al., *Charge collection in silicon strip detectors*, Nuclear Instruments and Methods in Physics Research 214(2-3): 253−260, 1983.

[9] T.P. Ma and P.V. Dressendorfer, *Ionization Effects in MOS Devices and Circuits*, John Wiley & Sons, New York, 1989.

[10] T.R. Oldham, *Ionization Radiation Effects in MOS Oxides*, World Scientific Publishing Co. Pte. Ltd., Singapore, 1999.

PoS(TIPP2014)040