On the cutting edge of semiconductor sensors: towards intelligent X-ray detectors
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Active-edge sensors: performance of edge pixels

In the previous chapter, the electrical characteristics of active-edge sensors were studied. The results show that the distance between the active area and the sensor’s physical edge can be reduced to tens of micrometers without significantly affecting the leakage current in the active area.

This chapter studies the performance of the outer pixels of active-edge pixel sensors. Due to the edge implant, the electric field is locally distorted, which affects the detection properties of the pixels close to the edge.

In the first part of this chapter, the response functions of these pixels are measured using strongly focussed laser light of two different wavelengths. In the second part, their effective volume is reconstructed by studying the amount of collected charge as a function of the interaction depth.

5.1 Sample specifications

Silicon pixel sensors (fabricated by VTT Micro and Nano-electronics) of 150 µm thick with an edge distance of 50 µm are the subject of this study. In contrast to the structures examined in Chapter 4, these sensors have a doped edge across the entire thickness of the sensor. The pixel configuration is n-in-n, which makes the back side and edge of p-type.

The pixel matrix layout follows that of Medipix-2. Figure 5.1(a) schematically shows the process steps in which the active edges were realised. While on a support wafer, the sensors were separated by means of inductively coupled plasma etching. This allowed for edge implantation with boron atoms on the wafer level. At the back side, no aluminium electrode was deposited. Instead, it was heavily doped \(10^{20} \text{ cm}^{-3}\) with boron atoms. This benefited the quality of the sensor-separating trench and it kept the thickness of the entrance window at the back at a minimum, which allowed for detection of infra-red light (which will be used for the measurements presented).

\[1\text{VTT Micro and Nano-electronics, Tietotie 3, Espoo, FI-02044 VTT, Finland. } \text{http://www.vtt.fi} \]
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![Diagram of edge implantation and sensor specifications](image)

**Figure 5.1: The detector module**

(a) Schematic representation of the edge processing step. The sensors were separated by means of inductively coupled plasma etching and subsequently doped with boron atoms using an angled ion implantation process. (b) Two edgeless-Timepix assemblies mounted side-by-side on the quad carrier board. Due to its larger size, the Timepix chip extends from underneath the sensor. Consequently, there is a small gap of approximately 72 µm wide between the adjacent edges of the sensors.

in Section 5.3.1. Two of such sensors were mounted on Timepix read-out chips and the assemblies were subsequently juxtaposed on a quad-carrier board. The side-by-side configuration was chosen to conduct the measurements on the interaction-depth dependence of the collected charge, which will discussed in more detail in Section 5.3.2. Figure 5.1(b) shows a picture of the detector module together with a close-up view of the adjacent-edge region. Because of the larger area of the Timepix chips, due to the relaxed dicing margin that was used, there is small gap of approximately 72 µm wide between the two sensors. To check the electrical integrity of the sensors, their current-voltage characteristics were measured. The main parameters are listed in Table 5.1 together with the sensor specifications. For comparison with the results of Chapter 4, the currents are given for a bias voltage of 50 V. The measurements presented hereafter, however, are made at 40 V sensor bias.
Table 5.1: Sensor specifications and leakage-current characteristics.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch</td>
<td>55 µm</td>
</tr>
<tr>
<td>Type</td>
<td>n-in-n</td>
</tr>
<tr>
<td>Thickness</td>
<td>150 µm</td>
</tr>
<tr>
<td>Edge distance</td>
<td>50 µm</td>
</tr>
<tr>
<td>Full-depletion voltage</td>
<td>∼ 14 V</td>
</tr>
<tr>
<td>Break-down voltage</td>
<td>∼ 140 V</td>
</tr>
<tr>
<td>Leakage current-density (50 V)</td>
<td>∼ 60 nA/cm²</td>
</tr>
<tr>
<td>Generation current (50 V)</td>
<td>∼ 84 nA</td>
</tr>
<tr>
<td>Surface current (50 V)</td>
<td>∼ 11 nA</td>
</tr>
<tr>
<td>Surface current / Generation current (50 V)</td>
<td>∼ 0.13</td>
</tr>
</tbody>
</table>

5.2 Simulations

After equalisation of the discriminator thresholds of the Timepix pixels, the detector was homogeneously irradiated (so called flood-field irradiated) with a polychromatic X-ray beam of 30 keV mean energy to examine the response homogeneity across the active area. The output image is shown in Figure 5.2. Noticeably, the pixels of the three outer columns show an anomalous response with respect to more central pixels. This can be explained by the distribution of the electric field at the edge. Figure 5.3 shows TCAD simulations (see Appendix B) of the potential distribution at the edge of such sensors at different bias voltages. They show that the field at the edge alters the effective volume of the outer pixels. The ratio between their effective volume and that of the bulk pixels is indicated in the figure. At 10 V, the effective volume of the outermost pixels is reduced to approximately 55 % of the volume of bulk pixels, while their physical volume is ∼ 66 % larger. This reduction translates into an increase of the effective volume of the second outer pixels. At higher bias voltages, the difference between the effective volumes of pixels of the first and second column decreases. Moreover, the simulations show that the effective area of the outer pixels is depth dependent.

How the distortion affects the performance of edge pixels, is studied by means of sub-pixel position-defined measurements on the charge collection. In Section 5.3.1, strongly focussed laser light of two different wavelengths is used to determine the edge-pixel response functions for charge generated in two different interaction volumes. In addition, an estimate is made of the edge of the sensitive volume relative to the physical edge of the sensor.

[^2]: Here, and for all results presented hereafter, the response refers to the time-over-threshold information of the Timepix chip, i.e. the amount of collected charge.
Figure 5.2: Flood-field image
A flood-field image of both sensors. The anomalous response of the two outermost pixel columns and rows becomes immediately apparent. This can be ascribed to the distorted electric-field distribution at the edge.

In Section 5.3.2 the profile of the effective volume is reconstructed by means of interaction-depth defined measurements on the amount of collected charge that is induced by high-energy muons and pions.

5.3 Results

5.3.1 Laser measurements

Strongly focussed laser light of two different wavelengths was used to measure the response functions of the outermost pixels. Figure 5.4 schematically shows how the measurement was conducted. A narrow beam of laser light was used to generate charge very locally. Subsequently, the amount of charge collected by the illuminated pixel(s) was studied as a function of the laser spot’s position, which results in a map of the pixel response at the sub-pixel level.

Set-up

Sub-pixel precision was achieved with a moveable X-Y stage for detector positioning with one micrometer resolution. The output intensity of the laser was controlled by a pulse generator and guided via an optical fibre to a focussing lens to achieve a minimum spot size of 9 µm. The lens itself was attached to a moveable Z stage, also with micrometer precision.
For the determination of the laser’s position relative to the pixel matrix, the detector was first placed in focus by minimising the size of the induced cluster, which varied from a maximum of approximately 100 pixels at 12 mm from the focal point to a minimum of one pixel in focus. Next, the laser position was derived by monitoring the response of the surrounding pixels as the detector was translated in x and y. To minimise the translational error on the measurement, the alignment procedure was always carried out in the region close to pixels under test.

On the right-hand side of Figure 5.4, the settings and corresponding photon input per acquisition are denoted for the results presented below.
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Figure 5.4: Pixel scanning
Laser light of two different wavelengths is used to scan the individual pixel response with sub-pixel resolution at two different interaction depths. The laser settings and the corresponding photon input rates are listed on the right-hand side of the figure.

Centre pixels
Before the edge was studied, the response functions of central pixels were measured. From this, the diameter of the observed part of the laser-induced charge cloud was derived. Figure 5.5 shows the fraction of collected charge as a function of the position of the laser (976 nm wavelength) relative to the pixel borders at 40 V reverse bias. It demonstrates that at about 6 µm from the pixel centre the adjacent pixel starts to respond, which implies a diameter of the observed charge cloud of approximately 43 µm. This is, to some extent, in agreement with the expected width, since the $3\sigma$ diffusion width (see Equation C.5) for 145 µm drift length at 40 V bias is approximately:

$$3\sigma = 3\sqrt{\frac{2kTd^2}{qU}} = 15.6 \mu m,$$

and the minimum focal spot size is approximately 9 µm. This equals to a charge cloud diameter of $(2 \times 15.6 + 9) \mu m \approx 40 \mu m$. The difference with the observation could be explained by: (i) an under-estimation of the spot size and/or (ii) an under-estimation of the diffusion, which may be larger than $3\sigma$ for high intensities.

Edge pixels
Similar measurements were performed on edge pixels. To study the depth dependence of the effective area, both photons of 683 nm and 976 nm wavelength were used to deposit
charge across two different penetration depths. Table 5.2 gives the absorption coefficients ($\alpha$) and the corresponding $1/e$ absorption depths in silicon, which are determined by the energy of the photon as well as the band gap of silicon (1.12 eV). For 683-nm laser light, photons are predominantly absorbed close to the back side of the sensor ($\sim 5 \mu m$), while photons of 976 nm wavelength penetrate silicon considerably deeper ($\sim 100 \mu m$).

Figures 5.6(a) and 5.6(b) show the response functions of the five outer pixels for both wavelengths. The physical edge is positioned at 0 µm. The laser was scanned from the centre of the fifth pixel towards the edge with decreasing step size and the collected charge was assigned to the laser’s spot centre position with respect to the physical

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>E (eV)</th>
<th>$\alpha$ (cm$^{-1}$)</th>
<th>$1/e$ abs. depth (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>683</td>
<td>1.82</td>
<td>$\sim 2.2 \cdot 10^3$</td>
<td>$\sim 4.5$</td>
</tr>
<tr>
<td>976</td>
<td>1.27</td>
<td>$\sim 9.6 \cdot 10^1$</td>
<td>1.0 - $10^2$</td>
</tr>
</tbody>
</table>
5. Active-edge sensors: performance of edge pixels

![Figure 5.6: Edge-pixel response function](image)

The amount of collected charge as a function of the laser’s spot-centre position relative to the physical edge, for both (a) 683 nm photons and (b) 976 nm photons.

edge. It clearly shows the difference between the mean effective area of edge pixels and that of non-edge pixels for two different interaction depths. From the response functions, the effective volume of each pixel is derived by integrating the mean amount of collected charge integrated over the effective width. Table 5.3 lists the volumes normalised to that of the fourth pixel from the edge. In agreement with the simulations on the profile of the effective volume as depicted in Figure 5.3, the difference between the effective volumes of the two outer pixels becomes smaller as the wavelength increases. Also, the sum of the normalised effective volumes of the three outer pixels is given in Table 5.3.

Table 5.3: The effective volume of pixels of the three outermost columns normalised to that of pixels of the fourth column from edge. The values are derived from the mean amount of collected charge for both wavelengths.

<table>
<thead>
<tr>
<th>Pixel column</th>
<th>( \frac{V_{\text{eff}}}{V_{\text{eff}}(\text{pixel 4})} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( 683 \text{ nm} )</td>
</tr>
<tr>
<td>1</td>
<td>0.36</td>
</tr>
<tr>
<td>2</td>
<td>1.93</td>
</tr>
<tr>
<td>3</td>
<td>1.23</td>
</tr>
<tr>
<td>4</td>
<td>1.00</td>
</tr>
<tr>
<td>1+2+3</td>
<td>3.52</td>
</tr>
</tbody>
</table>
this value, the edge of the sensitive volume (see Figure 5.4) relative to the physical edge can be estimated. The physical width of the three outer pixels is $3 \cdot 55 + 36.5 \, \mu\text{m} = 201.5 \, \mu\text{m}$ (see Figure 5.3). Consequently, for each wavelength an inactive volume with the following width is derived:

\[
(201.5 - 3.52 \cdot 55) \, \mu\text{m} \approx 8 \, \mu\text{m} \quad (683 \, \text{nm})
\]

\[
(201.5 - 3.62 \cdot 55) \, \mu\text{m} \approx 2 \, \mu\text{m} \quad (976 \, \text{nm})
\]

The larger width obtained from the data taken with the 683 nm laser can only be explained by a loss of charge in the edge region.

![Figure 5.7: Mean edge response](image)

The mean response of pixels of the 20 outer columns to tens of thousands of tracks of high-energy particles. From this, the total effective volume of pixels of the six outer columns was determined, which allowed for deriving the edge of the sensitive volume with respect the physical edge.

Figure 5.7 shows the mean response of pixels of the 20 outermost columns to tens of thousands of tracks of high-energy particles, which were used for the study presented in the next section. From this, it is derived that the edge of the sensitive volume is approximately 12 µm from the physical edge:

\[
(201.5 - 3.44 \cdot 55) \, \mu\text{m} \approx 12 \, \mu\text{m}
\]

The discrepancy between this result and that of the laser measurements can be explained by the fact that part of the charge deposited by the muons is not detected by the pixels, simply because it is below the threshold value of the pixel. The mean energy loss of a minimum ionising particle is 3.9 MeV/cm, which means that the particle’s path length through the pixel should be at least 10 µm in order to be detected.

\[36.5 \, \mu\text{m} \text{ is the width of the extra sensor volume at the edge.}\]
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5.3.2 Test-beam measurements

The depth dependence of the charge collection was studied further at the SPS H6 test beam facility at CERN. By using finite-length tracks of 120 GeV/c muons and pions that cross the two adjacent sensor edges in the centre of the module, the interaction depth could be reconstructed and related to the amount of collected charge in edge pixels.

Set-up

To determine the interaction depth at a given pixel, it is necessary to reconstruct the track in three dimensions. The left part of Figure 5.8 shows a schematic representation of the detector’s positioning relative to the beam. It was placed almost parallel to the beam, as a result of which particles traversed both sensors (only 150 µm thick) nearly parallel to the pixel planes. A small elevation angle benefited two-dimensional track reconstruction, whereas a shallow inclination angle (see side view) provided long but finite-length tracks, the entrance and exit point of which was used for reconstructing the third dimension. An exemplary frame for the study presented below is shown in the right part of Figure 5.8. Most tracks consist of approximately 140 pixel hits. Both coordinate axes and the beam direction are indicated in the figure as well. For convenience in the discussion below, the sensors are labelled Left and Right. Hence, particles entered at the right sensor’s back side and exited the pixel plane of the left sensor.

Tracks that are contained in one sensor are being referred to as single-sensor tracks, while tracks that traverse both sensors and thus cross the adjacent-edge region in the centre of the module are called double-sensor tracks. No trigger was used. Acquisition of 5 ms frames was controlled by the software.

Track finding

Every event frame was stored as an integer array of hits. Each element contains the position and the amount of collected charge of each individual hit. As many frames contain more than one track, a track finding algorithm was used to isolate individual tracks for further study. The hits of each frame were sorted such that possible tracks formed sub-sequences of elements in the hit array. The arrows in Figure 5.9 indicate the hit order after sorting. Every sub-sequence was then selected by looping over the array elements and applying a selection criterion on the maximum difference between the coordinate values of consecutive hits. A hit was considered to be part of a sub-sequence, if its position with respect to the previous hit differed no more than 2 pixels in the y-direction and less than 10 pixels in the x-direction. The latter criterion was determined by checking the number of double hits between single-hit segments for a given elevation angle. As soon as the criterion on the consecutive hit position was not met, the sub-sequence was selected as a track candidate if its length was larger than 100. If not, the sub-sequence was excluded from further analysis.
Figure 5.8: Detector orientation
A schematic representation of the detector’s orientation with respect the beam direction is shown on the left side. The right-hand side shows a typical event frame containing six tracks, one of which crosses the adjacent-edge region in the middle. Due to a small elevation and inclination angle, tracks could be reconstructed in three dimensions. The xy-dimensions of the left figure scale 1:1 with the real dimensions. The sensor thickness and event frame are enlarged for better viewing.

|Δx| > 10 && |Δy| > 2 => end of array
If array > 100, store as track candidate

Figure 5.9: Track finding
Tracks were found by sorting the hits of each frame such that sub-sequences in the hit array could be selected. The arrows indicate how the hits were sorted, which allowed for hit selection by applying restrictions to the distance between consecutive hits. Sub-sequences of more than 100 hits were selected as track candidates.

Track fitting
As discussed above, tracks of particles that cross the adjacent-edge region in the centre of the module allow for reconstruction of the interaction depth at edge pixels. The depth was derived from the length of the track projected onto the pixel plane. Figure 5.10 shows, however, that the true track is longer than only the difference between the pixel coordinates at which the particle enters and exits the sensors. In addition, each particle had to bridge a small gap between the sensors, the width of which varies in the y direction due to a slight angular displacement. As a result of the gap and displacement, tracks crossing

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5. Active-edge sensors: performance of edge pixels

the edge region show a discontinuity. To reconstruct the gap width, each track was split into a left and a right segment, which were separately fitted using a linear least-squares fitting algorithm.

The fitting algorithm was tested using single-sensor tracks. Every track was halved into two segments, which were each fitted up to the third pixel from the track-centre’s x-coordinate (to match the fitting conditions of the double-sensor tracks discussed below). Figure 5.11(a) shows a close-up view of a track in the right sensor together with fits to each of the segments. As denoted in Figure 5.9 for double hits the particle’s y-position was interpolated using the amount of charge collected in both pixels. The angular distributions for both left and right segments of more than 80 thousand tracks are plotted in Figure 5.11(b). It shows there is an almost negligible difference between the mean values of both distributions of approximately 18 µrad, which indicates good-quality fits. To evaluate the quality of fits, the residuals of more than 40 million hits are plotted in

\[4\] This method finds a linear function that best fits the hit pattern by minimising the sum of squares of the hit residuals in the y-direction.
Figure 5.11(c). They are nicely distributed around zero and only a small fraction of hits shows values of more than half a pixel, which may attributed to delta-electrons. The black line shows the residuals of the hits of charge shared events. Moreover, the coefficient of determination of the segment fits were determined, the distributions of which are plotted in Figure 5.11(d). This quantity expresses the proportion of the variance in the hits’ y-positions that can be explained by the fit function and is therefore a measure of the goodness of fit. Approximately 81% of the tracks show fits to both segments with a coefficient of determination higher than 0.8.

After evaluating the fit quality, double-sensor tracks were studied to determine the gap width. Each track was split into a left-sensor and right-sensor segment as shown in Figure 5.12. The angle of the individual segments was then used to correct for the angular displacement and to subsequently reconstruct the particle’s path length between the sensors. To avoid the anomalously responding and larger edge pixels to negatively affect the fit, only hits up to the fourth column from the edge were used. The angular distributions of both left and right segments of approximately 10,000 tracks are shown in the centre-left plot. From the means of the Gaussian fits to the distributions, an angular displacement of 0.27 mrad is derived. This translates into a gap-width increase along the y-axis of approximately 4 µm, which is in good agreement with microscope measurements that show a gap-width difference of around 2 µm between the top and bottom of the sensors. The corrected angular distributions are shown in the centre-right plot.

After correction, the segment fits were extrapolated to the edge, in order to determine the difference in y at the edge of both sensors. Using the angle of its right segment, the path length between the sensors was reconstructed. The extra 128 µm that is added to the gap width in the top figure, accounts for twice the edge distance of 50 µm plus two times radius of the pixel implant of 14 µm (see Figure 5.3). Distributions of the difference in y before and after angle correction are plotted at the bottom of Figure 5.12. A mean value of 0.156 pixels difference in y-position is derived. This translates into a gap of approximately

$$\frac{0.156}{\tan(0.0428)} \approx 55 \, \mu m = 72 \, \mu m \, \text{wide},$$

which shows excellent agreement with the measurements made with the microscope (see Figure 5.1(b) on page 94).

For both the fit-quality study and the detector alignment, only tracks with segments containing more than 40 hits were used. Moreover, for the detector alignment a cut of 0.8 was applied on the coefficient of determination.

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5 The coefficient of determination takes values between 0 and 1, which describes how well a regression fits the data. A coefficient of determination close to 1 indicates that the line fits the data well.
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Figure 5.11: Single-sensor tracks

(a) A close-up view of the centre of a single-sensor track, together with fits to each of the segments. (b) The angular distributions of each segment, which show an angular difference of approximately 18 µrad. (c) The distributions of the perpendicular residuals to the fits. The residuals of the weighted hits of charge shared events are indicated by the black line. (d) The distributions of the fits’ coefficient-of-determination.
Figure 5.12: Detector alignment

Top: Each track was split into a left-sensor and a right-sensor segment, which were separately fitted. This allowed for correction of the angular displacement between the sensors and subsequent determination of the gap width.

Centre: The angular distributions of the left and right segments before and after angle correction.

Bottom: The distributions of the difference in y-position between the extrapolated fits to each of the segments before and after angle correction.
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**Interaction-depth dependence**

After sensor alignment, the interaction depth at edge pixels was determined. To analyse the entire depth of the sensor, tracks with a minimum segment length of 5 pixels in either one of the two sensors were used. Subsequently, the path length between the sensors was determined by using the angle of the longest segment (corrected in case of left segments) and a constant value of 72 µm for the gap width. This path length was added to the differential distance between the entrance and exit pixel. Figure 5.13(a) depicts the situation at the edge: by relating the interaction depth to the amount of collected charge, which is dependent on the effective pixel size at a certain depth, the electric-field distribution can be reconstructed. These tracks entered the right sensor and exited the left.

Figure 5.13(b) shows the amount of collected charge as a function of the interaction depth for both sensors. Clearly, the outermost pixels measure a smaller amount of charge at the sensor’s back side than more central pixels, while the opposite is true for the second outer pixels. As expected, the amount of collected charge in pixels of the third and fourth column is virtually constant across the entire sensor depth. The error on the collected charge is largest at the back side of the left sensor and at pixel side of the right sensor. This is due to the fact that these points are derived from tracks with a small segment in the corresponding sensor. Moreover, there are a number of oddly responding pixels at the edge of the left sensor, as can be seen in the flood-field image of Figure 5.2. Nevertheless, the reconstruction does show that the potential distribution closely matches that of the simulations, which is even more clearly depicted in Figure 5.13(c). It shows the accumulated amount of charge collected by pixels of the four outer columns. This summed amount is proportional to the path length through the effective part of the corresponding pixels. The resemblance with the field lines that separate the pixels from each other is clear, which emphasises the excellent accordance to the simulation. The anomalous response of edge pixels is therefore understood and simulations may be used for correction.

**Correction**

An example of such a correction is shown in Figure 5.14. The top figure shows a raw image of an anchovy, whereas the bottom part shows the image taken after a flat-field correction was applied. Clearly, the anomalous response at the edge is eliminated. The correction procedure calibrates the response of each individual pixel with respect to the mean response over the entire detector area. First, a large number of images is taken under open-field conditions, i.e. homogeneous irradiation. Subsequently, the response of each individual pixel is normalised to the mean count-rate density of the average of the open-field images. This results in a so called flat-field map, which can be applied to the raw image in order to equalise the response. As will be discussed in Chapter 6, the effectiveness of the procedure depends largely on the response variance of the raw image as well as the number of open-field images used to create the correction map.
Figure 5.13: Interaction-depth dependence

(a) Particles traversed the edge pixels at different depths. This allowed for a determination of the effective pixel area at various depths across the sensor. (b) The amount of collected charge as function of interaction depth for pixels of the four outer columns. The mean values are scaled to those of pixels of the fourth column. (c) By plotting the cumulative amount of collected charge, which corresponds to path length through the effective part of the pixels, the pixel-separating field lines are revealed.
Figure 5.14: Correction
A raw image of an anchovy taken with a single detector assembly, which contains a sensor that is equal to those used for the study presented in this chapter. The bottom part shows the same image after flat-field correction. Figure from [84].
5.4 Conclusion

In this chapter, the performance of edge pixels of active-edge silicon sensors has been studied. Two complementary measurements were made to determine the sensitive volume at the edge as well as to study the interaction-depth dependence of the amount of collected charge.

The edge-pixel response functions obtained by the 683-nm laser and those measured with the 976-nm laser show a clear difference in the distribution of the collected charge among the pixels. They show a reduction of the effective area of pixels closest to the edge and an increase of that of the second outer ones in the direction towards the back plane. From the summed amount of charge collected by the three outer pixels, the width of the inactive region at the edge was derived. The data taken with the 976-nm laser indicate that the edge of the sensitive volume and the physical edge are only 2 µm apart.

A similar analysis was carried out with data from high-energy muons that traversed the sensor almost parallel to the pixel planes and indicate an inactive width of approximately 10 µm. The discrepancy between this result and that of the laser measurements can be explained by the fact that part of the charge deposited by the muons is not detected by the pixels, simply because it is below the threshold value of the pixel.

The long tracks of the high-energy particles were also used to determine the depth dependence of the effective pixel area. Tracks that crossed the adjacent-edge region were reconstructed in three dimensions to determine their length through the sensor, from which the local interaction depth was determined. By relating the interaction depth to the amount of collected charge, the effective area of edge pixels was reconstructed for various depths across the sensor.

The results are in good agreement with simulations on the electrostatic potential distribution at the edge, which show that the effective volume of the outer pixels is different from their physical volume due to a distortion of the electric field that is caused by the biased edge implant. As expected, this alteration and therewith the depth profile of the effective volume of edge pixels is bias-voltage dependent. The resemblance with the results shows that the simulations are realistic and hence can be used for correction of the non-uniform response at the edge. The effectiveness of the correction, however, is largely dependent on variance of the response over the entire detection area. For shallow interactions and low bias voltages, the ratio between the effective volume of the pixels closest to the edge and that of the second outer ones is significantly larger than for deep interactions at high bias voltages. Nonetheless, the good understanding of the anomalous response of edge pixels allows for a first-order correction and is a step forward to a seamlessly responding tessellation of detector modules.