Study of edgeless radiation detector with 3D spatial mapping technique

X. Wu, a,1 J. Kalliopuska, a,b M. Jakúbek, c J. Jakúbek, c A. Gädda a and S. Eränen a

a VTT, Microsystems and Nanoelectronics, Tietotie 3, Espoo, P.O. Box 1000, FI-02044 VTT, Finland
b Advacam Oy, Tietotie 3, Espoo, FI-02150, Finland
c Institute of Experimental and Applied Physics, Czech Technical University in Prague (IEAP-CTU), Horska 3a/22, CZ 12800 Prague 2, Czech Republic

E-mail: xiaopeng.wu@vtt.fi

ABSTRACT: Edgeless radiation detector has gained increased attention due to its superiority in the defect-free edge fabrication and the capability to minimize the insensitive area at the detector edge. The doped edge in the edgeless detector is at the same potential with the back plane and causes a local distortion of the electric field at the detector edge. The deformed electric field alters the charge collection of the edge pixel and leads to an inaccurate charge interpolation. To study the influence of active edges on the response of edge pixels, we used an advanced X-ray based 3D spatial mapping technique to visually show the charge collection volumes of pixels. Various edgeless detectors with diverse polarities, thicknesses and edge-to-pixel distances were investigated. For the n-on-p (n+/p−/p+) edgeless detector, the mapping shows that the p-spray isolation method has the advantage of achieving a greater sensitive edge region compared to the p-stop method. And the p-on-p (p+/p−/n+) edgeless detector, reported for the first time, functions for both spatial and energy signals. The n-type edgeless detectors were studied together with a standard Medipix detector with the guard ring design. The results show that the edgeless detector is capable of maximally utilizing the edge region of the detector as the charge sensitive volume, while the standard Medipix detector has still vast insensitive region at the edge. The X-ray spectroscopic measurements with 241Am and 55Fe sources performed on all detectors gives a similar conclusion and proves the 3D spatial mapping results.

KEYWORDS: Solid state detectors; X-ray detectors; Particle tracking detectors (Solid-state detectors)

1 Corresponding author.
1 Introduction

Edgeless (active edge) silicon pixel detectors have been of great interest for the radiation detection community, with their superiority in minimizing the insensitive edge region and enabling the construction of a large-area camera by tiling them towards four sides. To obtain the active edges, one way is to separate the sensor with plasma etching and introduce dopants to the sides of the sensor by ion implantation [1]. Saw dicing is therefore not needed and a smooth defect-free edge is achieved. In the edgeless detector, the guard rings (GR) or the current terminating structure (CTS) can be totally omitted whilst the leakage current remains in the range of several nA/cm² [2]. The absence of the GR/CTS and the perfect edge fabrication enable the segmented electrode to be placed close to the detector edge, reducing the pixel-to-edge distance and therefore the insensitive volume at the detector borders. When properly designed, the insensitive region at the edge of the detector can be theoretically controlled below one micrometre, which is mainly caused by the silicon sidewall passivation and the highly doped region at the detector edge.

As to the edgeless detector, the edge sensitivity is of great importance. The conventional detector has a homogeneous electric field uniformly distributed between the segmented electrodes and the back plane. In the edgeless detector, however, the doped edge has the same potential as the back plane, and deforms the electric field locally near the edge. Depending on the applied bias voltage and the design of the detector, the deformed electric field may alter the charge collection volume of one or several pixels close to the edge. As a result, the charges generated in the volume vertically under one pixel might be collected by its neighboring pixels, which results in the inaccurate charge interpolation that degrades detection efficiency and position resolution of the detector close to the physical edge.

In many applications, the radiation detector requires a bias voltage higher than the depletion voltage (V_{dep}) to ensure the maximum depleted volume inside the silicon bulk. A voltage lower or dramatically higher than the V_{dep} leads to either a low detection efficiency or a high power consumption as well as a low operational reliability (the risk of breakdown). At the desired bias voltage, it is preferred to have the whole edge of the detector sensitive to the ionizing radiation,
to avoid any loss of the inspected signal. Therefore, a clear mapping of the charge collection volume distribution inside the detector is desired and essential for maximizing the charge collection efficiency at all regions of the detector.

The charge collection performance close to the edge of the radiation detector has been widely studied with TCAD simulations [3–5]. The simulations reveal visually the distribution of the electric field as well as the depleted volume in the silicon bulk. However, the result strongly depends on the device modelling and the technology parameters used, which results in different simulation conditions from study to study and difficulties as examining the results.

In this work, a novel 3D spatial scanning [6] has been used for various edgeless silicon detectors, providing images that show the real charge collection volumes in the bulk of the detector. The scanning is based on X-ray measurement and does not need any input of the device modelling or the technology parameters. It gives a straightforward and quick way to reveal the charge collection inside the silicon bulk and to study the differences of detectors of various designs.

## 2 Detectors

The detectors in the study are edgeless pixel detectors. One standard 300 µm thick Medipix [7] p-on-n (p⁺/n⁻/n⁺) detector was measured at the same time as a reference. All detectors have a matrix of 256 × 256 pixels with a 55 µm pitch. Sensors were hybridized on the Timepix [8] readout chips. There are guard rings on the reference Medipix detector but not on the edgeless detectors. The fabrication and hybridization of the edgeless detector were done at VTT and Advacam (Advacam is a spin-off company of VTT). The process and the basic electrical characterization of these edgeless detectors were published in [9]. Table 1 lists all the variations of the investigated edgeless detectors.

The hybridized detector modules were assembled on a stack PCB board [10]. The data acquisition was performed utilizing the FITPix [11] USB interface and the Pixelman [12] software. All measurements were performed at the lab of IEAP-CTU in Prague.

## 3 3D spatial mapping

As shown in figure 1, the 3D scanning system is based on a collimated X-ray source, a lead slit with an adjustable window and a motor-controlled detector holder. The X-ray tube is a Hamamatsu L8601-01 micro-focus source with a 5 µm focal spot size and a tungsten target, and it operated at 55 kV and 179 uA. A 1 mm thick aluminum filter was used for the measurement of 100 µm detectors and a 4 mm thick aluminium filter for 300 µm detectors. The lead slit between the X-ray source

| Polarity     | Thickness (µm) | Edge-to-pixel distance (µm) | 3D scanning | X-ray spectroscopy |
|--------------|----------------|-----------------------------|-------------|--------------------|
| P-on-N       | 100            | 20, 40, 60, 80              | ×           |                    |
|              | 300            | 100                         | ×           |                    |
| N-on-N       | 300            | 200                         | ×           | ×                  |
| N-on-P (p-spray) | 100         | 50, 150                     | ×           | ×                  |
| N-on-P (p-stop) | 100          | 50, 100                     | ×           | ×                  |
| P-on-P       | 100            | 50, 100, 150, 200           | ×           | ×                  |
and the detector is adjusted by a motorized stage. The incident X-ray is shaped when passing the slit and only a narrow beam reaches the detector. The detector is tilted to a sharp angle with respect of the incident beam plane so that the X-ray beam interacts with several pixels at various depths when penetrating the detector. For example, in our study the 100 $\mu$m thick detector was tilted to allow the X-ray beam to go transversely through five pixels. The pixel of incidence collects charges from a 0–20 $\mu$m depth and the next one from a 20–40 $\mu$m depth and so on. The tilt angle could be calculated from the arc-tangent function providing the information of the interaction width (5 $\times$ 55 $\mu$m) and the depth (100 $\mu$m). The tuning of the tilt angle was then made with a motor. For each pixel, the charge collection at different interaction depths is obtained by shifting the detector along the y-axis. The scanning step was decided by the pixel size and the tilt angle. In our measurement, the step is 94 $\mu$m for the 100 $\mu$m thick sensor and 282 $\mu$m for the 300 $\mu$m thick sensor. After scanning the whole sensor, a 3D map of the detector charge-sensitive volume is obtained.

Accurate positioning of the slit with the pixel array of the detector is essential to ensure that only one pixel column on the detector surface is irradiated by the collimated X-ray beam. To achieve it, the width of the slit has to be dramatically narrower than the pixel size of the detector (55 $\mu$m) to avoid the spreading of the beam to the neighboring pixels. During the alignment, the detector was first placed perpendicularly to the beam direction. When the detector is well aligned to the beam, the image frame will show only one pixel column with high counts. Then the detector will be tilted to desired angles and fine-tuned for the measurement. A Pixelman plug-in was developed to control all motor stages for the alignment. In the study, the distance between the detector and the slit is 72 mm and the slit width was set to 9 $\mu$m with a precision within 1 $\mu$m.

4 X-ray spectroscopic measurement

All detectors in the study were per-pixel calibrated to energy with two radioactive sources ($^{55}$Fe: 5.9 keV and $^{241}$Am: 59.5 keV) and five X-ray fluorescence ($^{69}$Cu: 8.0 keV, $^{40}$Zr: 15.8 keV, $^{42}$Mo: 17.5 keV, $^{48}$Cd: 23.2 keV, $^{49}$In: 24.2 keV) excited with an Amptek Mini-X X-ray tube. The method used for the energy calibration was published in [13].
The Timepix was operated in the ToT (Time-over-Threshold) mode allowing a direct energy measurement in each pixel. In the measurement, the detector was irradiated by radioactive source or X-ray fluorescence and a very short exposure time was used to keep small number of hits in each frame avoiding signal pileup in the individual pixels. A large amount of frames was recorded to be able to generate the full spectrum for each pixel.

The spectroscopic measurements are discussed in section 5 and the measurement results with $^{55}$Fe and $^{241}$Am sources were processed as a supplementary method to examine the mapping results of the 3D spatial scanning.

5 Results and discussion

During the 3D spatial scanning, all detectors were configured to be working in the “counting” mode. The applied bias voltages (20 V for the 100 $\mu$m detector and 100 V for the 300 $\mu$m detector) were above the full depletion voltages given in [9]. The energy thresholds were set to 3–5 keV so that they are well above the noise level. All measurements were performed at room temperature.

In the measurement, all pixels were operated in the integration mode. The acquisition time was set to 0.5 s and the number of acquisition is 30. After scanning, each pixel will record points corresponding to interactions at different depths. The measurement data of pixels from the same column was then summed, normalized and plotted against the interactive depths to show a general 2D map of the charge collection volume of pixels towards the scanning direction.

Figure 2 and figure 3 show the mapping results of 100 $\mu$m thick p-type and 300 $\mu$m thick n-type detectors. Ten pixels close to the detector edge were emphasized and their charge-sensitive volumes are marked with different colours. The pixel-to-edge distance marked in the figure indicates the length from the diffusion border of the outermost pixel to the physical edge of the sensor.

The line charts attached to the mapping images show the spectroscopic measurement results with $^{55}$Fe and $^{241}$Am sources. All detectors were measured at the same bias voltages and the threshold settings. The events registered to the pixels were summed along the edge direction and the results were normalized to show the relative change of charge collection from pixel to pixel.

The excited X-ray from $^{55}$Fe and gamma ray from $^{241}$Am are attenuated as they pass through the silicon detector and have different depths of penetration due to various absorption coefficients. Nearly 60% of the X-rays excited from $^{55}$Fe (5.9 keV) are absorbed and stopped at the depth of about 12 $\mu$m from the incident surface. The penetration depth of the gamma rays emitted from $^{241}$Am is several millimetres. So it interacts with the whole volume of the investigated detectors. Therefore, the $^{55}$Fe curve illustrates the relative change of the pixel sensitive volumes close to the surface, while $^{241}$Am curve shows the variation of the whole charge collection volumes of the pixels.

It can be seen from figure 2 and figure 3 that the electric field distortion occurs at the edge of the edgeless detector, due to the existence of the doped edge. The distorted electric field causes the deformation of the pixel’s sensitive volume at the edge. The variation of the pixel’s sensitive volume at the edge is determined by the pixel-to-edge distance, the detector thickness and the applied bias voltage. In all detector maps, there is a blank edge corner on the segmented pixel side. The electric field is not strong enough to deplete this region, which brings a dead corner to the detector edge. However, the dead corner can be eliminated with a higher bias voltage.
Figure 2. The spatial mappings of 100 µm p-type edgeless detectors. The results are combined with the spectroscopic measurement results from two radioactive sources to show the effective charge collection volume of the edge pixels. The detectors have the bias voltage set at 20 V.

In figure 2, the distorted electric field at the edge of the 100 µm thick detector influences two edge pixels. The sensitive volume of the outermost pixel expands towards the edge and it was the largest sensitive region compared to the other pixels. The second outermost pixel was influenced only slightly by its neighbour. All other pixels have relatively uniform sensitive volumes.

As widely reported, two isolation techniques, mainly p-spray or p-stop, are used for the n-on-p detector to suppress the electron accumulation near the surface and improve the isolation between the pixels. It is interesting to note that the two methods result in a distinct distribution of the sensitive volume at the detector edge. In the detector with the p-spray isolation, the sensitive volume of the edge pixel extends over 100 µm towards the detector edge. It means that almost the whole edge region of the detector will be sensitive once the edge distance shrinks to 100 µm. However, for the detector with the p-stop isolation, the sensitive volume of the edge pixel remains almost constant when the edge-to-pixel distance extends from 50 µm to 100 µm, leaving a large portion of insensitive region to the edge. In this case, the p-stop scheme needs a higher bias voltage in order to maximally use the edge volume.

The p-type detector does not suffer from the space charge sign inversion (the irradiation damage causes a drop in the effective doping concentration in the n-type detector until the detector inverts from n to p-type), and has been proven to be more radiation hard [14, 15]. However, all studies on the p-type detector refer to n-on-p configuration. There is little research on the p-on-p detector, probably due to its disadvantages of the slow hole collection and the low charge collection efficiency because the electric field maximum locates at the back plane of the sensor which
Figure 3. The spatial mappings of 300 \( \mu m \) n-type edgeless detectors and one standard 300 \( \mu m \) n-type Medipix detector with guard ring structures. The detectors operates at a bias voltage of 100 V.

is far away from the charge collection electrodes. However, the problem can be alleviated in very thin p-on-p detectors where the drift distance of holes is greatly reduced. In addition, the p-on-p edgeless detector does not need the pixel isolation, thus it is more cost-efficient.

The measurement result shows that the p-on-p edgeless detector works well. Since the maximum electric field is at the back plane and at the edges, the high-field causes depletion to spread quickly from the back-plane and the edges towards the pixel side. Given the same condition, the p-on-p detector has the advantage to gain a greater depletion region than the n-on-p detector. In figure 2, the edge sensitive volume in the p-on-p detector extends over 150 \( \mu m \). The value is 110 \( \mu m \) in the n-on-p with the p-spray method and 50 \( \mu m \) in the n-on-p with the p-stop isolation. Also, the line charts in figure 2 made from the X-ray spectroscopic measurement shows that the outermost pixel has roughly 5 times higher response than the center pixels in the p-on-p, while it is 2.1 times higher in the n-on-p with the p-spray and 1.6 times higher in the n-on-p with the p-stop. Therefore, it is proven that the p-on-p edgeless detector has a higher edge utilization efficiency than the n-on-p designs.

The electric field deformation is more pronounced when the thickness of the edgeless detector increases. As shown in figure 3, four pixels close to the edge are influenced in 300 \( \mu m \) thick edgeless detector by the distorted electric field. In the 300 \( \mu m \) thick p-on-n edgeless detector with a 100 \( \mu m \) pixel-to-edge distance, the sensitive volume of the outermost pixel is so heavily bent that it cannot reach the back plane. The same phenomenon is proved by the measurement with \(^{55}\text{Fe}\) source from which it shows that no charge is collected by the outermost pixel.
Figure 4. The spectra of radiation from $^{55}$Fe (5.9 keV) and $^{241}$Am (59.541 keV) and fluorescence radiation from the indium foil (24.136 keV) measured by various n-on-p and p-on-n edgeless detectors.

A similar edge electric field distortion was observed in the 300 $\mu$m n-on-n ($n^+/n^-/p^+$) edgeless detector with the 200 $\mu$m pixel-to-edge distance. The outermost pixel has the largest sensitive volume but its sensitive volume close to the back plane drops compared to its neighbouring pixel. The spectroscopic measurements with the $^{55}$Fe and $^{241}$Am show that the near-surface sensitive volume of the outermost pixel drops 30% compared to the second outermost pixel, while its total sensitive volume increase by 60%. In addition, the n-on-n mapping image reveals a dead edge corner close to the back plane which is caused by the electric field dispersion.

For comparison, a standard 300 $\mu$m thick p-on-n Medipix detector was examined. This detector has a grounded guard ring and few floating guard rings surrounding the pixel array and a gap greater than 500 $\mu$m is left between the outermost pixel and the physical edge. The gap is allocated to fit the guard ring structures and prevents the sensitive volume reaching the damaged cutting edge. It can be seen from figure 3 that the electric field distortion in the standard Medipix detector is suppressed and the sensitive volume of the edge pixel is as uniform as the central pixels. However, this detector has a large portion of insensitive region at the edge, resulting in a loss of the spatial information at the edge.

Figure 4 shows the spectral responses of n-on-p and p-on-n edgeless detectors. The spectra of the outermost pixels is compared with the spectra measured by pixels inside the matrix (center pixels) where the influence of edges can be neglected. It can be seen that the edge pixels with various edge distances show a similar energy resolution as the center pixels. The pixels with a wider pixel-to-edge distance have larger charge collection area, which leads to a higher signal count rate.
6 Conclusion

Various VTT/Advacam edgeless detectors have been scanned with the 3D spatial mapping setup at IEAP-CTU. The results were processed to 2D cross-sections to visualize the sensitive volume of each pixel under the given conditions. The method provides a straightforward way to study the detector’s edge effects introduced by the active edge and to qualify the detector for various applications.

The mapping results of the 100 $\mu$m p-type edgeless detectors show that two edge pixels are influenced by the distorted electric field at the edge. Compared to the center pixels, the outermost pixel has the largest sensitive volume expanding towards the physical edge. As to the n-on-p configuration, the p-stop isolation poses a restriction to the expansion of the sensitive volume towards the detector edge. Given enough edge space, the detector with the p-spray isolation has a larger edge sensitive volume than that with the p-stop isolation. The p-on-p detector has been never studied in the community and was proven to be working well. At the bias voltage of 20 V and the thickness of 100 $\mu$m, the outermost pixel in the p-on-p edgeless detector has a 2 times larger sensitive volume than that of the n-on-p edgeless detector, which implies that the p-on-p detector has a higher edge utilization efficiency than the n-on-p detector.

Two 300 $\mu$m thick n-type edgeless detectors and one 300 $\mu$m thick standard Medipix pixel detector were measured under the same conditions with the 3D spatial scanning. The result shows that the electric field distortion at the edge is more pronounced in the 300 $\mu$m edgeless detector than that in the thin edgeless detector. At the 100 V bias voltage, the sensitive volume of the four edge pixels was influenced and bent towards the detector edge. The heavily bent sensitive volume at the edge keeps itself away from the back plane, leading a low charge collection efficiency at low X-ray energy. In the standard Medipix detector, the uniform sensitive volume of the edge pixels is achieved by its guard ring design and a large margin reserved at the detector edge. However, the uniformity comes at the cost of leaving a vast “dead” area to the detector edge.

The spectroscopic measurement results show that the edge pixels have similar energy resolution with the pixels in the center of matrix. The higher count rates of the edge pixels are caused by their wider charge collection volume. In addition, the measurement results with the $^{55}$Fe and $^{241}$Am radioactive sources reveal quantitatively the relative change of the pixel sensitive volumes at different interaction depths. The results perfectly agree with the 3D spatial mapping results and provide a supplementary method to examine the mapping results.

Acknowledgments

This work was supported by the VTT Graduate School and the funding grants No. DF12P01OVV048 of the Ministry of Culture and No. LM2011030 of the Ministry of Education, Youth and Sports of the Czech Republic.

The research carried out in frame work of the Medipix Collaboration based at CERN.
References

[1] J. Kalliopuska, S. Eränen and T. Virolainen, *Alternative Fabrication Process for Edgeless Detector on 6 in. SOI Wafer*, Nucl. Instrum. Meth. A 633 (2011) S50.

[2] X. Wu, J. Kalliopuska, S. Eränen and T. Virolainen, *Recent advances in processing and characterization of edgeless detectors*, 2012 JINST 7 C02001.

[3] E. Noschis, V. Eremín and G. Ruggiero, *Simulations of planar edgeless silicon detectors with a current terminating structure*, Nucl. Instrum. Meth. A 574 (2007) 420.

[4] J. Balburna, G. Pellegrini, M. Lozano, G. Ruggiero, M. Ullan and E. Verbitskaya, *Simulation of Irradiated Edgeless Detectors*, IEEE Nucl. Sci. Symp. Conf. Rec. (2008) 2553.

[5] M. Bosma, E. Heijne, J. Kalliopuska, J. Visser and E. Koffeman, *Active-Edge Planar Silicon Sensors for Large-area Pixel Detectors*, IEEE Nucl. Sci. Symp. Conf. Rec. (2011) 1329.

[6] M. Jakubek, J. Jakubek, J. Zemlicka, M. Platkevic and V. Semian, *3D Imaging of Radiation Damage in Silicon Sensor and Spatial Mapping of Charge Collection Efficiency*, 2013 JINST 8 C03023.

[7] X. Llopart, M. Cambell, R. Dinapoli, D. San Segundo and E. Pernigotti, *Medpix2: A 64 k Pixel Readout Chip with 55 µm square elements working in single photon counting mode*, IEEE Trans. Nucl. Sci. 49 (2002) 2279.

[8] X. Llopart, R. Ballabriga, M. Cambell, L. Tlustos and W. Wong, *Timepix, a 65 k Programmable Pixel Readout Chip for Arrival Time, Energy and/or Photon Counting Measurements*, Nucl. Instrum. Meth. A 581 (2007) 485.

[9] J. Kalliopuska, X. Wu, J. Jakubek, S. Eränen and T. Virolainen, *Processing and Characterization of Edgeless Radiation Detector for Large Area Detection*, Nucl. Instrum. Meth. A 731 (2013) 205.

[10] P. Soukup, J. Jakubek and Z. Vykydal, *3D Sensitive Voxel Detector of Ionizing Radiation Based on Timepix Device*, 2011 JINST 6 C01060.

[11] V. Kraus, M. Holik, J. Jakubek, M. Kroupa, P. Soukup and Z. Vykydal, *FITPix: Fast interface for Timepix pixel detectors*, 2011 JINST 6 C01079.

[12] D. Turecek, T. Holy, J. Jakubek, S. Pospisil and Z. Vykydal, *Pixelman: A Multi-platform Data Acquisition and Processing Software Package for Medpix2, Timepix and Medipix3 Detectors*, 2011 JINST 6 C01046.

[13] J. Jakubek, *Precise energy calibration of pixel detector working in time-over-threshold mode*, Nucl. Instrum. Meth. A 633 (2011) S262.

[14] G. Casse, P.P. Allport, T.J.V. Bowcock, A. Greenall, M. Hanlon and J.N. Kackson, *First results on the charge collection properties of segmented detectors made with p-type bulk silicon*, Nucl. Instrum. Meth. A 487 (2002) 465.

[15] Y. Unno et al., *Development of n-on-p silicon sensors for very high radiation environments*, Nucl. Instrum. Meth. A 636 (2011) S24.