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

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Summary

Detector developments for medical radiography systems focus on improving image quality while using a lower dose of X-rays. This requires low-noise detectors with a high spatial resolution capable of accurately measuring both small and large intensity variations. To realise such a detector, the sensor as well as the read-out electronics must be optimised.
Current CCD-based and TFT-based detectors measure intensity by integrating the amount of charge generated by X-ray conversion in the sensor. As a result, high-energy photons count more than low-energy ones, at the expense of the signal-to-noise ratio. This thesis presents an alternative detector, based on a counting chip (Medipix). It measures photon intensity by counting the number of induced signal pulses and thus the number of converted X-rays. In this way, each photon is treated similarly, irrespective of its energy. Output images of such photon counters are therefore in better agreement with intensity distributions at the detector's input than those of charge integrating detectors. The latest descendant of the Medipix chip family (Medipix-3) even allows to combine signals induced on clusters of pixels, which benefits energy resolution. Alternatively – and perhaps even more important for radiographic applications – the electronics that enable communication between neighbouring pixels can be used to distinguish between photons of different energies. As a consequence, the energy dependence of the intensity attenuation through the object under study can be accounted for.
Detectors based on Medipix chips are so called hybrid pixel detectors. In this context, hybrid means that both the sensor and the read-out chip are fabricated separately before they are assembled together. Inherently, this allows for independent optimisation and offers the freedom to use a wide range of sensor materials, such as gallium arsenide and cadmium telluride.
Crystalline semiconductor sensors of such high atomic numbers are very attractive for tomorrow's radio-diagnostic systems. In comparison to amorphous selenium, a widely used conversion material in today's medical X-ray detectors, they have a higher quantum efficiency due to their higher absorption efficiency, lower effective electron-hole pair creation energy and relatively good charge transport properties. On top of that, they show low leakage currents in a large temperature domain.
Nevertheless, the area of the Medipix chip (~ 2 cm^2) as well as the limited area of currently available crystals (~ 10 cm^2) form a real challenge to make competitive large-area diagnostic systems. A solution is to realise a tessellation of Medipix-based detectors.

However, current Medipix-based detectors are insensitive at their edges and would therefore introduce seams in a tessellated image. For a relevant part, the inactive edge is caused by so called guard electrodes at the edge of the sensor. Although these electrodes protect the sensor's active area from detrimental effects induced by the often imperfect edge, they are responsible for a significant loss of sensitive sensor volume near the edge. The width of this inactive volume is referred to as edge distance and is for conventional sensors typically comparable to the sensor's thickness.
For the purpose of minimising the inactive edge, this thesis presents a study on the performance of both active-edge and slim-edge sensors. Both sensor types are characterised by edge distances that are only 5 % to 35 % of the sensor's thickness. Active-edge sensors differ from slim-edge sensors in the way their edges are processed. Active edges are doped, as a result of which the electric-field distribution in the sensor is such that the sensitive volume is isolated from the edge. Slim-edge sensors do not have such an electrode.
To minimise the influence of unwanted edge effects on the detection performance of the active area, minimally damaging dicing methods need to be used. Two examples of such techniques are anisotropic etching using a chemically active ion plasma and cutting by means of strongly focussed laser light.
Inter alia, edge effects translate into a locally increased conductivity, which may cause an unwanted increase of leakage current in the sensor's active area. In this thesis, a batch of active-edge p-in-n silicon sensors is electrically characterised. They all have a partially doped edge and a narrow guard electrode of different width and polarity at the edge, so called stop rings. Results show that the leakage current of these prototypes is comparable to that of conventional sensors, while the edge distance is reduced by a factor 5 to 10. Next to that, the results suggest that stop rings of positive polarity protect the active area better against edge-induced leakage currents than stop rings of negative polarity.
Although active edges allow for a reduction of the inactive edge, they cause an alteration of the effective volume of edge pixels. Simulations of the potential distribution in 150 µm thick overdepleted sensors with an edge distance of 50 µm (without stop ring), indicate that only $\sim 60\%$ of the physical volume of outermost pixels can be considered effective, while the effective volume of second outer pixels exceeds the physical volume by $\sim 60\%$. Measurements on the charge collected by the outermost pixels show good agreement with these simulations. Three-dimensional reconstruction of the effective volumes even shows resemblance with the simulated pixel-separating field lines. The same data also allowed to estimate the edge of the sensitive volume with respect to the physical edge. The most optimistic results show that this volume is only 2 µm apart from the edge, which indicates a very small insensitive area. That suggests that such sensors are very suitable as building blocks for a tessellation of detectors.
The influence of edge effects on the detection performance of edge pixels of slim-edge sensors of both crystalline gallium-arsenide and cadmium-telluride were studied as well. Whereas the leakage current of the cadmium telluride sensors show long settling times ($\sim$ 60 s), the edge pixels do not show higher leakage-current densities than non-edge pixels do. Moreover, no significant decrease of the charge collection efficiency is observed at the edge. Results concerning the noise power demonstrate that the response of high-Z sensors is dominated by fixed-pattern noise, which is most probably caused by crystalline

inhomogeneities. Nevertheless, this noise component can be suppressed by applying a so called flat-field correction. Of all studied high-Z sensors, the edge pixels of the cadmium-telluride sensors show the least increase in noise power with respect to non-edge pixels, while the ratio between the edge distance and thickness is smallest for these sensors (only 6.5%). This shows that cadmium-telluride sensors can be diced very close to the active area without significantly affecting the response of edge pixels. Apart from its moderate homogeneity, it indicates that this high-Z material is suitable for realising a tessellation of detectors with slim-edge sensors.

It can be concluded that both active-edge silicon sensors and slim-edge cadmium-telluride sensors have potential to be used in future intelligent and dose-efficient large-area detectors. It is likely that the width of the insensitive edge can be reduced to below the size of one pixel.