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

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Introduction

X-rays are often used to image objects or structures that are invisible to the human eye, for example to examine the interior of the human body. Medical radiography allows for diagnosing problems or monitoring minimally invasive surgery, such as Dotter procedures[1], without physically entering the body. That does not mean, though, that X-ray imaging can be considered non-invasive. X-rays are ionising and consequently damage tissue cells. The amount of radiation absorbed by the patient should therefore be kept to a minimum. Image quality, however, strongly benefits from a high dose of X-rays. Hence, a compromise must be found between the maximum allowable dose and the image quality needed. This trade-off poses stringent demands on the performance of a detector.

Today, many medical radiography systems use flat-panel detectors, because flat-panel technology enables fabrication of electronic circuits over large areas and therefore gives access to human digital radiography. In combination with large-area sensors that convert X-rays directly into a measurable signal, such as photoconductive amorphous selenium, these detectors can provide good-quality image of large size.

Yet, current flat-panel detectors have a couple of shortcomings. First, they 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. Secondly, the efficiency with which amorphous semiconductor material converts X-ray photons into a measurable signal is moderate. As a consequence, a substantial fraction of X-ray photons is not detected and the dose needed is higher than ideally required.

A promising candidate that could provide better image quality while using a lower dose of X-rays, is a detector that combines a high-quality crystalline semiconductor sensor with an intelligent photon counting chip (the Medipix-3 chip). This chip measures photon intensity by counting the number of converted X-rays, while determining the energy of the photon at the same time. This enables to correct for the energy dependence of the intensity attenuation through the object under study. Output images of such photon counters are therefore in better agreement with the actual X-ray intensity distribution than those of charge integrating detectors. This sophisticated way of signal processing is achieved by advanced electronic circuits that are realised in pixels of only $(55\ \mu\text{m})^2$

[1] Named after Charles Theodore Dotter, who invented angioplasty and the catheter-delivered stent.

by commercial chip processing technologies that enable fabrication of ultra-small scaled[2] electronic components. An important limitation of this technology, however, is that the probability of a circuit imperfection scales with the chip's area. Hence, such pixel chips can only be fabricated cost effectively if the maximum area is restricted. Concretely, the area of Medipix chips is limited to approximately 2 cm^2. In addition, the area of currently available semiconductor crystals that are suitable for absorbing X-rays of diagnostic energies, is limited to approximately 10 cm^2. Hence, to compete with current radiography detectors, the area of Medipix-based detectors must be increased. One solution is to realise a tessellation of multiple Medipix detectors. However, current Medipix-based detectors are insensitive at their edges and would therefore introduce seams in a tessellated image. Edgeless detectors, i.e. detectors with minimal inactive area at the edge, are therefore needed.
The development of such an edgeless detector is not trivial. First, the detector module must be designed such that the sensors can be tiled without physical seams. Secondly, the sensors itself should respond uniformly over their entire area. However, conventional crystalline semiconductor sensors have so called guard electrodes at their edges that protect the active area from unwanted effects induced by the often imperfect edge. Hence, to be able to minimise or even eliminate these guard electrodes, a good understanding of such edge effects is required.

Thesis outline

This thesis studies the influence of edge effects on the detection properties of pixels at the edge of two types of edgeless sensors: active-edge and slim-edge sensors. Both types are characterised by the fact that the distance between the active area and the physical edge of the sensor is of the order of the pixel size.
The results are preceded by three introductory chapters. Chapter 1 deals with the principles of X-ray imaging. It particularly focusses on the parameters that determine image quality and it evaluates the status of current radiography detectors. Chapter 2 covers semiconductor sensors. The first part discusses how they work and how they are fabricated, whereas the last part is concerned with edge effects as well as the design and manufacture of edgeless sensors. Chapter 3 introduces the Medipix-chip family and addresses the main bottlenecks of current Medipix detectors for the realisation of a seamless detector tessellation.
To determine the viability of active-edge sensors, the electrical characteristics of prototype active-edge sensors are studied in Chapter 4. Chapter 5 presents results on the performance of pixels at the edge of active-edge sensors and evaluates the potential of such sensors for a tessellation of detector modules. Finally, the imaging performance of edge pixels of slim-edge sensors is examined in Chapter 6. Whereas Chapters 4 and 5 focus on silicon as sensor material, materials of higher atomic number, namely gallium arsenide and cadmium telluride, are studied in Chapter 6.

[2]Nowadays, transistors with gate lengths of less than 50 nm can be realised.