Fan Ji, Mikko Juntunen, and Iiro Hietanen. 2009. Electrical crosstalk in front-illuminated photodiode array with different guard ring designs for medical CT applications. Nuclear Instruments and Methods in Physics Research A, volume 607, number 1, pages 150-153.

Nuclear Instruments and Methods in Physics Research A 607 (2009) 150–153

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Electrical crosstalk in front-illuminated photodiode array with different guard ring designs for medical CT applications

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ARTICLE INFO

Available online 25 March 2009

Keywords:
Silicon photodiode array
Electrical crosstalk
Guard ring
Quantum efficiency

ABSTRACT

This paper presents electrical crosstalk studies on front-illuminated photodiode arrays for medical computed tomography (CT) applications. Crosstalk is an important factor to the system noise and image quality. The electrical crosstalk depends on silicon substrate properties and photodiode structures. The photodiode samples employed in this paper are planar processed on high-resistivity n-type silicon substrate, resulting in a p+/n−/n+ diode structure. Two types of guard ring structures are designed and applied to the same geometry of two-dimensional photodiode arrays. One structure is an n guard ring in the gap area between pixels, and the other structure is an additional p+ guard ring around each pixel together with the n guard ring. A 10 μm light spot with wavelength of 525 nm is used to scan across the surface of the photodiode array in the electrical crosstalk measurements. The electrical currents of two neighbor pixels are measured and the results are compared between two guard ring designs. The design with the p+ guard ring structure gives better electrical crosstalk suppression. Moreover, the measurement results show much smaller influence on surrounding pixels with the p+ guard ring structure in the case of disconnected pixel. Besides the electrical crosstalk, the light sensitivity within the gap area is also discussed between two guard ring designs.

1. Introduction

Medical X-ray imaging, especially computed tomography (CT), has been developing fast over the past 10 years [1]. In the CT equipment, the X-ray source and an array of X-ray detectors are placed opposite to each other in a gantry, which is rotated around the patient. The intensity of X-ray through the patient is measured by a typically two-dimensionally pixellated X-ray detector. The data collected is then used to calculate X-ray attenuation along its path, resulting in data set consisting of X-ray attenuation within volume elements through which the radiation passed. Shown on a screen these slices look like cross-sections of the patient. Piling these slices together, three-dimensional (3D) X-ray attenuation images can be reconstructed.

The current state-of-the-art photodiode-based X-ray detectors used in CT consist of a photodiode array covered by a collimated scintillator. X-ray hitting the scintillator causes excitations, which are relaxed through the emission of optical photons. In photodiode, these photons generate charge carriers, which are collected as photocurrent.

Considering the X-ray entering into an individual element of a two-dimensional detector array, crosstalk is defined as the amount of signal not recorded by this specific pixel but leaking to the neighbor pixels. There are four main sources of crosstalk in this kind of detector [2,3]. One is the primary X-ray crosstalk caused by X-ray scattering, resulting in part of the incoming X-ray energy being absorbed into other scintillator element(s) than the one it originally entered. Second one is the optical leakage through the reflector or septa between two scintillator elements, and the third one is the crosstalk caused by part of the light transmitted through the cement between the scintillator pixel and photodiode pixel into the neighbor photodiode pixels. The fourth one is the electrical crosstalk between adjacent pixels, the subject of this study, which is mainly determined by the characteristics and structures of the photodiode array.

The electrical crosstalk is mainly caused by the diffusion of photons created by charge carriers from the illuminated pixel to the non-illuminated pixels [3,4]. This paper presents the electrical crosstalk studies on front-illuminated photodiode arrays for medical CT applications comparing two different guard ring structures.

2. Test sample, measurement setup

The sample photodiode arrays used in this paper were designed according to typical CT pixel dimensions, having about $0.7 \times 2\,\mathrm{mm}^2$ active area and 0.32 mm gap between pixels.

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doi:10.1016/j.nima.2009.03.144

Two types of guard ring structures were designed and applied to the same geometry of two-dimensional photodiode arrays. One structure is an n guard ring in the gap area between pixels, and the other structure is an additional p+ guard ring around each pixel together with the n guard ring. The cross-section of the test sample with two neighbor pixels is shown in Fig. 1, which is drawn not to the scale but to best illustrate the structures. The photodiode arrays were processed on high-resistivity n-type silicon using typical planar-processing steps of integrated circuit manufacturing industry. The doped p+ area is the anode of each photodiode pixel in the n GR sample. The narrower p+ area in the n/p+ GR sample is the p-type guard ring around each pixel. All the diode pixels share the common cathode on the bottom side of the sample.

The electrical crosstalk was measured in a dark Karl Süss probe station using a 10 μm light spot of 525 nm wavelength. The light spot was scanned across the test sample, while the photocurrents of two neighboring pixels, pixel 12 and pixel 13, were measured by an HP 4156A Parameter Analyzer. In order to prevent any chip cutting edge effects disturbing the measurements, only two central pixels were used for measurements.

3. Measurements and results

The electrical crosstalk measurements were performed at 0 V bias condition based on the typical CT readout system. All anodes were at 0 V bias condition. Cathodes and the p+ guard ring (if it applies) were also connected to 0 V potential. The photocurrents were measured from central pixels 12 and 13.

In one of the measurements, the illuminated pixel was disconnected from the measurement setup to measure the amount of photocurrent collected by the neighbor pixel. This configuration simulates the situation in an imaging system where the connection to one of the pixels is lost for whatever reason.

3.1. *Electrical crosstalk with different guard ring structures*

Fig. 2 depicts the electrical crosstalk of two adjacent pixels when the light spot scans within the pixel area, and the current ratio between pixels 12 and 13 when the light spot scans within the gap area. Considering Fig. 1, scanning is started from 0.5 mm within pixel 12, across the gap area between the pixels and about 0.2 mm into the pixel 13. In Fig. 2, the active area of pixel 12 ends at *X*-axis position 0 μm and the active area of pixel 13 starts from *X*-axis position 320 μm. According to the definition of the crosstalk, Fig. 2 shows the photocurrent of the non-illuminated pixel to the photocurrent of the illuminated pixel, and the actual photocurrent of the illuminated pixel is about 1.5 nA. It is apparent that n/p+ guard ring gives much better overall electrical crosstalk suppression over n guard ring alone. Taking illumination point at −250 μm as an example, the crosstalk is about 0.6% with n guard ring, but only 0.35% with n/p+ guard ring. The crosstalk gets even smaller when the illumination is further within a pixel and the difference in favor of n/p+ guard ring is maintained. On the other hand, it can be noted that when the light spot hits the gap area between the pixels, from 40 to 280 μm in Fig. 2, the current ratio with n/p+ guard ring is larger than with n guard ring alone. This means photon-generated carriers in the gap area can be more evenly collected by neighbor pixels with the n/p+ guard ring. However, as can be seen later, the absolute photocurrents collected by neighbor pixels with n/p+ guard ring are much smaller compared to the n guard ring alone.

Fig. 3 shows the absolute crosstalk current value of pixel 13 as a function of light spot distance within the active area of pixel 12. This result supports the theory that the electrical crosstalk is caused by charge carriers generated at the boundary or outside the space charge region within bulk silicon, that is, beneath the detective diode volume. Since these charge carriers are subjected to diffusion and have a limited lifetime or diffusion length, some of them will eventually be collected by the diode under which they were generated, and some be recombined, and the further within the illuminated pixel they are, the smaller chance they will be ending up into neighbor pixel. The crosstalk behavior in this paper is consistent with what was reported by Zhou et al. [5].

Since scintillators typically have their light output highest at the edge area, these results emphasize the importance of aligning the pixellated scintillator structure properly so that light hits the correct photodiode pixels.

3.2. *Electrical crosstalk in case of pixel disconnection*

Fig. 4 shows the crosstalk current collected by pixel 13 while the light spot was scanned from 0.5 mm within pixel 12 into the

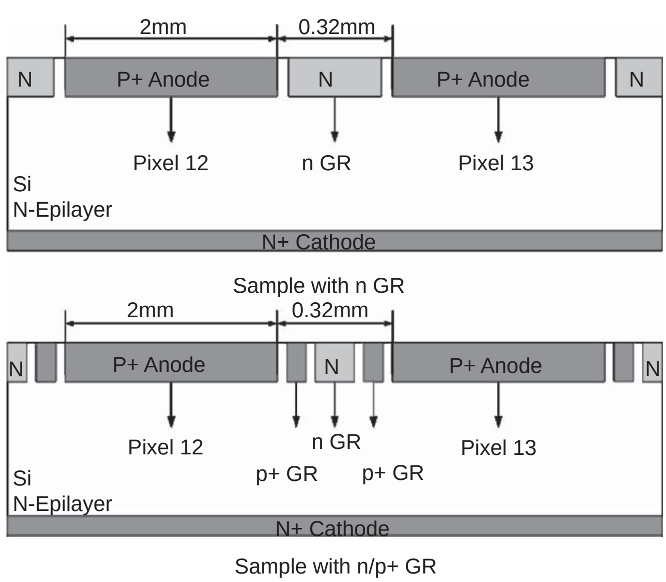

Fig. 1. Cross-sections of the test samples.

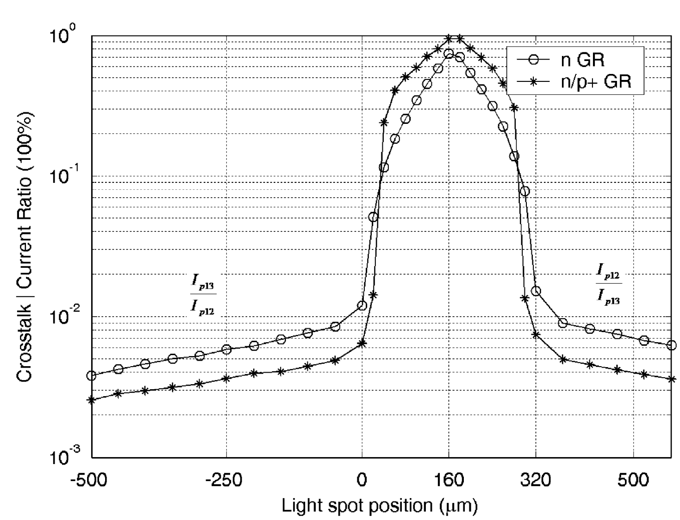

Fig. 2. Electrical crosstalk from pixel 12, pixel 13 and current ratio in the gap area between pixels 12 and 13. (Right edge of pixel 12 is at 0 μm, and left edge of the pixel is at 320 μm.)

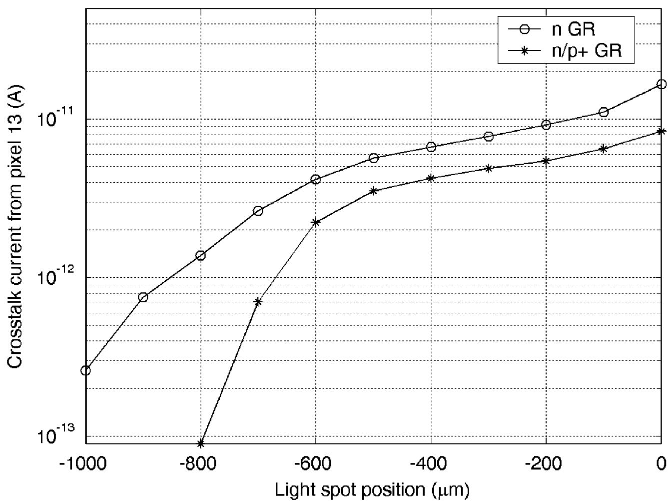

Fig. 3. Crosstalk current from pixel 13 at different illumination points within pixel 12. (Right edge of pixel 12 is at 0 μm.)

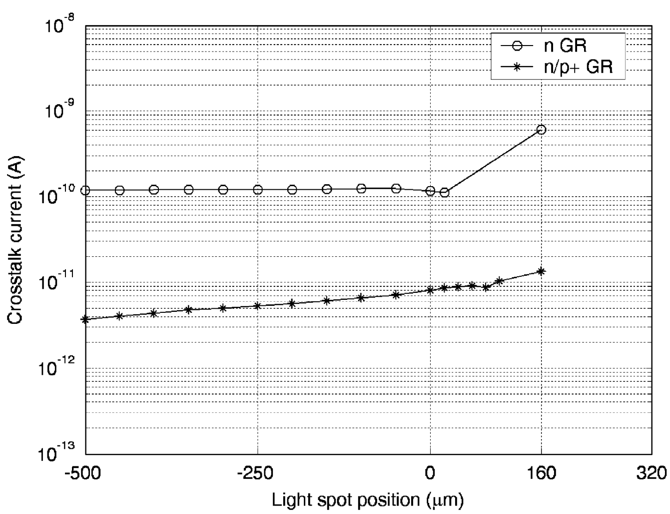

Fig. 4. Crosstalk current from pixel 13 at different illumination points on disconnected pixel 12. (Right edge of pixel 12 is at 0 μm.)

gap area between pixels, while having pixel 12 completely disconnected from the setup. This represents a situation where signal collection from a pixel is not possible due to loss of connection in the readout chain.

The photocurrent of the connected pixel before the disconnection was about 1.5 nA. It can be seen from Fig. 4 that regardless of where the light hits the disconnected pixel, almost 10% of its signal leaks to the immediately neighboring pixel measured in this study with n guard ring. From previous measurements we have seen that depending on the design details, about 60–80% of the total signal will eventually be collected by all eight neighbors at such a situation if the chip has only n guard structure, matching with this result. The n/p+ guard ring suppresses this leakage more effectively. The photon-generated charge carriers are first collected by the n/p+ guard ring around the disconnected pixel, and then the rest of the charge carriers will be mostly collected by the n/p+ guard ring around the neighbor pixels. The very small portion of charge carriers reaching the neighbor pixels has to cross both n/p+ guard rings, and this presents more crosstalk between

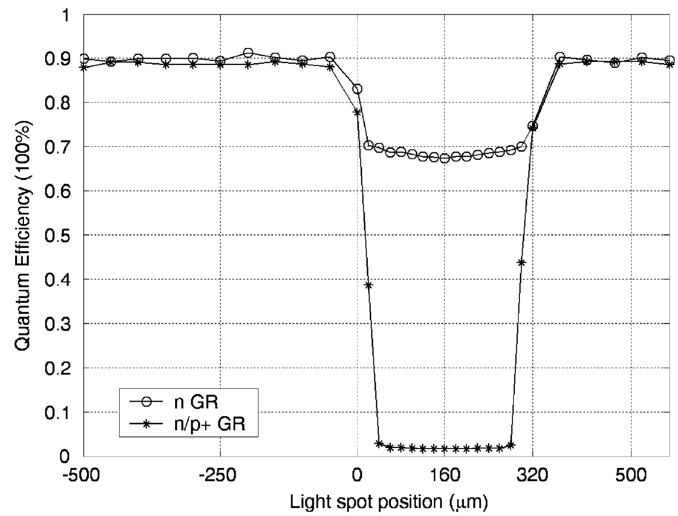

Fig. 5. Quantum efficiencies in pixel 12, pixel 13 and the gap area between pixels 12 and 13. (Right edge of pixel 12 is at 0 μm, and left edge of pixel 13 is at 320 μm.)

guard rings and pixels than the crosstalk from the disconnected pixel.

3.3. Light response suppression by different guard ring structures

Referring back to the Introduction, the guard ring designs can be used to suppress not only the electrical but also the optical crosstalk in an imaging system. Part of the optical crosstalk results in electrical crosstalk signal due to the light hitting the gap area between the photodiode pixels, generating charge carriers. If these carriers are collected by another pixel than the illuminated pixel under the emitting scintillator, the collected charges create crosstalk signal that is fundamentally of optical nature.

Fig. 5 shows the results of quantum efficiency across the gap area from both samples with n guard ring and n/p+ guard ring. The quantum efficiency can be calculated by [6]

$$\eta(\lambda) = \frac{hc(I_{p12} + I_{p13})}{\lambda q P_{opt}} \tag{1}$$

where h is the Plank's constant, c the light speed, q the electronic charge, P_{opt} the power of the light spot, and I_{p12} and I_{p13} are the photocurrents from pixels 12 and 13, respectively. From the left side until position 0 μm and from position 320 μm onwards, a quantum efficiency of 90% is shown for the active area of pixels, and in the gap area, the total signal collected by the two pixels is combined and interpreted as the quantum efficiency of the intermediate area. It can be seen from Fig. 5 that a photodiode array with n guard ring has practically the whole gap surface being active; collecting ~70% of photon-generated carriers in the gap area. However, with n/p+ guard ring any collection of unwanted photocurrent from the gap area between the pixels is very effectively suppressed to ~2%.

4. Conclusions

In this paper we presented the electrical crosstalk studies on front-illuminated photodiode arrays comparing two different guard ring structures. One structure has an n guard ring between pixels, and the other one has a p+ guard ring around each pixel together with the n guard ring between pixels. The results show that from the two design options studied, n/p+ guard ring gives much better overall electrical crosstalk suppression over n guard ring alone. In addition, it was shown that the n/p+ guard ring very effectively suppresses signal leakage from a disconnected pixel to its surrounding neighbors. This gives the benefit that in the case of a disconnection, only the disconnected pixel is affected and can possibly be excluded from the data analysis, whereas in the case of n guard alone, the whole group of nine pixels, the one disconnected plus all pixels surrounding it, will be affected.

As a further result, it has been shown that n/p+ guard ring structure allows for effectively collecting the signal only from the areas defined as being active areas in the design. This is accomplished by effectively suppressing any photocurrent collection from the gap area of the photodiode array.

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