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Evaluation of electrical crosstalk in high-density photodiode arrays for X-ray imaging applications

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A R T I C L E I N F O

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A B S T R A C T

Electrical crosstalk is one of the important parameters in the photodiode array detector for X-ray imaging applications, and it becomes more important when the density of the photodiode array becomes higher. This paper presents the design of the high-density photodiode array with 250 μm pitch and 50 μm gap. The electrical crosstalk of the demonstrated samples is evaluated and compared with different electrode configurations: cathode bias mode and anode bias mode. The measurement results show good electrical crosstalk, ~0.23%, in cathode bias mode regardless of the bias voltage, and slightly decreased or increased electrical crosstalk in anode bias mode. Moreover, the quantum efficiency is also evaluated from the same samples, and it behaves similar to the electrical crosstalk. Finally, some design guidance of the high-density photodiode array is given based on the discussion.

1. Introduction

X-ray imaging in medical applications, especially computed tomography (CT), has been developing very quickly. The multi-slice detectors have been used to increase the scanning speed, and sub-millimeter slices have been introduced to improve the spatial resolution. A state-of-the-art CT scanner with 320 slices detector was recently prototyped by Toshiba, capable of scanning the whole human heart with one gantry rotation. Increasing spatial resolution and potentially temporal resolution requires high-density photodiode array detectors. Moreover, the existing through-wafer interconnection technology makes the connection of high-density photodiode array possible in the real application [1,2]. The crosstalk is one of the important parameters of the detector, and it impacts on the system noise and image quality. The CT detector usually consists of a photodiode array and a collimated scintillator. There are mainly four kinds of crosstalk sources in the scintillator-based detectors [3,4]. One of them is the electrical crosstalk, which is dependent on the characteristics and structures of the photodiode array. The noise current of detector will increase significantly if high electrical crosstalk is applied [3]. The electrical crosstalk can be defined as the photocurrent from the non-illuminated neighbor pixel to the photocurrent from the illuminated center pixel, due to the diffusion of photons generated carriers [5,6]. High-density photodiode array with smaller gap between neighboring pixels will be more sensitive to the electrical crosstalk.

2. Sample design and measurement setup

A test sample of high-density photodiode array was designed with 4×4 pixels for the study.. The photodiode array was processed on the epilayer of N-type silicon. The pitch of the pixel is 250 μm in both directions, and the gap between two pixels is 50 μm. The active area of each pixel is 200 μm × 200 μm. In order to reduce the leakage current, an N-type guard ring (channel stopper) was designed on the gap area between pixels. The cross-section of the test sample can be seen from Fig. 1, where the doped P+ area is the anode of each pixel and all the pixels are sharing the common cathode on the bottom side of the sample with N+.

According to the definition of electrical crosstalk, the photocurrent was measured in the dark probe station from the anode of pixels. A light spot with the wavelength of 525 nm was focused in 10 μm diameter on to the test sample surface through an optical fiber and microscope lens. The test sample was scanned by the light spot with 10 μm steps, while the photocurrent of two neighboring pixels A and B was measured by the HP 4156A Parameter Analyzer. Two types of electrode configuration were used for the measurement. One configuration, cathode bias mode, is to bias all the pixels with the same voltage through the common cathode, while all the anodes are grounded. Another configuration, anode bias mode, is to bias individual pixel through the separated anode, and ground the common cathode and all other

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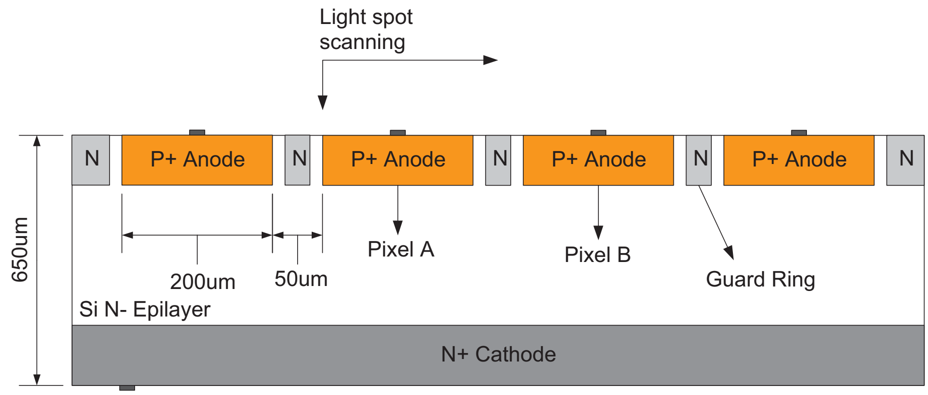

Fig. 1. Cross-section of the test sample.

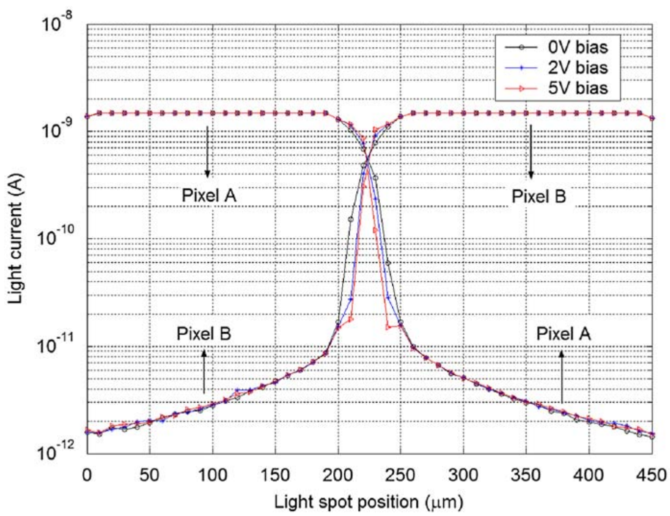

Fig. 2. Photocurrent measured from pixels A and B at the cathode bias mode; the leakage current between pixels A and B is negligible.

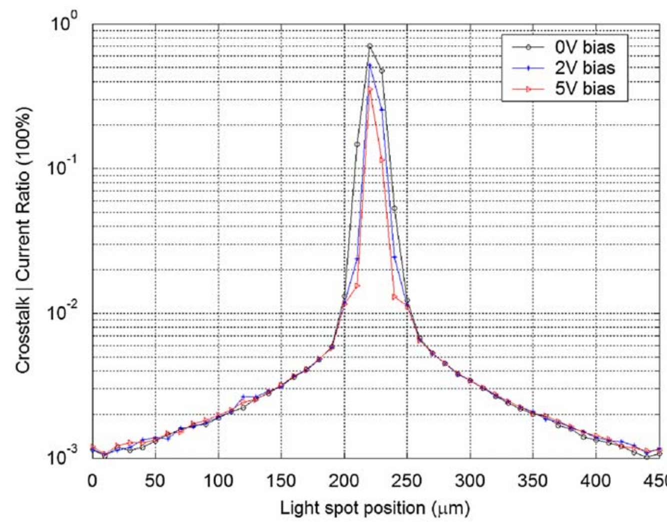

Fig. 3. Electrical crosstalk or current ratio between pixels A and B at the cathode bias mode.

anodes. In both configurations, the N-type guard ring is at the same potential of cathode.

3. Results and discussion

3.1. Cathode bias mode

The photocurrent measured from pixels A and B with the light spot position changing from the left edge of pixel A to the right edge of pixel B is shown in Fig. 2. There are three sets of photocurrent curves, presenting the bias voltage at 0, 2 and 5 V. According to the definition, the electrical crosstalk (crosstalk) between pixels A and B is shown in Fig. 3 at 0, 2 and 5 V bias voltages separately. It can be seen that the crosstalk increases exponentially as the light spot moves towards the neighbor pixel. There is no crosstalk difference at the same position in the active area as the bias voltage changes, indicating the photons generated carriers beyond the bottom of space charge region (SCR) mainly contribute to the crosstalk and it is not affected by the vertically expanded SCR. The crosstalk behaves symmetrically to the center of the gap area, since there is no potential difference between the anodes of pixels A and B. On the other hand, the photocurrent ratio in the gap area changes much faster as the bias voltage increases, which indicates the laterally expanded SCR dramatically affect the diffusion behavior of photons generated carriers between pixels A and B. The average crosstalk of 0.23% can be calculated by

$$\mathrm{Crosstalk}_a = \frac{\sum_{n=1}^{N} t\,\mathrm{Crosstalk}(n)}{Nt} \tag{1}$$

where N is the total number of scanning steps in the active area, t is the distance of each step and Crosstalk(n) is the crosstalk measured at step n.

The quantum efficiency can be calculated by [6]

$$\eta(\lambda) = \frac{hc(I_A + I_B)}{\lambda q P_{opt}} \tag{2}$$

where h is Plank's constant, c is the light speed, q is the electronic charge, P_{opt} is the power of the light spot, I_A and I_B are the photocurrents measured from pixels A and B. Fig. 4 shows three curves of quantum efficiency at bias voltages of 0, 2 and 5 V, which present no change of the quantum efficiency regardless of the bias voltage. The quantum efficiency is ~91% on the active area of pixel A or B and ~72% on the gap area. The quantum efficiency on the gap area indicates that most of the photons-generated carriers in the N-type guard ring can still be collected by adjacent pixels.

3.2. Anode bias mode

The photocurrent measured from pixels A and B at the anode bias mode is shown in Fig. 5. Pixel A was biased from the anode, and all other pixels were grounded. There are also three sets of

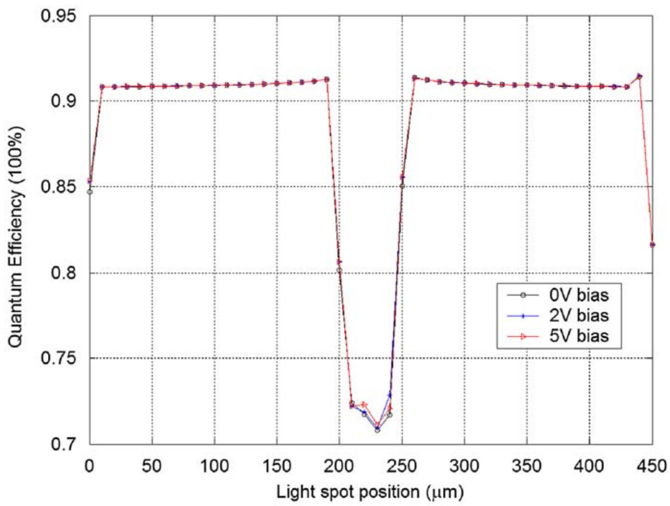

Fig. 4. Quantum efficiency of pixel active area and gap area at the cathode bias mode.

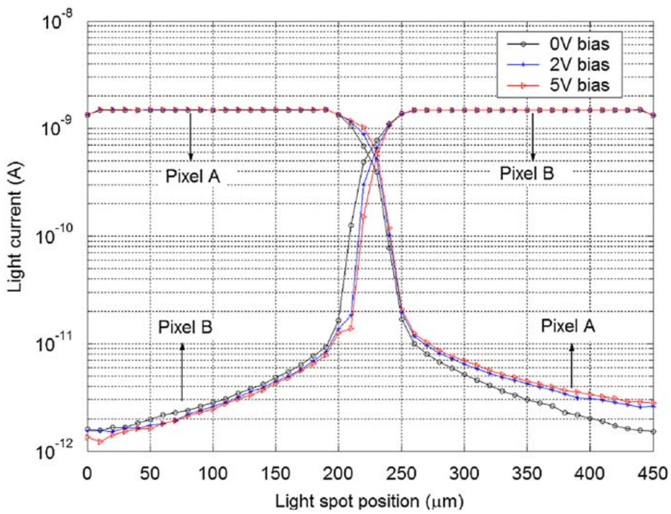

Fig. 5. Photocurrent measured from pixels A and B at the anode bias mode, the leakage current between pixels A and B has been deducted.

photocurrent curves in Fig. 5, presenting the bias voltage at 0, -2 and -5 V. Due to the potential difference on the anodes, there is leakage current between pixels A and B, which has been excluded from Fig. 5. The crosstalk curves are shown in Fig. 6 accordingly. It can be seen that the trend of the crosstalk is the same as in cathode bias mode, but the crosstalk becomes smaller with higher bias voltages in pixel A. The biased crosstalk curves are tilted from the 0 V biased curve. The asymmetric curves indicate that the potential difference between the anodes of pixels A and B imposes additional electrical field; therefore, it affects the diffusion behavior of the photons-generated carriers beyond the SCR in the substrate between pixels A and B. The average crosstalk is 0.20% on pixel A and 0.42% on pixel B area at -5 V bias voltage by using formula (1).

The value of quantum efficiency at anode bias mode is very similar as it is at cathode bias mode in Fig. 4. The only difference is

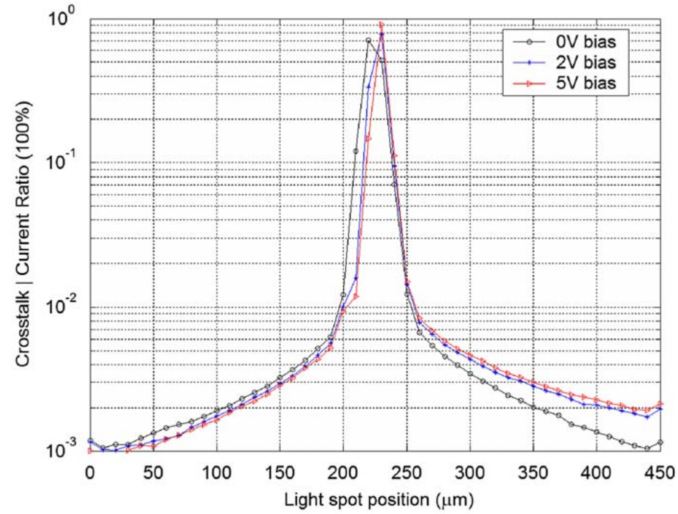

Fig. 6. Electrical crosstalk or current ratio between pixels A and B at the anode bias mode.

that the quantum efficiency is slightly higher, ~92%, in the biased pixel A at -5 V. Because the bias voltage creates electrical field in the substrate between pixels A and B, pixel A can collect more photons-generated carriers beyond the SCR diffusing to all the directions.

4. Conclusion

The electrical crosstalk has been evaluated with the designed high-density photodiode arrays. Photocurrent was measured and the average electrical crosstalk of 0.23% was obtained with 0 V bias. Moreover, the quantum efficiency of ~91% was obtained on the active area. The cathode bias shows no impact on the electrical crosstalk and quantum efficiency, but the anode bias has an influence on both. Most of the photons-generated carriers contributed to the electrical crosstalk follow the path from the bottom of SCR of illuminated pixel to the neighbor pixels; making the guard-ring junction deeper will help to improve the crosstalk. In addition, the quantum efficiency of the gap area is ~72%, so that the recombination of the photons-generated carriers is not efficient enough in the N-type guard ring. In order to improve the crosstalk, the guard ring can be doped more heavily, or use P-type doping.

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