Crosstalk characterization of single-photon avalanche diode (SPAD) arrays in CMOS 150nm technology

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Abstract

In this paper, crosstalk characterization results of single-photon avalanche diode (SPAD) arrays in CMOS 150nm technology are reported and discussed. SPADs are implemented in two different sizes (15.6 and 25.6\textmu m pitch) and three guard ring widths (0.6, 1.1 and 1.6\textmu m). A SPAD array is composed of 25 (5\times5) devices, which can be separately activated. Measurement results show that total crosstalk probability is well below 1\% for arrays with conservative guard ring SPADs, and decreases with distance between devices. We also observed crosstalk is dependent on geometry parameters of SPADs.

1. Introduction

Over the last few years, photon detection systems based on Single-Photon Avalanche Diode (SPAD) arrays have been proposed for different imaging applications such as \textgamma-ray detection in Positron Emission Tomography [1] and fluorescence lifetime imaging microscopy [2]. One possible issue of SPAD arrays is crosstalk: when an avalanche event is triggered, a large number of hot carriers will be generated in the SPAD high-field region. These carriers will recombine and may emit photons, which can be absorbed and thus trigger an avalanche in an adjacent SPAD. Moreover, crosstalk can also be caused by the lateral diffusion of carriers. This phenomenon becomes a correlated...
noise source, which may severely impact performance in some applications [3]. The most straightforward way of reducing crosstalk is to increase the distance between devices, which, however, limits the array density [4, 5].

In the next section, we discuss SPAD array design, read-out circuits and measurement setup. In section 3, we present and report characterization results of dark count rate (DCR) and crosstalk probability as a function of distance and geometry parameters. Finally, we conclude with a discussion on the implication of this work.

2. SPAD array and chip description

A SPAD is an avalanche photodiode working above its breakdown voltage (Geiger mode). Under this condition the electrical field of the junction is so strong that even a single carrier (electron or hole) may trigger an avalanche. A quenching circuit (passive or active) is required to quench the avalanche and restore the initial bias condition.

The cross-section of the SPAD, fabricated in a 150nm CMOS process, is schematically sketched in Fig 1 (a). The avalanche region is formed by p+/n-well junction, and an isolation layer (n-iso) is applied to realize a lower doped region as guard-ring, preventing early periphery breakdown [ref. ESSDERC 2011]. Finally, a metal shield is formed to avoid light transmission to non-active area. The pitch size is indicated as r_{pitch} and active region as r_{act}. The guard ring width has been designed in different sizes (0.6, 1.1 and 1.6 \mu m) to experimentally assess the trade-off between high fill-factor and low crosstalk probability. Two different SPAD sizes (15.6 and 25.6 \mu m) are realized to investigate the relationship between crosstalk probability and SPAD pitch. The fill-factor of the different SPAD arrays is shown in Table 1. Each SPAD array is composed of 25 (5 \times 5) devices, which can be separately selected. The layout of one of the arrays is also shown in Fig 1(a).

| SPAD type | con_15\mu m | con_25\mu m | mod_15\mu m | mod_25\mu m | ext_15\mu m | ext_25\mu m |
|-----------|-------------|-------------|-------------|-------------|-------------|-------------|
| Fill-factor (%) | 46.3 | 65.4 | 55.6 | 71.9 | 64.9 | 78.4 |

![Fig. 1. (a) SPAD array layout and SPAD cross-section; (b) schematic of SPAD front-end.](image_url)

Each SPAD is integrated together with a pixel circuit, as shown in Figure 1 (b). The SPAD is connected to a quenching transistor M2, an enable transistor M1, a Schmitt-trigger comparator, which converts voltage pulse from the SPAD to a 1.8V digital output signal and protects the following digital electronics. SPADs can be individually selected through a decoder, while only one output can be enabled.

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1 For simplicity, a SPAD with guard ring width of 0.6, 1.1 and 1.6\mu m are named as con, mod and ext. As an example, con_15\mu m represents conservative guard ring SPAD of 15.6\mu m pitch.
A dedicated printed circuit board (PCB) provides power supply, bias and reference voltage for the SPADs, while the acquisition was conducted with an external ripple counter connected to the common output. A series of measurements have been conducted in order to extract SPAD dark count rate (DCR) and crosstalk probability.

3. Characterization results

Dark count rate (DCR), which indicates events generated by a SPAD even in the absence of illumination, was measured for all the SPAD arrays. Measurements performed on SPADs having 0.6μm guard ring width showed an extremely high DCR, indicating the presence of early breakdown at the borders. This behavior is not present in the two other types of SPADs (1.1 and 1.6μm guard ring width) which are fully functional. The histogram of DCR for both device types biased at 3V excess voltage is shown in Fig 2. Moderate SPADs have higher DCR than conservative ones due to their larger active area.

![Fig. 2. Dark count rate histogram of SPADs at 3V excess bias voltage.](image)

Pseudo-crosstalk measurements were performed to characterize the crosstalk probability for all SPAD arrays [4]. During the measurements, two different devices are activated at a time, forming an emitter-detector pair. The emitter is the device generating photons during an avalanche event, while the detector can be triggered by these photons. To obtain a crosstalk probability mapping, the central SPAD is considered as emitter, and all the other 24 SPADs are considered as detectors and are activated one at a time. The measurement is conducted in two time intervals: during the first time interval, the count rate of a detector is evaluated with the emitter disabled; in the second time interval, the count rate of the detector is measured with the emitter enabled. Crosstalk probability was calculated by subtracting the two count rates and dividing the difference by the DCR of the emitter. This procedure was repeated for all 24 SPADs to obtain the crosstalk mapping of an array.

The crosstalk probability mapping for a conservative SPAD array with 15.6μm pitch at 3V excess bias voltage is shown in Fig 3(a). As shown in the figure, the crosstalk probability of conservative guard ring SPADs (15.6μm pitch) is well less than 1%, and decreases with distance between devices. Crosstalk probability of nearest neighbors for each type of SPAD arrays is measured, and results are shown in Fig 3(b). Comparison of conservative and moderate SPADs (con_15μm vs. con_25μm and con_25μm vs. mod_25μm) shows that, as expected, crosstalk probability increases as guard ring width decreases and increases with SPAD size.
Fig. 3. (a) crosstalk probability mapping of conservative SPAD array (15.6 μm) at 3V excess bias voltage; (b) minimum, mean and maximum crosstalk probability between nearest neighbors in different SPAD arrays at 3V excess bias voltage.

4. Conclusion

Crosstalk represents a source of correlated noise in SPAD arrays. In this paper, we present a test chip for characterization of crosstalk probability. The results show that crosstalk is well below than 1% for conservative SPAD arrays (15.6 μm) and decreases with increasing distance between devices. We also observed that larger SPADs have higher crosstalk probability. However, the average worst-case crosstalk probability, measured on an array having 25.6μm pitch and a fill factor larger than 70%, is lower than 2.5%. This result supports the application of high fill-factor SPAD arrays in single-photon imaging applications requiring low crosstalk probability.

References

[1] Braga, L.H.C.; Gasparini, L.; Grant, L.; Henderson, R.K.; Massari, N.; Perenzoni, M.; Stoppa, D.; Walker, R., "An 8×16-pixel 92kSPAD time-resolved sensor with on-pixel 64ps 12b TDC and 100MS/s real-time energy histogramming in 0.13μm CIS technology for PET/MRI applications," IEEE International Solid-State Circuits Conference Digest of Technical Papers (ISSCC). pp.486,487, 17-21 Feb. 2013.
[2] Veerappan, C.; Richardson, J.; Walker, R.; Day-Uey Li; Fishburn, M.W.; Maruyama, Y.; Stoppa, D.; Borghetti, F.; Gersbach, M.; Henderson, R.K.; Charbon, E., "A 160×128 single-photon image sensor with on-pixel 55ps 10b time-to-digital converter," IEEE International Solid-State Circuits Conference Digest of Technical Papers (ISSCC). pp.312,314, 20-24 Feb. 2011.
[3] Gola, A.; Tarolli, A.; Piemonte, C., "SiPM crosstalk amplification due to scintillator crystal: Effects on timing performance," IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), pp.421,423, Oct. 27 2012-Nov. 3 2012.
[4] Rech, I., A. Ingargiola, R. Spinelli, I. Labanca, S. Marangoni, M. Ghiion, S. Cova "Optical crosstalk in single photon avalanche diode arrays: a new complete model," Opt. Express, vol. 16, no. 12, pp.8381 -8394, 2008.
[5] Finocchiaro, P.; Pappalardo, A.; Cosentino, L.; Belluso, M.; Billotta, S.; Bonanno, G.; Di Mauro, S., "Features of Silicon Photon Multipliers: Precision Measurements of Noise, Crosstalk, Afterpulsing, Detection Efficiency," IEEE Transactions on Nuclear Science, vol.56, no.3, pp.1033,1041, June 2009.
[6] Pancheri, L.; Stoppa, D., "Low-noise single Photon Avalanche Diodes in 0.15 μm CMOS technology," Proceedings of the European Solid-State Device Research Conference (ESSDERC), pp.179,182, 12-16 Sept. 2011.