First Characterization of the SPADnet-II Sensor: a Smart Digital Silicon Photomultiplier for ToF-PET Applications

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***Abstract*– SPADnet-II, a 9.85×9.85 mm^2, 16×16 pixels array digital silicon photomultiplier has been developed based on a 130nm through silicon via (TSV) CMOS image sensor technology for TOF-PET imaging. Spectrometric characterization was conducted with a 3.5×3.5×20 mm^3 LYSO needle for clinical imaging and a 1.3 mm pitch LYSO needle matrix for preclinical imaging were made using a 22-sodium source.**

I. Introduction

THE integration of magnetic resonance imaging (MRI) with time-of-flight (ToF) positron emission tomography (PET) combines multi-functional information to visualize cellular activity and metabolism with anatomical information and soft-tissue contrast in a single patient examination. Combining these two advanced imaging technologies implies the use of a photon detector with excellent timing properties that operates properly in presence of a magnetic field, as in the SPADnet technology [1].

In this paper, we report on the first characterization of the second generation of SPADnet sensors, known as SPADnet-II, a smart digital silicon photomultiplier (D-SiPM) array based on CMOS technology. The paper is organized as follows: the sensor architecture is described in Section 2, while the characterization is presented in Section 3 and Section 4 concludes the paper.

II. Sensor Description

The SPADnet-II sensor design inherits the SPADnet-I architecture [2, 3], but it has twice the surface area (9.85 × 9.85 mm^2) and a higher fill factor, when compared to its predecessor. It is also included a number of new features: on-chip frame buffer to decouple pixel array readout from data transmission, revised triggering system (faster, single threshold operation), post-event triggering, and on-chip event centroid calculation. Many of them have still to be tested.

The chip comprises 172,032 single-photon avalanche diodes (SPADs) arranged in 16×16 pixels array, whereas each pixel measures 606x560 µm^2; it was developed in 0.13-µm 1P4M CMOS front side illuminated (FSI) imaging technology. The fabrication process of the chips could be either wire-bonded (WB) or benefit from through silicon via (TSV) technology, enabling 4-side buttable tiled PET modules. In this work, the chip features WB technology. Each pixel has 2 x 4 digital mini-SiPMs, each one consisting of 12x7 SPADs, with two time-to-digital converters (TDCs) working in time-interleaved fashion. The pixel array provides several photon timestamps for each scintillation event in order to supply a robust estimation of the gamma-photon timemark with high timing resolution.

Each SPAD has a rounded square shape to reduce dark count rates (DCR), while maximizing fill factor. Thanks to this new SPAD shape and to improvements in the front-end electronics, the pixel fill factor of SPADnet-II was increased to 54.8% up from 42.6% in SPADnet-I. In order to reduce DCR, noisy SPADs can be disabled by groups of two using programmable memories. Consequently, the whole pixel array has 384 x 448 SPADs, being programmed by 192 x 448 SRAMs.

The sensor´s clock is tunable up to 90 MHz. In this study, the clock was set to 71.4 MHz. The total number of SPADs that fired across the whole chip is generated at each clock cycle, providing a digitized photon flux that can be read out in real time. The discrete photon flux is compared to an internal threshold to determine when an event occurred, triggering the integration. For each gamma event, the chip provides the number of counts per pixel during the integration period, the TDC value for each pixel, and a time histogram containing the number of counts; the data rate is 71.4 MS/s.

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III. CHIP CHARACTERIZATION

The experimental setup for chip characterization comprises the SPADnet-II evaluation kit, a sodium-22 calibration source, a single LYSO crystal and an array of LYSO crystals from Saint Gobain. The SPADnet-II evaluation kit is composed by a SP605 development board from Xilinx and a support board to easily plug the chip under test. PC based data acquisition and chip control are performed over Ethernet protocol using LabVIEW. The integration time was 420 ns; the clock bin was 14 ns. All measurements were conducted at room temperature.

A. Dark Count Rate

By using a memory-programming module, a pair of SPADs per pixel could be selected at any time and a DCR map could be obtained for a given excess bias, so as to identify and turn off the noisy SPAD pairs. For the sample used in this study, the median DCR was 47 kHz at 0.9 V excess bias.

B. Power Consumption

The power consumption of SPADnet-II (measured in the darkness and at room temperature) included contributions from on-chip processing logic (190mW), SPADs (140mW), and TDCs (100mW).

C. Using a Single Crystal

A LYSO scintillator of 3.5×3.5×20 mm^3 was wrapped with Teflon and it was optically coupled to the SPADnet-II sensor active area using optical grease, as shown in Fig. 1. The scintillator was irradiated using a sodium-22 source (1 MBq). Measurements were done having 85% of the SPADs enabled, with a total DCR rate of 4 GHz. The measured energy spectrum is plotted on Fig. 2. The energy resolution was 12% FWHM at 511 keV. An energy resolution of 9.7% FWHM at 511 keV was obtained with a 3×3×5 mm^3 LYSO crystal.

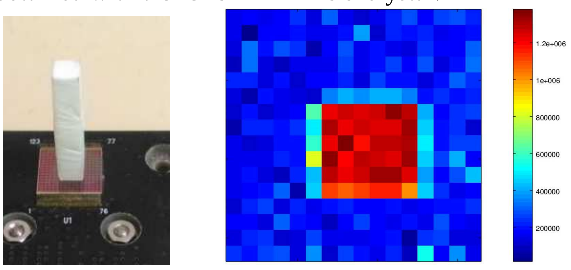

Fig. 1. Left: Photography of the SPADnet-II sensor coupled with a LYSO needle. Right: Accumulated photon count obtained with SPADnet-II.

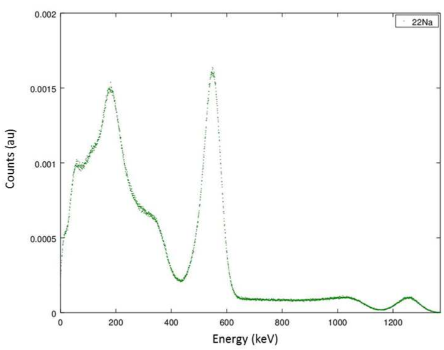

Fig. 2. Gamma spectrum obtained with a Sodium 22 source.

D. Using a Crystal Array

In order to evaluate SPADnet-II for preclinical PET imaging, a 13 mm thick LYSO array with 35×35 pixels, 1.3mm pitch and optical separator was coupled to the active area of the sensor using optical grease. As the LYSO array area is larger than the SPADnet-II sensor area, only part of the pixels of the array were optically coupled to the sensor. No alignment between the crystal matrix and the pixel matrix was performed. The position of each scintillation event was determined by the center of gravity calculation of the 256 pixels counts, after removing the pixels for which the photon counts were below 5 counts. Each LYSO needle is clearly resolved as can be seen in Fig. 3. The energy spectrum corresponding to each needle can be measured and it will be presented by the time of the conference.

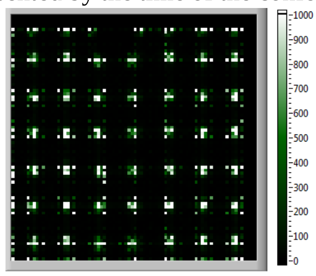

Fig. 3. Flood map of scintillations.

IV. CONCLUSION

SPADnet-II, a MRI compatible fully digital SiPM has been presented. First characterization results show suitable performance for ToF PET/MRI applications.

Spectrometric characterization with 3.5×3.5×20 mm^3 LYSO needle, designed for clinical PET shows an energy resolution of 12 % FWHM. A 1.3 mm pitch LYSO needle matrix designed for preclinical PET was coupled to the sensor and the needles were clearly resolved.

In the final version of the paper, at the Conference, a DCR distribution and an energy calibration curve will be presented.

V. ACKNOWLEDGMENTS

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