SPADnet: A Fully Digital, Networked Approach to MRI Compatible PET Systems Based on Deep-Submicron CMOS Technology

E. Charbon[1], Claudio Bruschini[2], Chockalingam Veerappan[1], Leo Huf Campos Braga[3], Nicola Massari[3], Matteo Perenzoni[3], Leonardo Gasparini[3], David Stoppa[3], Richard Walker[4], Ahmet Erdogan[4], Robert K. Henderson[4], Steve East[5], Lindsay Grant[5], Balázs Játékos[6], Ferenc Ujhelyi[6], Gábor Erdei[6], Emöke Lörincz[6], Luc André[7], Laurent Maingault[7], Vincent Reboud[7], Loick Verger[7], Eric Gros d'Aillon[7], Péter Major[8], Zoltán Papp[8], Gábor Németh[8]

[1]) TU Delft, Delft, Netherlands; [2]) EPFL, Lausanne, Switzerland; [3]) Fondazione Bruno Kessler, Trento, Italy; [4]) University of Edinburgh, Edinburgh, Scotland; [5]) STMicroelectronics, Edinburgh, Scotland; [6]) BUTE, Budapest, Hungary; [7]) CEA-LETI, Grenoble, France; [8]) Mediso, Budapest, Hungary

Abstract[1]– This paper is the first comprehensive presentation of the SPADnet concept. SPADnet is a fully digital, networked MRI compatible time-of-flight PET system, exploiting the speed and integration density of deep-submicron CMOS technologies. The core enabling technologies of SPADnet are a sensor device comprising an array of 8x16 pixels, each composed of 4 mini-SiPMs with *in situ* time-to-digital conversion, a multi-ring network to filter, carry, and process data produced by the sensor devices at 2Gbps, and a 130nm CMOS process enabling mass-production of photonic modules that are optically interfaced to scintillator crystals. The SPADnet photonic modules comprise a matrix of tightly packed sensor devices; each module is networked in multiple rings, where coincidence pairs are identified and readily used in reconstruction algorithms, enabling scalable, MRI compatible pre-clinical PET systems for multi-modal imaging.

1. INTRODUCTION

Enabled by deep-submicron CMOS processes, a continuous trend towards miniaturization has led single-photon avalanche diode (SPAD) technology to smaller pitch and larger formats [1]. Digital silicon photomultipliers (D-SiPMs) have profited from this trend, with higher granularity of detection for improved coincidence time resolution (CRT) at a relatively small cost in terms of photon detection efficiency (PDE) [2]. Higher granularity, in spatial and temporal domains, leads to fundamental time resolution limits, enabling time-of-flight PET to achieve significant improvements in image quality [3][4].

In this paper, the SPADnet concept is presented for the first time. SPADnet proposes a fully digital, networked approach to detect gamma events and to perform coincidence in multi-modal time-of-flight PET. SPADnet uses the novel technique of **deferred coincidence detection**, whereas a single-ring or multi-ring arrangement of photonic modules individually detects gamma photons, as well as thermal and Compton events, creates a timestamp and energy estimate, and injects these data into a network. The network can process up to 3.3 million events per second, thus enabling the use of a large number of high-granularity sensors.

The SPADnet approach is scalable, since the number of photonic modules and their arrangement in space requires virtually no changes in the architecture of a new system. In addition, the concept is suitable to major expansions of an existing architecture, such as full-body clinical PETs, with minimal or no hardware redesign. Figure 2 shows the SPADnet photonic module and its individual components.

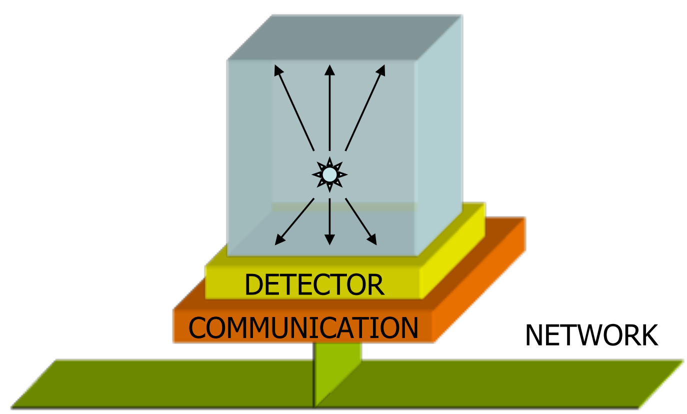

Figure 1. SPADnet photonic module concept.

An artist's rendering of a PET ring composed of SPADnet photonic modules is shown in Figure 2. The arrows indicate the timestamp and energy data flow from photonic modules to network. As shown in the figure, adding an extra photonic module does not impact the architecture, whereas only the reconstruction algorithm needs to be aware of the existence of a new module.

The research leading to these results has received funding from the European Union Seventh Framework Program under Grant Agreement n◦256984 – www.spadnet.eu.

Disclaimer: This publication reflects only the authors' views. The European Community is not liable for any use that may be made of the information contained herein.

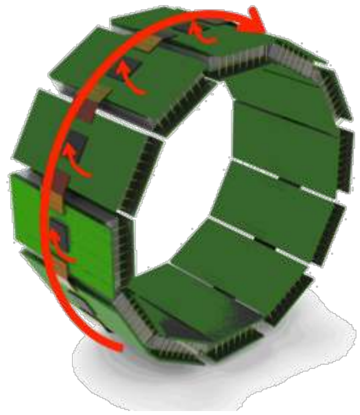

Figure 2. PET ring assembly of coincidence data network.

2. TECHNOLOGY

SPADnet's core enabling technologies are: a fully digital sensor architecture, a gigabit/s (Gbps) digital data network, and a standard 130nm CMOS imaging process with through-silicon via (TSV) technology.

2.1. Photonic Module

The photonic module consists of a matrix of tightly packed sensor devices, or *sensor tile*, whereas TSVs replace wire bonding, thereby enabling reduction of insensitive areas. The photonic module also features highly optimized optical coupling between scintillating crystal and sensor tile, as well as microstructures on all sides, shown in Figure 3, for photon collection maximization during a gamma event. Examples of microstructures for light concentration are shown in Figure 4.

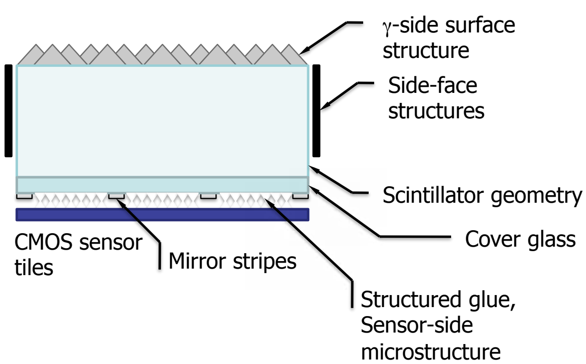

Figure 3. SPADnet photonic module building blocks.

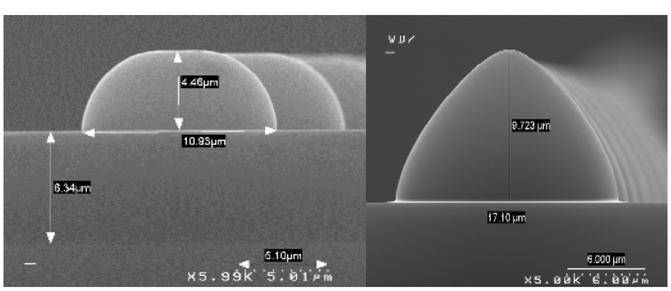

Figure 4. Concentrators fabricated at the interface between scintillator and sensor tile.

Most of the optical structures were conceived to be compatible with ST's commercial CMOS imaging process with TSVs.

2.2. Sensor Device and Sensor Tile

The sensor device, shown in Figure 5, comprises an array of 8x16 pixels, each containing 4 mini-SiPMs and two 12-bit time-to-digital converters (TDCs), with a time bin (LSB) of 64ps. Each pixel contains 720 SPADs and measures 610.5x571.2μm^2, with a fill factor of 42.9%; it is capable of delivering a timestamp and energy measurement at a rate of 100Msamples/s [5]. The sensor tile, combined together onto a rigid substrate, is assembled through a highly automated procedure that also ensures high levels of planarity and good coupling with a slab scintillator, as shown in Figure 6.

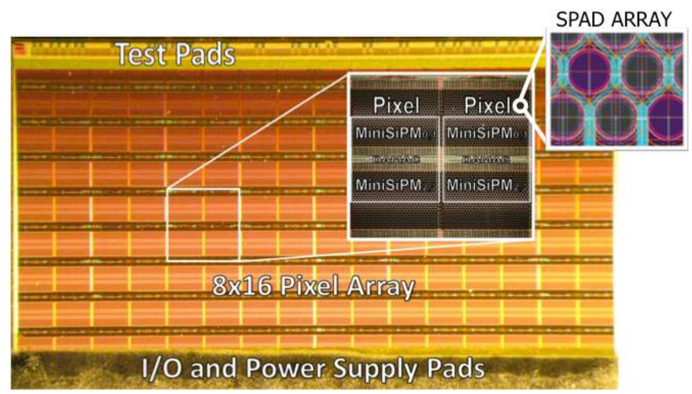

Figure 5. SPADnet sensor device. Inset: pixel and SPAD array detail.

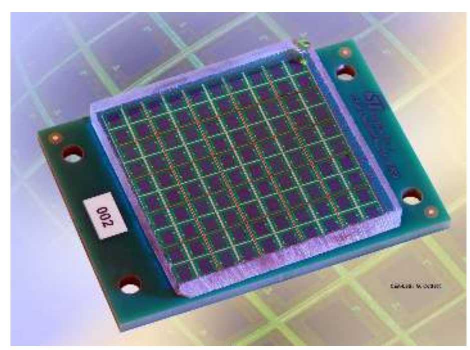

Figure 6. Photonic module assembly with equivalent TSV chips and LYSO-like scintillator crystal slab.

2.3. Network

The network, implemented on a Spartan-6™/Virtex-6™ backbone, reaches a data rate of over 2Gbps in module-to-module communication; it comprises two sub-networks, a *coincidence network* and a *true even network*. The network has been designed to support single-ring and multi-ring schemes; Gamma-ray timestamps and energy measurements detected in a sensor tile are organized as an *event packet* and injected into the coincidence network at each node, shown in Figure 7 as a circle. The node represents a data processing and communication unit that is interfaced to a sensor tile. Each node has the capability to recognize a coincidence pair and to appropriately tag the involved packets. Once the pair is formed, it is transferred to the true event network, designed to act in the opposite direction of the coincidence network so as to help nodes monitor the status of their neighbors. Coincidence pairs are then transferred to the external PC/Mac via the snooper that empties the true event network [6].

The figure shows the direction of data flow during timestamp circulation in a multi-ring system; radial and longitudinal circulation is done simultaneously, thus enabling a more thorough and efficient process. This scheme was adopted to handle inter-ring communication and to ensure scalability to various configurations (pre-clinical, brain, and full-body clinical configurations).

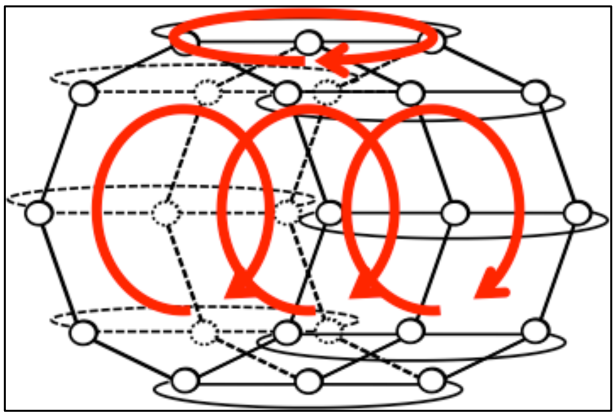

Figure 7. Multi-ring network that can be used in pre-clinical, brain, and full-body clinical PET configurations.

Figure 8 shows the actual implementation of the network; at the center of the ring, one can see a module capable of synchronizing all the nodes in the network with picosecond accuracy at a relatively low frequency, thanks to local clock generators based on phase-lock loops (PLLs).

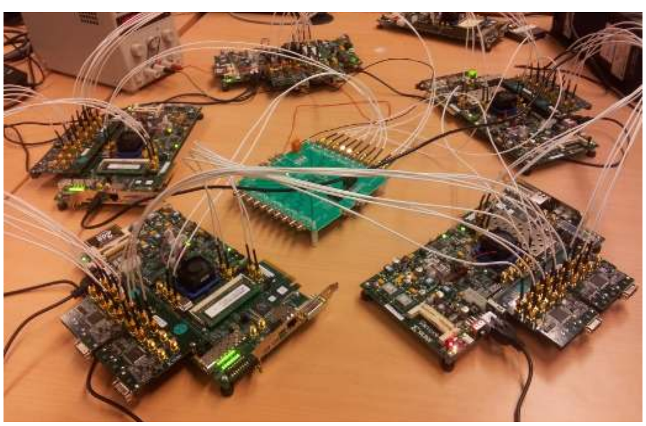

Figure 8. Network experimental implementation; a synchronization unit is also shown at the center of the ring.

3. Preliminary Testing

The sensor device was fabricated on a commercial 130nm CMOS image sensor process with TSVs. The chip is shown in Figure 9 (front and back) in comparison to a 1-Euro coin. It measures 5.4x9.8mm^2. An experimental, partially populated sensor tile is shown in Figure 10; it demonstrates how sensor devices can be tightly packed thanks to TSV based packaging. This demonstrator houses 25 sensor devices, so as to achieve an active area approaching that of the final sensor tile.

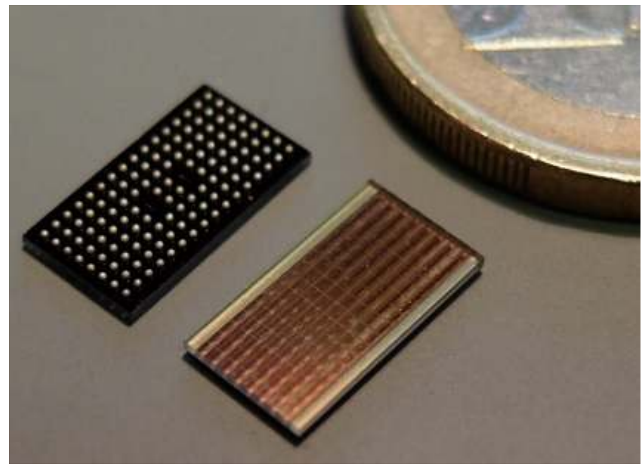

Figure 9. SPADnet Sensor device fabricated in a commercial 130nm CMOS image sensor process. The chip measures 5.4x9.8mm^2.

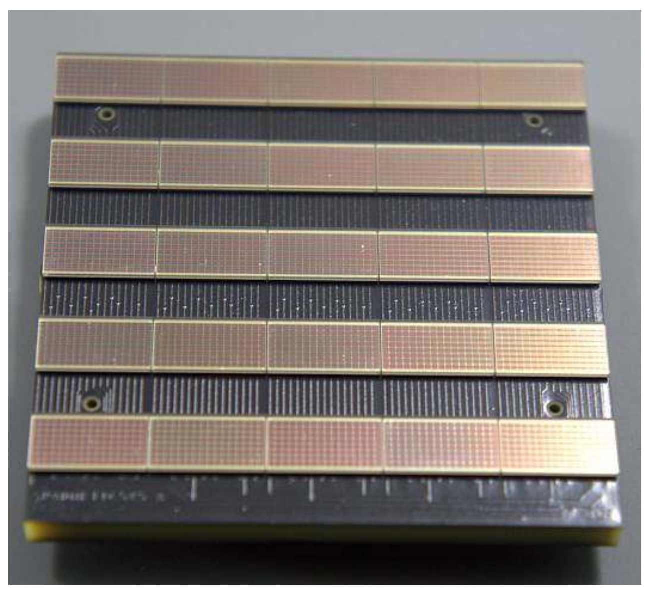

Figure 10. Preliminary SPADnet sensor tile mounted on a rigid PCB and housing 25 sensor devices.

The SPADnet concept has been tested by measuring both energy resolution and CRT, using a standard ^{22}Na and double 3x3x5mm^3 LYSO crystal setup [7]. Energy resolution was measured at 10.8% (Figure 11); CRT was measured at 288ps FWHM (Figure 12).

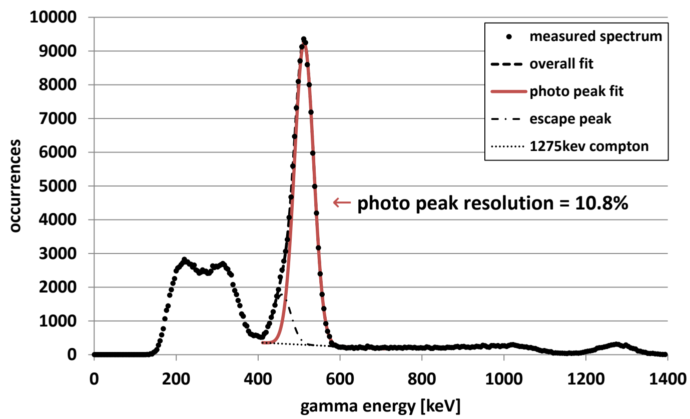

Figure 11. Energy resolution measurement [7].

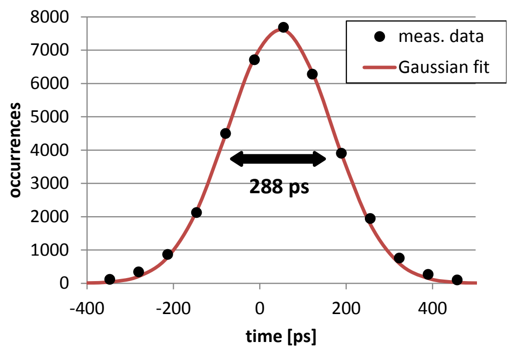

Figure 12. Coincidence resolving time (CRT) obtained using a ^{22}Na source. The Gaussian fit on measured data yielded a CRT of 288ps FWHM [7].

The network was tested with standard photon emission rates expected from LYSO scintillation, achieving nominal data rates and negligible coincidence losses. The plot in Figure 14 shows the latency of a timestamp as a function of Gamma event rates for pre-clinical, brain, and clinical PET configurations for bitrates of 3Gbps.

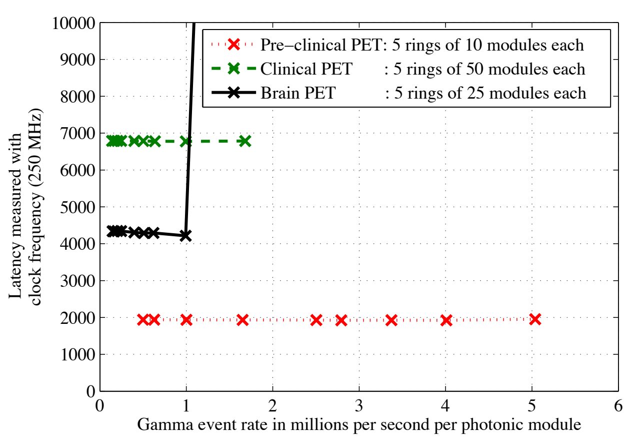

Figure 13. Network latency as a function of Gamma event rate for pre-clinical, brain, and clinical PET configurations.

Figure 14 shows node-to-node bandwidth as a function of Gamma event rates for pre-clinical, brain, and clinical PET configurations for bitrates of 3Gbps.

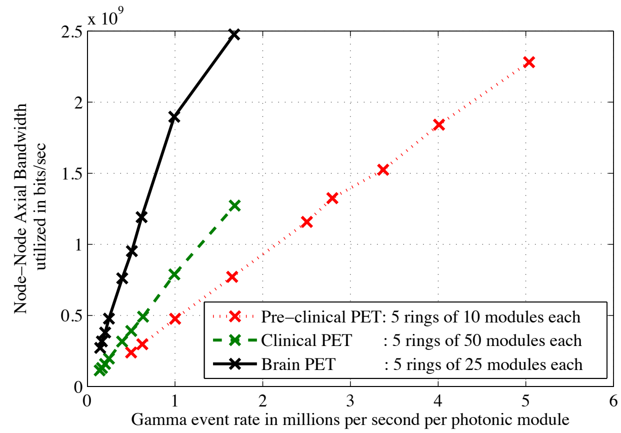

Figure 14. Network performance as a function of Gamma event rate for pre-clinical, brain, and clinical PET configurations.

A CAD drawing of the final system is presented in Figure 15, showing a compact design that will be compatible with up to 9.4T static fields, so as to enable multi-modal PET imaging. The design of a pre-clinical PET based on networked SPADnet photonic modules is well underway. We expect the first reconstructed PET images in the upcoming months.

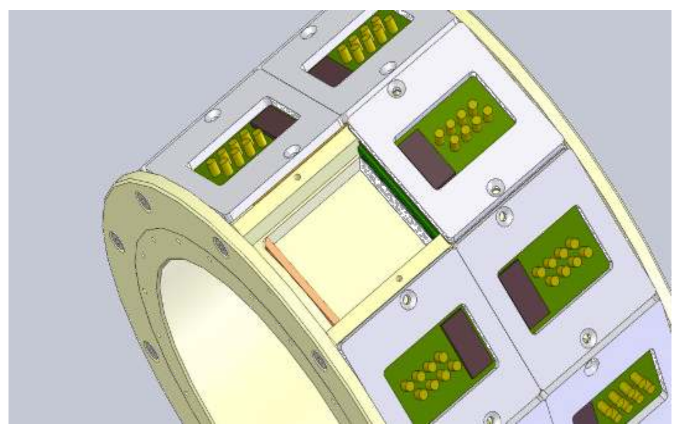

Figure 15. CAD drawing of the final MRI compatible pre-clinical system assembly.

ACKNOWLEDGEMENTS

The authors are grateful to Xilinx, Inc. for its generous FPGA donations.

REFERENCES

[1] E. Charbon, "Single-Photon Image Sensors in CMOS", *SPIE Single-Photon Imaging*, San Diego, (2010).

[2] T. Frach *et al.*, "The Digital Silicon Photomultiplier – Principle of Operation and Intrinsic Detector Performance", *IEEE NSS/MIC* (2009).

[3] M. W. Fishburn and E. Charbon, "System Tradeoffs in Gamma-Ray Detection Utilizing SPAD Arrays and Scintillators", *Trans. Nuc. Sci*., **57**(5), 2549-2557 (2010).

[4] S. Seifert, H.T. van Dam, D.R. Schaart, "The Lower Bound on the Timing Resolution of Scintillation Detectors", *Phys Med. Biol.*, **57**, 1797-1814 (2012).

[5] L.H.C. Braga *et al*., "A 8x16 pixel, 92k SPADs Time-Resolved Sensor with on-pixel 64ps 12b TDC and 100Msamples/s Real-Time Energy Histogramming in 0.13µm CIS Technology for PET/MRI Applications", *IEEE ISSCC* (2013).

[6] C. Veerappan C. Bruschini, E. Charbon, "Sensor Network Archiecture for a Fully Digital and Scalable SPAD based PET System", *IEEE NSS* (2012).

[7] L.H.C. Braga, L. Gasparini, L. Grant, R.K. Henderson, N. Massari, M. Perenzoni, D. Stoppa, R. Walker, "Complete Characterization of SPADnet-I – A Digital 8×16 SiPM Array for PET Applications", *IEEE NSS*, N8-6 (2013).