SPADnet
a Digital Silicon PhotoMultiplier for Positron Emission Tomography: presentation and characterization

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Positron Emission Tomography

- Functional imaging of radio-isotope which emit a positron.
- Positron and electron annihilate. Two 511keV gamma photons are emitted in coincidence at 180°.
- Mainly used for oncology.
The SPADnet Concept

Photonic Component, comprising:
- Scintillator (LYSO)
- Sensor (SiPM)
- Network (Gbps)

Scalable, modular System
The sensor
Sensor Requirements for PET

- We want to build a large format, compact, MRI compatible sensor capable of TOF-PET.

- We need to measure for each gamma-ray:
  - Position Of Interaction
  - Energy
  - Time of arrival

- Proposed solution: a fast sensor sensitive to a few photons in CMOS technology
  - Small pixels → Improve spatial resolution
  - Embedded Time to Digital Converters → Time stamp more than one visible photon
  - Real-time energy output → Provide scintillation decay time information
  - Through-Silicon-Via based packaging → Extensible to large format
Silicon Photomultiplier (SiPM)

- SiPM: array of Single-Photon Avalanche Diodes (SPADs)
- Each SPAD is a photodiode operating in Geiger mode
  - The number of fired SPADs is proportional to the number of incident photons
- Particularity of CMOS based SiPM
  - Digitization of the photon
  - Advanced functions could be embedded
SPADnet Pixel Architecture

- 0.57×0.61mm pixel
- 2 x 2 mini-SiPMs (Braga et al., NSS2011)
- 720 SPADs (Walker et al., NSS 2012)
- 1 active TDC
- 43% array fill factor

For more details, see Braga *et al.*, ISSCC 2013 and Walker *et al.* IISW 2013
Discriminating gamma event

- The chip is an array of 8x16 pixels
- Fast readout of the counted photons
- Integration is triggered by comparing the photon flux to a threshold
SPADnet1 chip: 16x8 pixels, ~600µm pitch. 720 SPADs per pixel. 92k SPADs
Characterization

1 – SPADs
   Dark Count Rate
   Dead Time
   Photon Detection Probability

2 – Sensor
   Gamma spectra
   Coincidence Timing Resolution
Dark Count Rate

- Selecting one SPAD per pixel at a time
- At 23 °C and 1.5V excess bias: median DCR = 330 Hz
- Noisy SPADs could be disabled
- DCR double every 15°C

Limited by tunneling
Limited by thermally assisted Shockley-Read-Hall
SPAD Dead Time

- Count with respect to the photon flux
- Deadtime: 50ns. Paralysable behaviour

\[ \text{Counts} = N_{ph}e^{-N_{ph}\tau} \]
\[ \tau = 50\text{ns} \]
Photon Detection Probability

- Selecting one SPAD per pixel at a time
- Peak SPAD PDP 32% at 450 nm at 20 °C and 1.5V excess bias (incl. afterpulse)

With respect to wavelength
Gamma measurements

- Single 3.5x3.5x20 mm³ LYSO crystal (clinical) on 9.8x4.6mm² active area
- Teflon wrapped. Optical grease coupled.
- Room temperature. No stabilization. 1.5 V excess bias
Triggering mechanism gives robustness with respect to DCR

Accumulation show the 3.5x3.5x20 LYSO needle
Gamma Spectra

20°C
1.5V excess bias
80% SPAD enabled

Energy resolution @ 511 keV
~ 11.5% FWHM

LYSO Background

59.5 keV

122 keV

356 keV

511 keV
Coincidence Resolution Time

20°C
1.5V excess bias
80% SPAD enabled

- Single 3.5x3.5x20 mm³ LYSO crystal (clinical) on 9.8x4.6mm² active area
- 128 TDCs per chips enable multi-timestamp processing
- Best CRT in this experiment : 530 ps FWHM
Gamma measurements

- LYSO matrix with 35x35 pixels and 1.3mm pitch, and optical separator, 13 mm thick (preclinical) on 9.8x4.6mm² active area. Optical grease coupled. GORE® Diffuse Reflector. No alignment with pixels.
- Room temperature. No stabilization. 1.5V excess bias
Small needle matrix

- Post processing: Filtering noise (5 count) + centroid

One 511 keV event

LYSO needles are clearly resolved
(overflow at edges)

Energy resolution @ 511 keV: ~13 % FWHM
Conclusion and future steps

- SPADnet is a 4 sides tileable Gamma sensor in CMOS technology
- 8 x 16 pixels, 0.6 mm pitch, 92k SPAD
- TDCs and event discriminator embedded.
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- Second version of the SPADnet chip, 9.8 x 9.8 mm², higher fill factor
Thanks for your attention