Photodetection Module: Photon-to-Digital Converters (aka Digital SiPM) and Enabling Technologies

Photon-to-Digital Converters

- SPAD Array
- CMOS Electronic Readout
- Through Silicon Via (TSV)
- Power Cu cables
- 2 × Optical fibers

Silicon Interposer

- Tile controller
- Silicon Photonics Communication Module

Power Management
From Analog to Digital Silicon Photomultiplier
Single photon avalanche diode (SPAD) is the basic unit cell of analog and digital SiPM.
The Analog SiPM Paradox

- A SPAD is a Boolean detector (“0” or “1”): digital information available at the sensor level

- Analog SiPM = Sum of boolean detectors (array of SPAD) to get a linear response...

- Then, use a current/transimpedance amplifier + shaper + ADC

To digitize the data... again!
Enabling Progress for Single-Photon Detection: Digital SiPM Advantages

- Each SPAD is coupled one-to-one with its individual readout circuit
  - Photon-to-bit conversion at the sensor level
- Improved noise immunity
- Output capacitance is not an issue (compared to analog SiPM)
- Single photon counting over the entire dynamic range
- Control over each SPAD: faulty or radiation damaged = shut off
- Mitigates afterpulsing noise (programmable holdoff/deadtime)
- No trigger = Low power consumption
Photon-to-Digital Converter: Motivation and going 3D
3D versus 2D Photon-to-Digital Converters

The solution: 3D vertical integration

- Enables high photosensitive fill factor with
- Advanced digital signal processing
- Choice of SPAD optimal technology with
- Choice of CMOS optimal technology for application specific functions

\[\text{SPAD} = \text{Electronics}\]
Photodetection Module

• Silicon-based solution for **cryogenic instrumentation** → coefficient of thermal expansion matching
  • Particle physics instrumentation: liquid argon and liquid xenon experiments
    • nEXO (neutrino) : ~5 m²
    • ARGO (dark matter) : ~250 m²
  • Quantum communication (quantum key distribution satellite receiver)

• Medical Imaging
  • Positron emission tomography (PET)
  • Computed tomography (CT)

• Neutron Imaging
Photon-to-Digital Converter: SPAD Array Technologies
3D Photon-to-Digital Converters : SPAD Array Technologies

- Frontside illumination
  - Sherbrooke – Teledyne DALSA custom process SPAD array
  - CMOS SPAD
    - TSMC 180 nm
    - TSMC 65 nm
- Backside illumination concept ongoing at Triumf (F. Retiere)
SPAD Array Technologies: Sherbrooke – Teledyne DALSA SPAD array
Sherbrooke – Teledyne DALSA SPAD and Flying Probe

- Single cell with various:
  - SPAD size and shape
  - process variation
- Small array (4 x 4 cells)
  - cell size and pitch
  - w/ or w/o trench
- 6" wafer-level flying probe
- Single channel
- Multichannel probe under development now

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Chip Probe + SPAD TDSI

Chip Probe + TDSI (35 um) p+/deep n-well
Temp. = 20°C
Vbd/Vov = 22.1 V/3.3 V (15%)
Median DCR/AP (deadtime) = 631 cps / 8% (60 ns)
PDE peak (%) = 60% @ 420 nm
PDE ≥ 30% = 400 – 565 nm
SPTR(ps FWHM) = 21 (820 nm) / 34 (410 nm)
• Delta-doping: surface energy band engineering to cause electron drift
• Increase internal quantum efficiency (▲)
• Delta doping + anti-reflective coating (+) : major PDE improvement in VUV range
• UdeS-TRIUMF-Lawrence Berkeley Lab collaboration « Towards high efficiency single VUV photon detectors »

Simulation of energy bands with delta-doping
Simulation of SPAD quantum efficiency with delta-doping
Photon-to-Digital Converter: CMOS Readout
3D Photon-to-Digital Converters: CMOS Readout

1. High resolution timing applications
   - Applications: Quantum key distribution, PET, CT
   - Time-to-digital converter target: 5 ps resolution, sub 5 ps RMS jitter *(measurements ongoing and very promising)*
   - CMOS 65 nm

2. Low power, large area experiments
   - Applications: Neutron Imaging and Noble liquids instrumentation
   - CMOS 180 nm
   - Rev. 2: Jan 2022

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Photon-to-Digital Converter: CMOS Readout

Microelectronic Readout Integrated Circuit for Precise Single Photon Timing Resolution
ASIC Overview (originally for PET)

- TSMC 65 nm CMOS (LP)
- 16 × 16 pixels in 1.1 × 1.1 mm²
- Jitter: 18 ps RMS for 256 pixels

Rev 1. 2019

Rev 2. 2021
Time-to-Digital Converter

Time-to-digital converter
• CMOS 65 nm
• 8x Vernier ring-oscillator-based TDC
• 5.5 ps RMS timing jitter (1 channel)
• 22 µW @ 1 Mevents/s

Data acquisition system:
• 8 input channels
• Common trigger for all channels in start-stop mode
• 2x 8-channel time-to-digital converters
• Leading and falling edge timestamping for TOF and TOT measurements
• Mezzanine with ZYNQ and gigabit Ethernet
• On-board calibration
Photon-to-Digital Converter: CMOS Readout

Microelectronic Readout Integrated Circuit for Low Power, Large area and Analog SiPM Replacement
CMOS: Low Power PDC Readout - Overview

- TSMC 180 nm BCD process
- 5 x 5 mm$^2$ active area
- 64 x 64 pixels (4096)
- 78 μm pixel pitch
- 3-side buttable (for tiles)
- Digital-on-Top design flow

One row of 61 2D SPADs for functional testing

A single pixel

Quenching circuit and 3D interconnect

Digital signal processing

5.3 mm

5.85 mm

64 x 64 pixel array (4096)

Active area: 5 x 5 mm$^2$

32 I/O pads in single row

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Low Power CMOS PDC Readout – 3 Outputs

1. Flag
   - Timestamped with an external TDC (TR < 100 ps RMS)
   - Used to trigger digital sum read request and discriminate dark count

2. Digital Sum
   - Executed on request (asynchronous) or
   - Sampling from 10 ns to 10 µs (128 bin FIFO)

3. Analog Monitor
   - Amplitude proportional to number of triggered pixels
   - Lower output capacitance than analog SiPM

Pixel functionalities:
   - Enable for each SPAD
   - Adjustable hold off (afterpulse)
   - Embedded testing in each pixel
Photon Detection Module: Silicon Interposer
Photodetection Module – Silicon Interposer: K. Deslandes #512

- Coefficient of thermal expansion matching between components:
  \[\rightarrow\] Cryogenic + space instrumentation
- Silicon-based « PCB »
- Collaboration with IZM Fraunhofer (Berlin)
- 8 redistribution layers
- 8” wafer
- Initial results conclusive
- Full stack interposer testing summer 2021
Interposer prototype: Characterization run

RF measurement over 8” wafer (4 RDL)

Kapton connector test structures
Transmission lines w/ wafer change
Surface mount footprints
Via daisy chains
Power mesh structures
Flipchip assembly
200 mm (8 in)
Wafer to wafer TSV daisy chain
Test structures on the wafer

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Photon Detection Module: Silicon Photonics-Based Low Power Communication Interface
Photodetection Module – Silicon Photonics Comm Module

• Cryogenic operation
  • Noble liquid experiments

• One laserless communication module per photodetection module
  → Laser only at the DAQ → Low power at the photodetection module

• Optical fibers: resistant to EMI and ground loops
Silicon Photonics Data Acquisition and Control System

- Based on passive optical networks
- $\lambda_1$:
  - Bits to program the module
- $\lambda_2$:
  - Down: Clock signal
  - Up: Data
- Tiles can be multiplexed to save on the number of fibers and hence feedthroughs

Standard ITU-T G.694.1
1. Photonic Wirebonds
2. Michelson Modulator 1:
   - Slow Thermal Phase Shifter
   - Fast PN Junction Phase Shifter
3. Michelson Modulator 3:
   - Slow PN Junction Phase Shifter
   - Fast PN Junction Phase Shifter
4. Germanium Photodiode
5. Michelson Interferometer (Passive)
6. Grating couplers (Optical I/O)
7. Electrical I/O
8. Germanium Photodiode
9. Michelson Modulator 2:
   - Slow PN Junction Phase Shifter
   - Fast PN Junction Phase Shifter
10. Germanium Photodiode
11. Micro-Ring Resonator
12. Michelson Interferometer
    - Fast PN Junction Phase Shifter

2.3 × 3 mm²
65 nm CMOS SPAD and Quenching Circuit

6.29 ps FWHM Single Photon Timing Resolution and Laser Beam Monitoring Device
Single SPAD Module based on CMOS 65 nm Architecture

- Single input (12 V) and single output (0-1 V)
- 17.6 um Ø, p+/n-well
- Vbd/Vov = 10 V/2.5 V (25%)
- avg. DCR/AP (deadtime) = 100 kcps / 5% (60 ns)
- PDE = 1% (820 nm) / 5% (410 nm)
- Single photon timing resolution (SPTR): 6.29 ps FWHM
Maitai
- Pulse rate: 80 MHz
- Pulse width: < 100 fs
- Wavelength: 820 nm (690-1040 nm)

OPO outputs
1. 820 nm (690-1040 nm pump laser)
2. 410 nm (345-520 nm) + … still some 820 nm!
3. (930-2500 nm)
4. (490-750 nm)
Single Photon Timing Resolution: No Filter

Black peak to black peak: 18.4 ps

Counts (a.u.)

Time (ps)

-75 -50 -25 0 25 50 75 100 125

No filters

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Single Photon Timing Resolution: Low Pass Filter

Black peak to blue peak: 4.6 ps $\rightarrow$ ~ lens filter thickness

Short pass filter (<600 nm)
SPTR: 9.1 ps FWHM
Single Photon Timing Resolution: High Pass Filter

Black peak to red peak: 3.8 ps $\rightarrow$ ~ lens filter thickness

High pass filter (>593 nm)
SPTR: 9.9 ps FWHM
65 nm CMOS SPAD and Quenching Circuit Module

Counts (a.u.)

Time (ps)

Short pass filter (< 600 nm)
High pass filter (> 593 nm)
No filters

Nice ultraprecise and simple laser beam monitoring system

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Conclusion

• Single photon instrumentation plays a key role in various fields.

• 3D Photon-to-digital converters have advantages over analog SiPM and can be tailored to the experiments.

• Silicon interposer has great potential for low background experiments.

• Silicon photonics communication enables:
  • minimize EMI + ground loops;
  • optical fiber bandwidth → can mux many readout in one fiber and minimize the number of feedthroughs in a cryostat.

• Precise timing systems:
  • 8 channel benchtop TDC module soon available with ~10 ps FWHM resolution;
  • SPAD + readout: handy time-based laser monitoring system with sub 10 ps FWHM SPTR

• Looking for collaborators to work on power management unit and full custom tile controller.

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Selected Publications from our Team


Selected Publications from our Team


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A team’s work

Université de Sherbrooke

- Roger Lecomte
- Henri Dautet
- Julien Sylvestre
- David Danovitch
- Caroline Paulin
- Catherine Pepin
- Danielle Gagné
- Étienne Paradis
- Étienne Grondin
- Konin Koua
- Simon Carrier

- Nicolas Roy
- Frédéric Nolet
- Samuel Parent
- Audrey Corbeil Therrien
- Benoît-Louis Bérubé
- Marc-André Tétrault
- Tommy Rossignol
- Gabriel St-Hilaire
- Jacob Deschamps
- Xavier Bernard
- Thomas Dequivre
- William Lemaire
- Philippe Martel-Dion
- Nicolas St-Jean
- Artur Turala

- Luc Maurais
- Maxime Côté
- Vincent Philippe Rhéaume
- Étienne Desaulniers Lamy
- Alexandre Boisvert
- Michel Labrecque-Dias
- Pascal Gendron
- Arnaud Samson
- Jonathan Bouchard
- Frédéric Dubois
- Marc-Olivier Mercier
- Frédéric Bourque
- Keven Deslandes
- Charles-Frédéric Gauthier
- Valérie Gauthier

Collaborators

- Fabrice Retiere (Triumf)
- Lorenzo Fabris (ORNL)
- Simon Viel (Carleton)
- nEXO Collaboration
- nEXO Canada

Teledyne DALSA Semiconducteur Inc

- Claude Jean (CEO)
- Stéphane Martel
- Robert Groulx
- Maxime Côté

Teledyne Imaging

Collaborations

- nEXO Collaboration
- nEXO Canada

Innovation.ca

Canadian Astroparticle Physics Research Institute

Canadian Foundation for Innovation

Research Excellence Fund

ApoGéé Canada

Bourse d'Excellence en Recherche

Institut Quantique

Québec

Fonds de recherche sur la nature et les technologies

Canadian Microelectronics Corporation

Triumf

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