The 3D digital SiPM for nEXO

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Front-End Electronics 2016
AGH University of Science and Technology
Krakow, Poland
May 31th – June 3rd 2016
FINALLY!
SHERBROOKE HAS WORKING
3D DIGITAL SIPM!

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Frédéric Bourque, Tommy Rossignol, Xavier Bernard, Samuel Parent, Vincent Philippe Rhéaume, Maxime Côté, Luc Maurais, Frédéric Nolet, Thomas Dequivre, Elias Al Alam, Réjean Fontaine, David Danovitch, Julien Sylvestre, Serge Charlebois

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Presentation outlines

• What is nEXO?
• Focus of the photodetectors and front-end for nEXO
  • Why go digital instead of analog SiPM?
• Sherbrooke’s architecture proposal based on 3D digital SiPM
• Power consumption
• Sherbrooke’s first 3D digital SiPM working prototype
Nobel prize in physics 2015
awarded to
Takaaki Kajita
Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan
and
Arthur B. McDonald
Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

Breakthrough Price in Fundamental Physics 2016
awarded jointly to the Daya Bay, Kamland, SNO, Super-Kamiokande (Super-K), and T2K/K2K collaborations “for the fundamental discovery of neutrino oscillations, revealing a new frontier beyond, and possibly far beyond, the standard model of particle physics.”
So, neutrino has mass, but the actual mass is unknown...

A measurement that would shed light both on the actual mass of a neutrino and the origin of this mass is the detection of an extremely rare process known as neutrino-less double beta decay (0νββ).

Additionally, observation of this process could shed light on another fundamental mystery: why in a Big Bang that started with pure energy we ended up with a universe composed almost entirely of matter but no anti-matter?

\[ \text{Standard model} \]

**2ν double β - decay**

\[ 2 \, n \rightarrow 2 \, p + 2 \, \beta^- + 2 \, \bar{\nu}_e \]

\[ \text{Lepton number conservation violated} \]

\[ \text{New physics} \]

**0ν double β - decay**

\[ 2 \, n \rightarrow 2 \, p + 2 \, \beta^- + 0 \, \bar{\nu}_e \]
• nEXO = (next) Enriched Xenon Observatory
• Recently, EXO-200 proved the existence of $2\nu\beta\beta$ in Xenon
  • If $2\nu\beta\beta$ did not exist, then $0\nu\beta\beta$ would not exist

• High sensitivity + excellent energy resolution required
Are you patient?... Some numbers

Natural radiation decay rates

A banana ~10 decays/s
A bicycle tire ~0.3 decays/s
1 L outdoor air ~1 decay/min

100 kg of $^{136}$Xe (2$\nu$) ~1 decay/10 min

$0\nu\beta\beta$ decay >1000 x more rare than 2$\nu\beta\beta$

$0\nu\beta\beta$ half life in the order of ~$10^{27}$ years
Age of universe 1.4 x $10^{10}$ years

For 5000 kg, < 20 events per year!

Source: Thomas Brunner
The EXO concept for the detection of $0 \nu \beta \beta$ decay

- Large ultra-pure volume of enriched liquid $^{136}$Xenon
  - Contaminants removed by filtering
  - Use ultra-low radioactivity material around the LXe
    - Then rely on self-shielding
- Measure ionization $e^-$
  - Reconstruct position on segmented anode (wires or pads/strips)
  - Excellent multi-pulse separation
- Measure scintillation photons
  - Timing for drift direction position reconstruction
  - Achieve excellent energy resolution combining with charge measurement

Source: nEXO collaboration, F Retiere
• Next-generation neutrinoless double beta decay detector
• 5 t liquid xenon TPC similar to EXO-200 (50x the size)
• Possible location in SNOLab Cryo Pit (Sudbury Canada) (6010 mwe)
Searching for $0\nu\beta\beta$ with nEXO

- Analog SiPM or 3D digital SiPM for light detection
- Tiles for charge read out
- 3D event reconstruction
- Expected $\sigma/E$ of 1% at Q-value

Source: nEXO collaboration
Photodetector + Front-End Electronics Requirements

- $\lambda^{136}\text{Xe} : 178$ nm
- PDE: $> 15\%$ at 178 nm
- DCR: $< 50$ s$^{-1}$/mm$^2$
- Correlated avalanche probability: $< 20\%$
- Very low photon counts
- Operating temperature: 161 K
  - **Very low power dissipation required**
  - Power budget: **40 W for 4-5 m$^2$** of photodetector!
  - Thermal and mechanical simulation required for packaging
- With less than 20 $0\nu\beta\beta$ events per year... can’t miss any ;-) 
- Radio purity, low organic contamination and tracking of materials
  $\rightarrow$ the main challenge is making sure we understand the background so we can actually really identify the events as $0\nu\beta\beta$. 

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Two possible solutions currently considered:

- Analog SiPM
  - FBK
  - Ketek
  - Hamamatsu
- Analog front-end + ADC (ref: BNL)
  - Series and parallel connections of SiPM per channel

OR

- 3D digital SiPM
  - Each SPAD digitized individually
    - Modified FBK or Ketek SiPM
    - Sherbrooke’s new SPAD array (underway)
  - Mixed-signal front-end electronics integrated under the SPAD array in 3D
Single Photon Avalanche Diode: the basic cell of SiPM

- **SPAD (Geiger mode)**
  - Gain = $10^4$-$10^6$
  - $V_{BR} < V_{bias}$
  - metastable

- **Avalanche Photodiode**
  - Gain = 10-1000
  - $V_{APD} < V_{bias} < V_{BR}$

- **Photodiode**
  - Gain = 1
  - $V_{bias} < V_{APD}$

Non linear response
It’s a binary detector!
Bottom line, in analog SiPM, we sum binary detectors to get a linear response...

Then, use a preamplifier/transimpedance amplifier + shaper + ADC to digitize the data... again!

• How to take advantage of the SPAD’s digital nature?
• Can power consumption be saved using a digital approach compared to the classic analog readout?

• 3DdSiPM is the “natural” evolution of analog SiPM
Why Go Digital

• No event = no (very low) power
  ▪ Analog readout always “ON”
  ▪ Digital SiPM: power consumption is a function of event rate

• Can disable noisy SPAD to lower noise

• SPAD afterpulsing: reduced by programmable holdoff
  ▪ Important at cryogenic temperature: trap life time ↑

• Calibration paradigm shift
  ▪ Analog SiPM: SPAD-to-SPAD and electronic channels variations, parameters drift with time...
  ▪ Digital: pixel to pixel variation irrelevant → 0 or 1
  ▪ Need to revisit calibration requirement
Proposed Solution for nEXO

3D digital SiPM:
• 1 cm²: nEXO resolution
• 40,000 SPADs per 3D digital SiPM
• SPAD: 50 x 50 µm²
• Total area = 4.096 m²

Silicon interposer:
• 8 x 12 cm²
• Commercial CMOS process
• 3D digital SiPM per interposer: 96
• 32 columns x 16 interposers per column around the barrel = 512

DAQ:
• Outside vessel
• FPGA-based

One of the silicon interposer could be used as a hub to minimize the number of feedthroughs. Compromise between electronic power consumption and feedthroughs “heat sink”
3D Digital SiPM Cross-section

TIER 1 - SPAD

TIER 2 - Electronics

~10 mm

~150 μm
3D Digital SiPM Cross-section

TIER 1 - SPAD

TIER 2 - Electronics

~30 µm
Silicon Interposer

~100-120 mm

~800 µm
Controller ASIC

Silicon Interposer

Interposer Controller

~10mm

~800 µm
2.5D integration of 3D Digital SiPM on Si interposer

TIER 1 - SPAD

TIER 2 - Electronics

Silicon Interposer

~60 µm

Interposer Controller

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Silicon Interposer

Advantages of the Silicon Interposer:

- Same Coefficient of Thermal Expansion (CTE)
- Commercial CMOS process already available (Teledyne DALSA CMOS HV 0.8 µm)
- Takes advantage of streamlined commercial 2.5D/3D assembly

- www.c2mi.ca
- www.usherbrooke.ca/3it
3DdSiPM Architecture for nEXO

- Wired-OR: Flag to the interposer logic
- Parallel adder provides the number of SPAD fired upon interposer request
- Low power digital asynchronous logic (no clock)
Interposer Architecture: Coincidence and Threshold

**Interposer**
- Adjustable coincidence window
- Adjustable threshold
- A trigger is generated when:
  - Flag count > threshold
  - Inside the coincidence window
- The parallel adder of each 3DdSiPM is activated for the duration of the scintillation
- Data transmission logic
The proposed 3DdSiPM has a total area of 1 cm\(^2\) and is composed of three modules.

- 40,000 quenching circuits to individually quench the SPAD
- A wired-OR for the flag
- A parallel adder for the sum

Power consumption of the 3DdSiPM depends on the event rates

- Power consumption evaluated for a DCR of 5 kHz/cm\(^2\)

<table>
<thead>
<tr>
<th>Consumption per 3DdSiPM (1 cm(^2))</th>
<th>Static (µW)</th>
<th>Dynamic (µW)</th>
<th>Total (µW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quenching circuit (40k)</td>
<td>10</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>Wired-OR</td>
<td>0.3</td>
<td>1.3</td>
<td>1.6</td>
</tr>
<tr>
<td>Adder</td>
<td>5.2</td>
<td>1E-3</td>
<td>5.2</td>
</tr>
<tr>
<td>Total</td>
<td>15.5</td>
<td>2.3</td>
<td>17.8</td>
</tr>
</tbody>
</table>

So... for 4 m\(^2\), the digitization cost ~0.7 W!
Further evaluation must be done on the 3DdSiPM and the interposer:

- **3DdSiPM**
  - Output buffer to the silicon interposer

- **Interposer**
  - Communication management
  - Output buffer to the DAQ
  - Logic for the coincidence

All of the above are also required for the analog solution
Conclusion on 3D digital SiPM for nEXO

- Interposer design underway
  - for both analog and digital SiPM
  - Process development required (both side RDL + decoupling cap)
- CMOS readout ASIC design underway (Fab: 12/2016)
- DOE down select 18-24 months
- Construction planned for ~2020
- Operation ~2025

- 3D digital SiPM is a relevant technology for cryogenic instruments
  - Low power consumption
  - No trade off in signal to noise ratio compared to the analog solution
  - Discriminate DCR while preserving 100% of good events
- Technology of interest for other noble liquid and single photon cryogenic detectors
University of Alabama, Tuscaloosa AL, USA — T Didberidze, M Hughes, A Piepke, R Tsang
University of Bern, Switzerland — J-L Vuilleumier
Brookhaven National Laboratory, Upton NY, USA — M Chiu, G De Geronimo, S Li, V Radeka, T Rao, G Smith, T Tsang, B Yu
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D Moore, I Ostrovskiy, A Schubert, M Weber
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Technical University of Munich, Garching, Germany — P Fierlinger, M Marino
TRIUMF, Vancouver BC, Canada — J Dilling, P Gumplinger, R Krücken, F Retière, V Strickland
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Scanning Electron Microscope Image

Top tier: SPAD array

50 µm thick

Bottom tier: CMOS readout

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Fig. 1. Block diagram of the 3DdSiPM. In the dashed box: the 3DdSiPM. Outside the dashed box: PCB.
It works!
• Pulsed laser, two intensities.
• Through Silicon Via backside isolation with substrate
• Under bump metallization connection to TSV end cap (Ti/Cu interface)
• ...

➢ 3D integration process related: will not be an issue when process moved to C2MI
Our « in-house » 3D process enabled us to learn a lot and achieve the proof of concept

Not suited for large scale production (we knew!... But that’s what we could afford)

Now that the proof of concept is done, it’s time to scale the process @ C2MI (www.c2mi.ca)

Require R&D
THANK YOU!
see you in Québec for FEE2018!

www.jouvence.com
• Studies of scintillation events detection and the reduction of dark counts:
  ▪ Cluster size (# dSiPM): 1, 2 x 2, 4 x 4, 4 x 10
  ▪ SiPM size in simulation: 1.37 x 1.37 cm²
  ▪ PDE: 5%, 15%, 20%
  ▪ DCR: 50, 100, 150 s⁻¹/mm²

• 1330 0νββ events were considered
  ▪ Within 0.6 m radius of the center point
2×2 cluster
DCR 100 s⁻¹/mm²
PDE ~ 5%

No threshold margin
GEANT4 Data Analysis: Missed Events

Blue curve: The number of missed events for a threshold value

- No event missed when threshold value = 3
- All events are missed at threshold value = 1330
- Only 8 missed events at threshold value = 5

2×2 cluster
PDE ~ 5%
Red curve: The effective DCR

All dark count events are sent

2×2 cluster
DCR 100 s⁻¹/mm²

Dark count threshold value = 4
GEANT4 Data Analysis: Combined results

- 2×2 cluster
- DCR 100 s⁻¹/mm²
- PDE ~ 5%

No threshold margin
**Trigger Scheme: DCR Variation**

- Cluster of 4x4 (~27 cm²)
- PDE of 5%

Threshold Margin Reduction with increased DCR

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Trigger Scheme: PDE Variation

- Cluster of 4x4 (~27 cm²)
- DCR of 50 s⁻¹/mm²

Threshold Margin Increase with PDE
Trigger Scheme: Cluster Size

- DCR of 50 s\(^{-1}\)/mm\(^2\)
- PDE of 20 %

Threshold margin increases with cluster size (even though the dark counts per cluster increases)
Power consumption

- Using SiPM, ~ 5mW static consumption per 5 cm² SiPM (~ 1mW/cm²)
  - Includes the front-end, shaper, peak/hold and the coincidence logic
  - Ref L. Fabris et al, “Concepts of SiPM readout electronics”, NSS/MIC 2014
- Power consumption of the 3D Digital SiPM depends on the event rates
- The proposed 3DdSiPM has a total area of 1 cm² and is composed of three modules.
  - 40 000 quenching circuits to individually quench the SPAD
  - A wired-or for the flag propagation
  - A parallel counter for the sum
- The 40 000 QC consumption is:
  - Static: ~ 10 uW
  - Per hit: ~ 300 fC
- The wired-or
  - Static: ~ 10 uW
  - Per Flag: ~ 300 fC
- The parallel counter:
  - Static: ~ 10 uW
  - Per hit: ~ 300 fC
Interdisciplinary Institute for Technological Innovation

3IT

The 3IT provides academic and industrial partners with a dynamic, flexible, cross-cutting and translational ecosystem for research and innovation.
**MiQro Innovation Collaborative Center (C2MI)**

**Investment:** 218 M$ + 135 M$

**Research areas:**
- Packaging
- Testing of complex microsystems
- 3D integration
- Micro electromechanical systems (MEMS)

**Cleanroom size:** 5300 m²

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So, **neutrino** has **mass**, but the actual mass is **unknown**...

A **measurement** that would shed light both on the **actual mass** of a neutrino and the **origin** of this mass is the detection of an extremely rare process known as neutrino-less double beta decay \((0\nu\beta\beta)\).

Additionally, observation of this process could shed light on another fundamental mystery: why in a Big Bang that started with pure energy we ended up with a universe composed almost entirely of **matter** but no **anti-matter**?

The **Standard Model** of particle physics says **0νββ should not exists**, → it is violation of lepton number conservation.

If we measure it, it will be the first direct observation of physics beyond the Standard Model.