Particle/Photon to Digital Converter
Harnessing the power of 3D integration

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Part of the PDC group but not all ideas have been discussed
This talk in one slide

Single Photon Avalanche Diode
- Visible/UV photon
- Ultra-thin contact (<10nm)
- Gain of ~10^6
- Pixel separation (guard ring/trench)

Digital Hybrid Photo-detector
- keV electron
- Thin passivation
- Gain of ~10^6

Low-Gain Avalanche Diode
- Minimum Ionizing Particle
- Gain of ~100

Diode
- Heavy Ionizing Particle
- No gain
- CMOS
- Aka. electronics

~15μm
<1μm
Starting point - SiPM

- Avalanche gain $\sim 10^6$
- Avalanche evolution jitter $<100\text{ps}$
Next step - 3D integrated digital SiPM

TIER 1 - SPAD

TIER 2 - Electronics

3D Digital SiPM

quenching circuit

quenching circuit

quenching circuit

Digital Signal Processing
How to Build a Fully Industrial 3D Digital SiPM?

Partnership with Teledyne DALSA Semiconductor Inc. (Bromont QC, Canada)

Wafer scale 3D digital SiPM technology

SPAD array layer

SPAD process

Wafer level process

CMOS readout

TSMC CMOS readout

3D process

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2D SPAD made-in Canada (Bromont, QC)

- 150 mm wafer (custom process using DALSA CCD production line)
- 1x1 to 5x5 mm² SPAD array
CMOS functionalities

• Timing with minimum position information for SPADs
• Not an intrinsic limitation
• In principle, can be tailored as needed
Direct Bond interconnect, the enabling technology

- Teledyne DALSA in Quebec expected to provide access to technology
Next step – backside illuminated

- Motivated by VUV photon detection
  - Need ultra-thin top contact (<10nm)
- Enabled by molecular bonding
  (Direct bond Interconnect)
  - Enable back-side thinning post bonding
  - CMOS chip is handle wafer
Hybrid solution for UV to visible (120-600nm) photon

Main motivation
- LXe (175nm) and LAr (128nm) scintillation light
- $0\nu\beta\beta$ and dark matter search

Single photon avalanche diode
- Gain $> 10^5$

Advantages
- Very high efficiency expected ($>50\%$) in UV and visible
- Single photon timing resolution $<50$ps
Hybrid solution for red to NIR photons?

- How far can the sensor be depleted?
- If not depleted – diffusion dominated

- Gain of ~10^6
- Ultra-thin contact (<10nm)
- Molecular bonding
- Thin passivation
- CMOS Aka. electronics
- Ultra-thin contact (<10nm)
- Molecular bonding
- Thin passivation
- CMOS Aka. electronics

UV photon

~15µm

<1µm

~20µm

Penetration Depth (nm)

Energy (eV)

Wavelength (nm)
Hybrid photo-detector for lower dark noise

Table 1: Resuming table of the outcomes due to physical behaviours. Legend: \(\checkmark\checkmark\) Fully satisfied; \(\checkmark\) Satisfied; \(\approx\) Partially satisfied; \(-\) Not satisfied

Understanding VSiPMT: a comparison with other large area hybrid photodetectors

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\(^b\)Istituto Nazionale di Fisica Nucleare - Section of Naples
Beating down dark noise using diffusion

- Essentially identical constraints to VUV photon detections
  - Limit material in path of photo-electron
  - Charge collection very close to surface
- Use diffusion to spread charge on more than one SPAD

Photo-cathode

Ultra-thin contact (<10nm)

Thin passivation

Sensor

Gain of $\sim 10^6$

Molecular bonding

CMOS

Aka. electronics

Pixel separation (guard ring / trench)

~15 µm

~20 µm

<1 µm

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Hybrid solution for tracking

- Low Gain Avalanche diode
  - You are the expert
- Very similar to SPAD though:
  - Proportional gain
    - No light production
  - Does not need trench but may be best for fill factor
SPAD + diffusion for tracking?

- **Pros:**
  - Timing of SPAD
  - <100ps

- **Cons:**
  - Need to fire multiple SPADs
  - Diffusion is slow (10-50ns)
  - Radiation hardness of high gain region
  - Photon emission
Luminescence, a SPAD problem
From sensor to module
Silicon interposer

• Motivated by low radioactivity constraint
• Development with Franhoffer IZM
Scaling up to m²

• Tiling constraints depend on application
  • Silicon interposer compelling for cryogenic, low radioactivity constraint
  • Minimizing radiation length and radiation damage at colliders would probably require a different solution

• Ultra-low power data transfer using photonics is attractive

• Building the capabilities for mass production with industry
# Summary

<table>
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Many technology transfer opportunities

• Time of Flight Positron Emission Tomography Single Photon Air Analyser (led by TRIUMF)
  • Used for smoke (even early forest fire detection) and pollution detection

• Quantum communication and computing
  • Very promising with compelling physics experiment “spin-off”

• 3D imaging coupled to pulse light source
  • LiDAR – major market but probably too big to chew