Current status and development of of Digital CMOS SiPM

for scintillation-based detectors towards All-Digital sensors

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Outline

A constructive-disruptive approach to new scintillator-based radiation detectors

- Application requirements and sensor concept
  - A CMOS process for a performant analog SiPM
    - A conservative digital circuit design
      - New Digital Signal processing approaches

Outline

A constructive-disruptive approach to new scintillator-based radiation detectors

Application requirements and sensor concept

Real-time portable Positron Emission Tomography for ***agriculture*** *sets a high demanding standard to* ***high spatial resolution*** *and* ***fast timing*** *digital sensors*

A CMOS process for a performant analog SiPM

A conservative digital circuit design

New Digital Signal processing approaches

PET in agriculture

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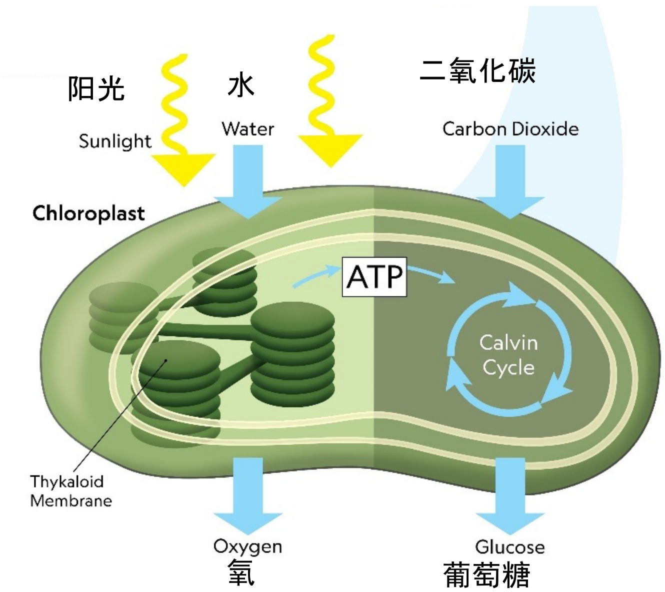
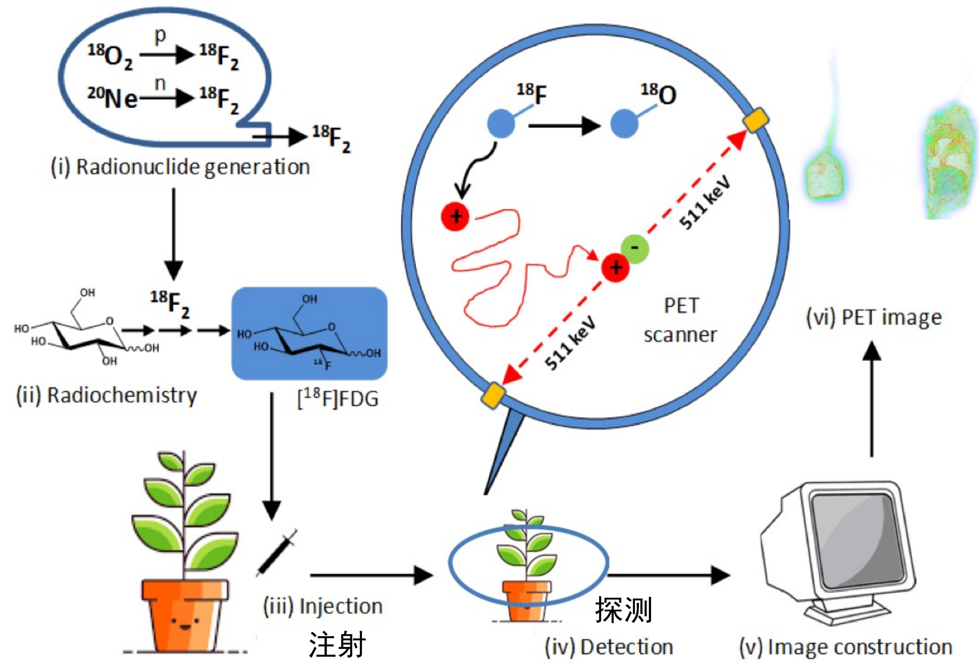
Quantify plants metabolism for the precise administration of Nitrogen fertilizers to reduce soil deterioration





Low energy gamma ray detectors, requiring spatial resolution < 0.5 mm and timing resolution < 100 ps

The detector concept

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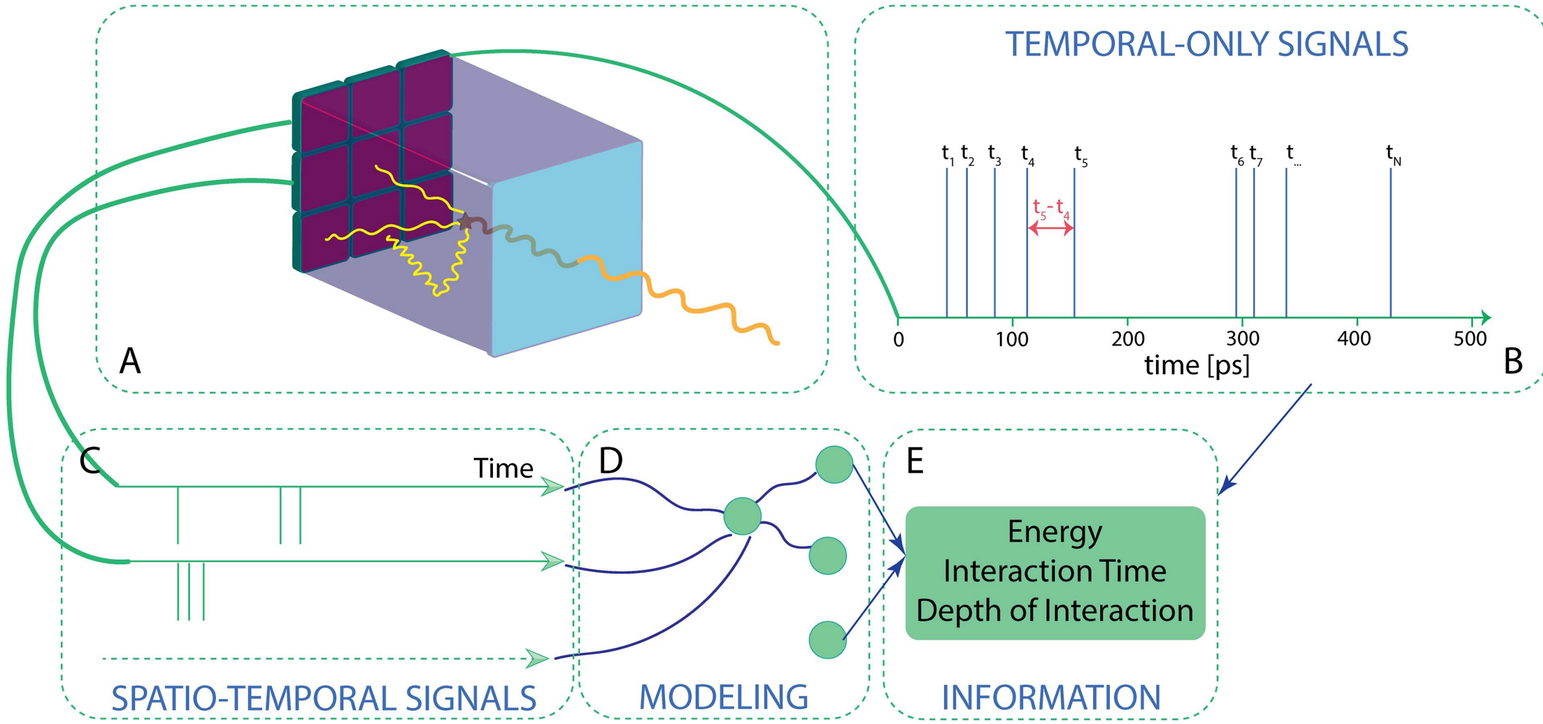
Timing accuracy at 100 ps level and impact localization at 1 mm level are necessary in scintillation/sensor detectors



Space-time information of the scintillation optical photons enables new digital signal processing approaches

SiPM target goals

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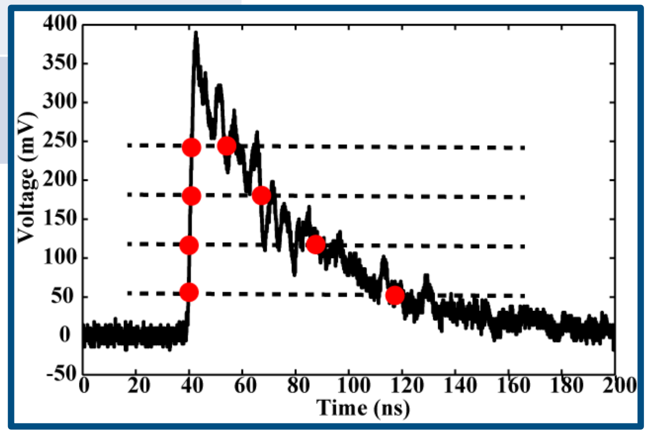
The target parameters to be achieved in order to guarantee a proper readout of scintillation light

Observable	Parameter	Value
Integral	PDE PDE	>40%@420 nm Possibly extendable below 350 nm
Temporal	SPTR PDE DCR	<100 ps >40%@420 nm <150 kcps/mm^2
Spatiotemporal	Frame Rate Microcell pitch	>5 MHz for 4x4 mm^2 <50 μm

$$R_E = 2.35\frac{\sigma}{E} = 2.35\sqrt{\frac{\sigma_{intr}^2}{E_\gamma^2} + \frac{1}{LY \times PDE \times E_\gamma \times \varepsilon_{opt}}}$$



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*The development of a performing digital SiPM is based on a solid CMOS process allowing a performant **analog SiPM***

A conservative digital circuit design

New Digital Signal processing approaches

PDE: shallow junction

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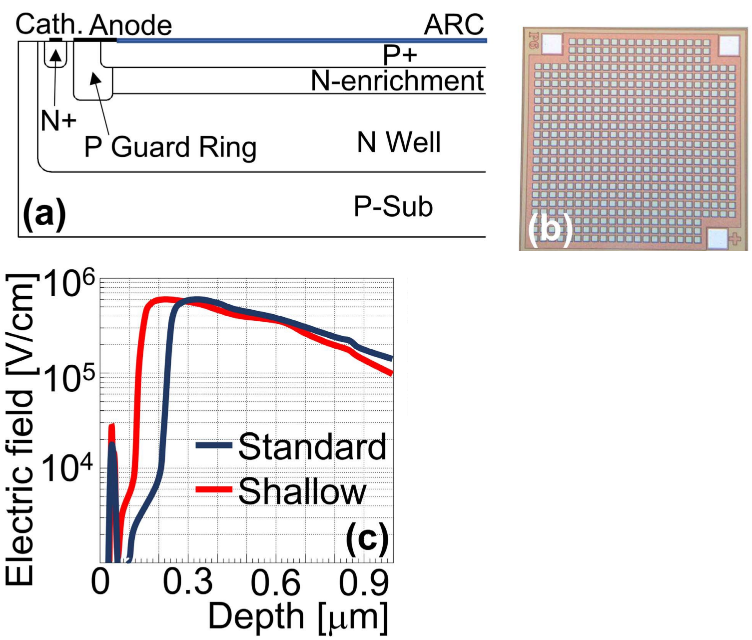
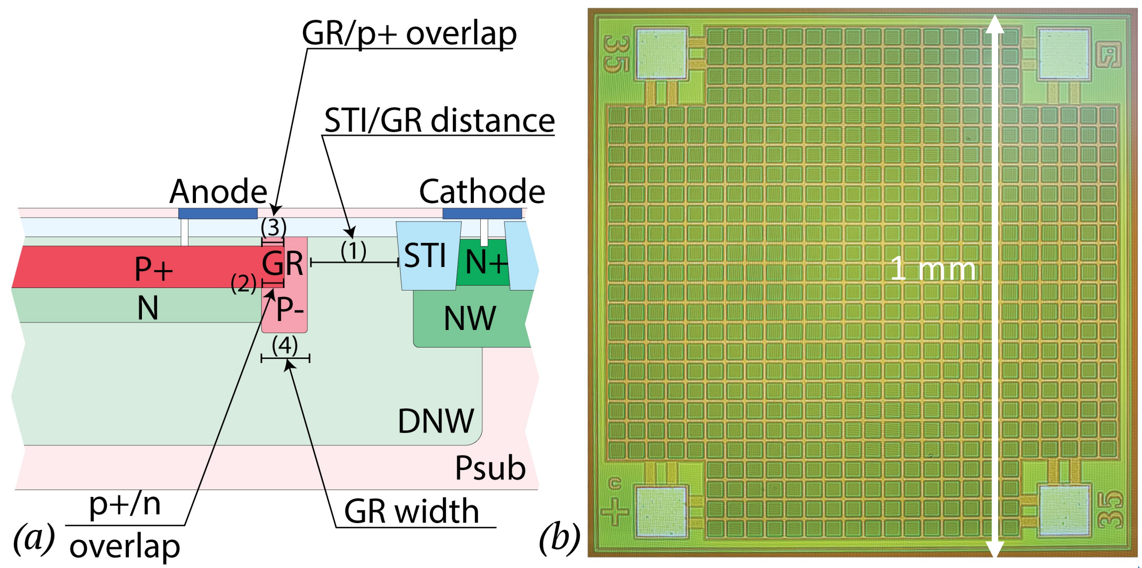
The path towards high PDE at the 420 nm spectral region is achieved by forming a shallow p/n junction





43%@ 420 nm 350 nm CMOS (2019)

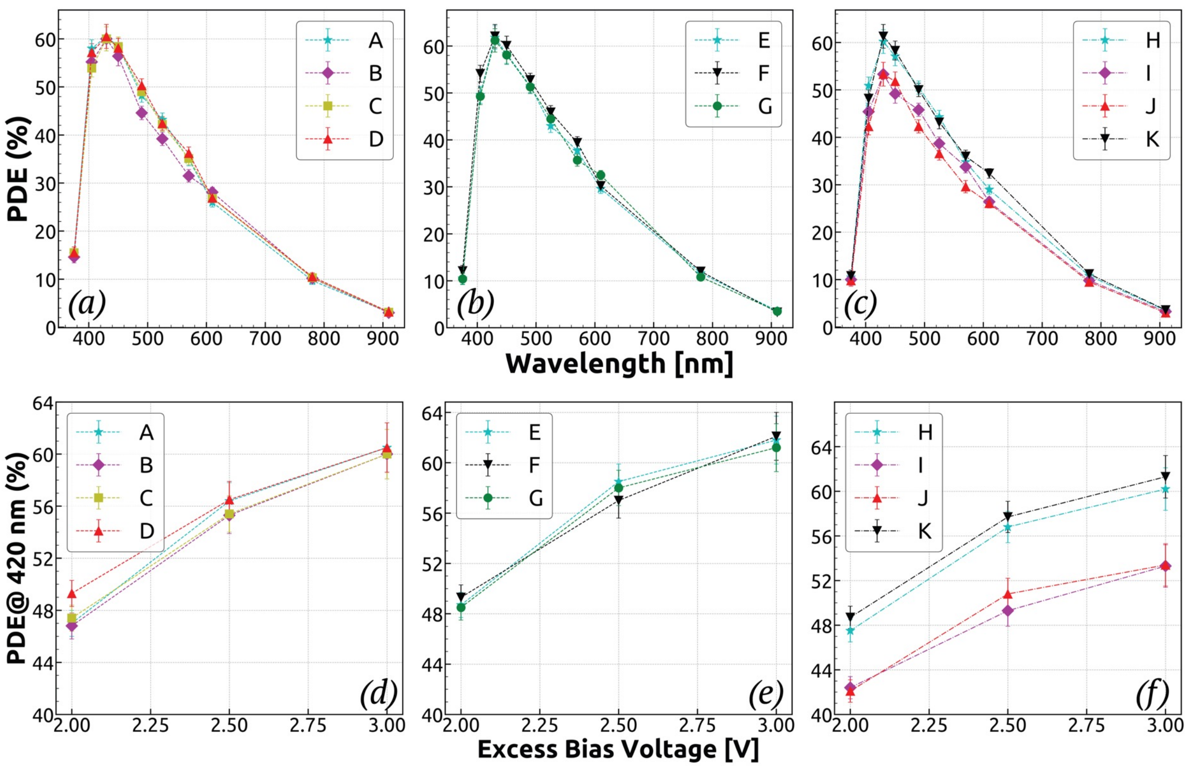
63%@420 nm 110 nm CMOS (2024)

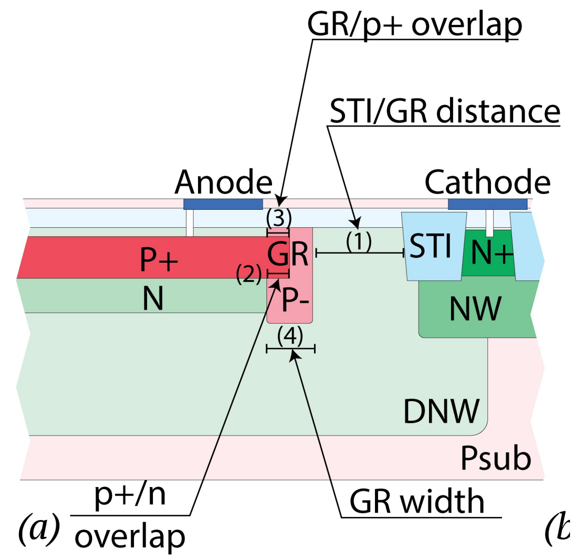
N. D'Ascenzo, IEEE Electron Device Letters, 2019

N. D'Ascenzo, submitted to IEEE Trans. Elec. Dev. , 2024

PDE

Several layout variations confirmed the correct dependence of the PDE on the excess bias voltages





N. D'Ascenzo, submitted to IEEE Trans. Elec. Dev. , 2024

PDE

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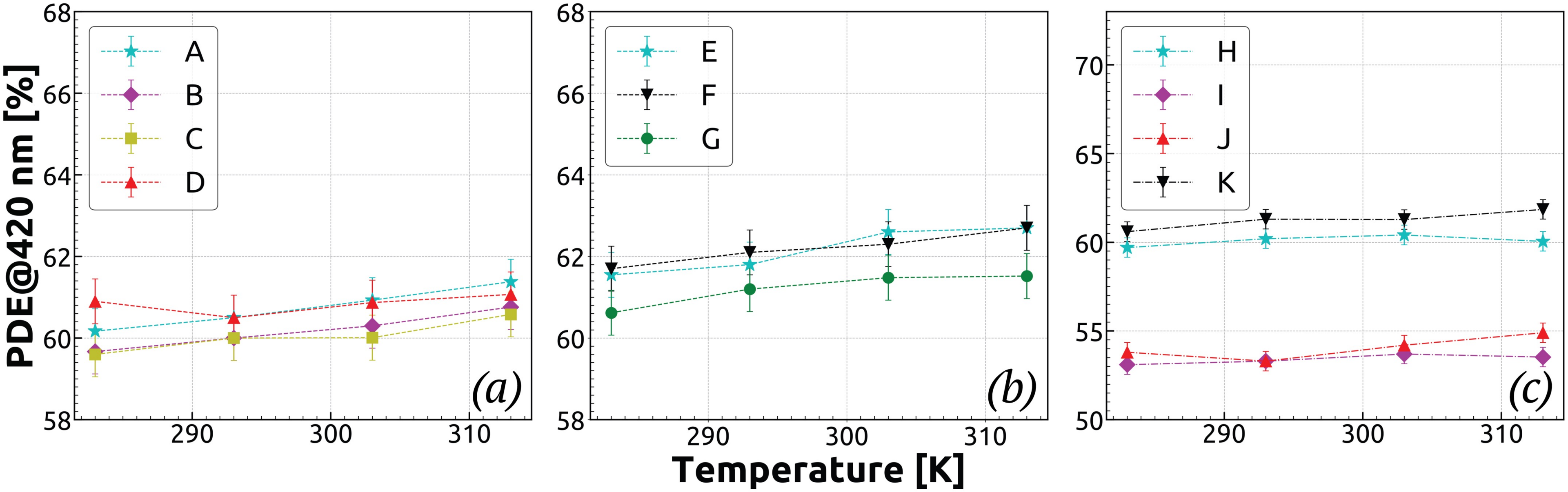
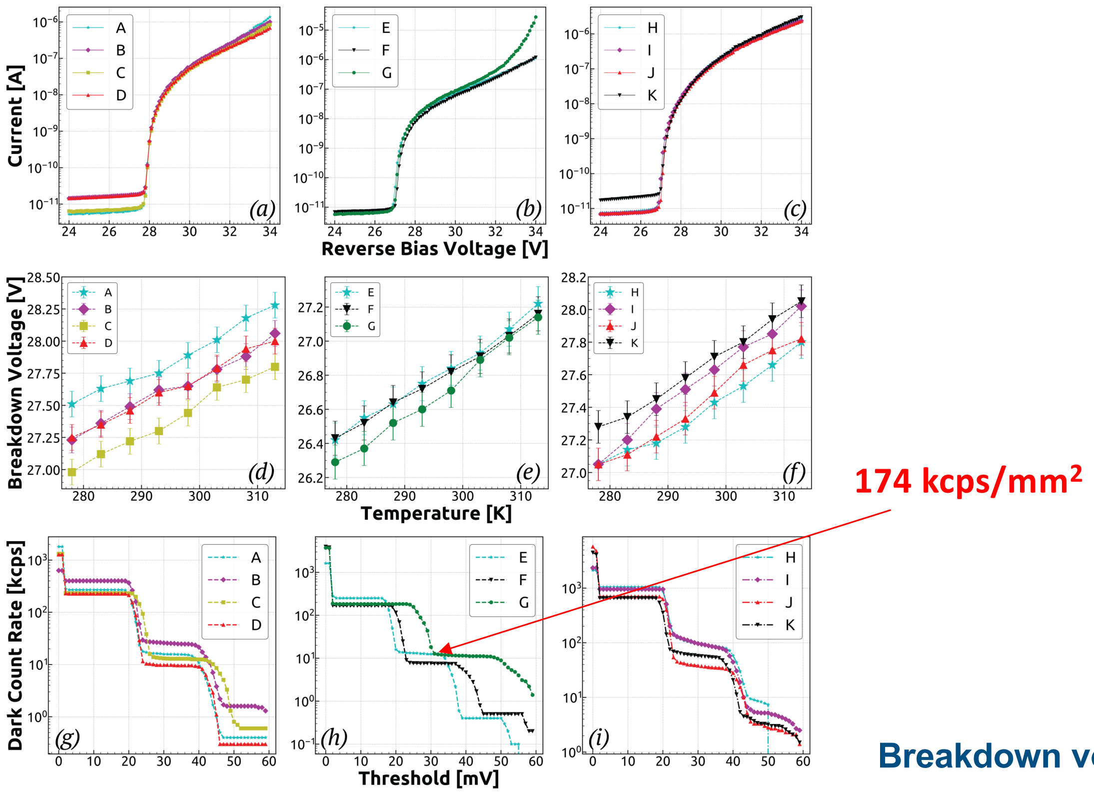
No significant trend of the PDE over the temperature is observed

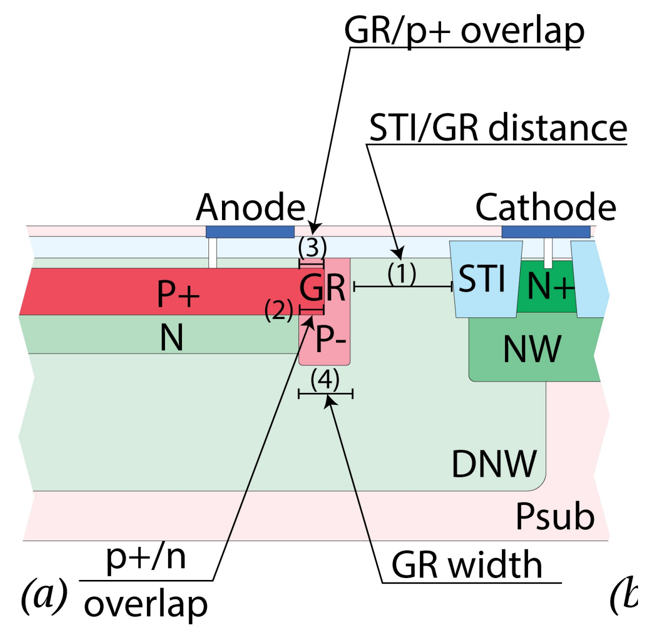


N. D'Ascenzo, submitted to IEEE Trans. Elec. Dev. , 2024

Noise characterization

The STI fabrication process causes a rise in the density of deep-level carrier generation centers at its interface





Breakdown voltage over temperature coefficient (23 ± 1) mV/K

Dark count rate

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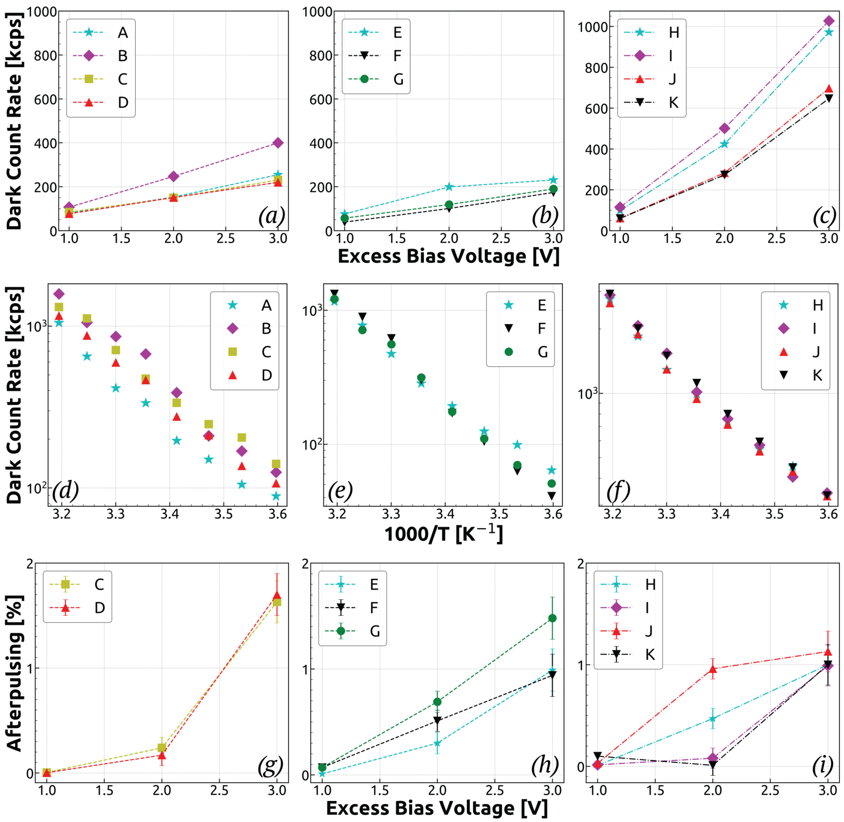
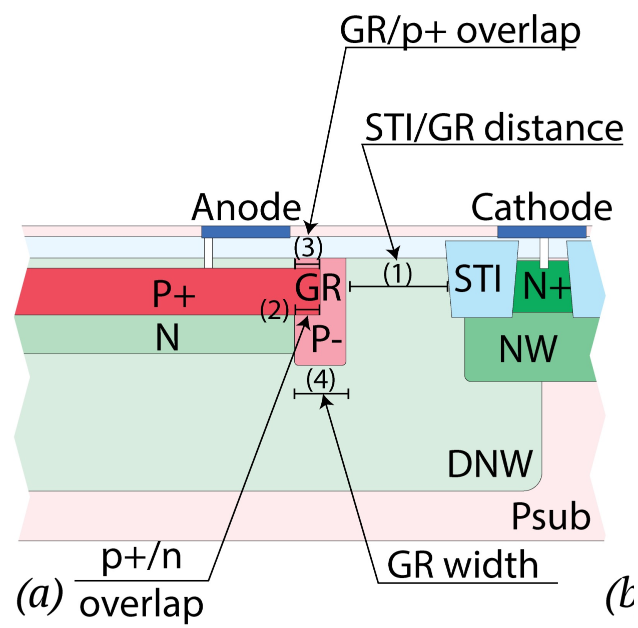
Temperature and voltage dependence of the dark count rate as expected





N. D'Ascenzo, submitted to IEEE Trans. Elec. Dev. , 2024

Single Photon Timing

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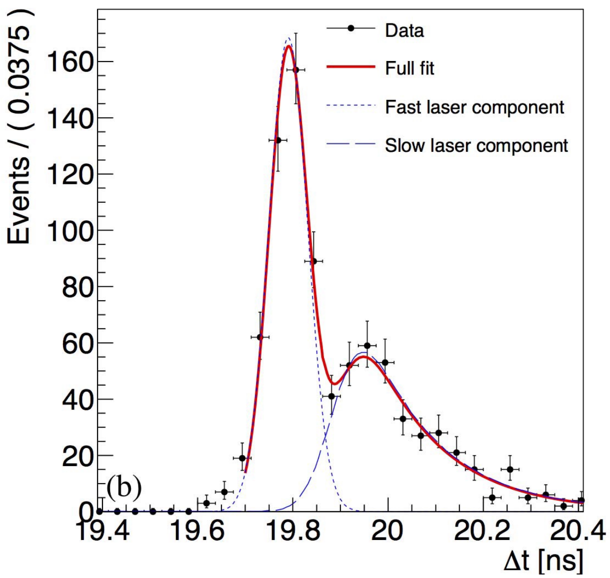
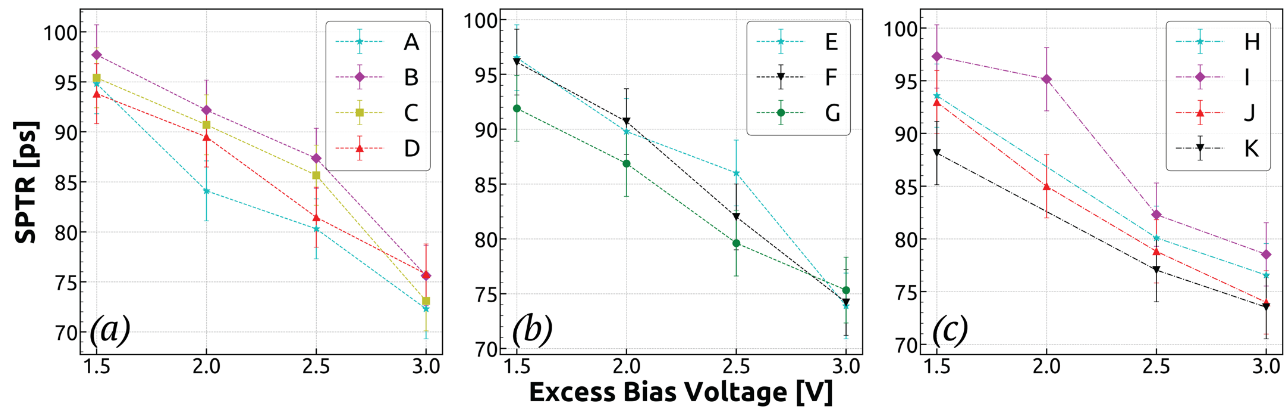
SiPM timing properties depends on the electric field strength and on the p/n junction width

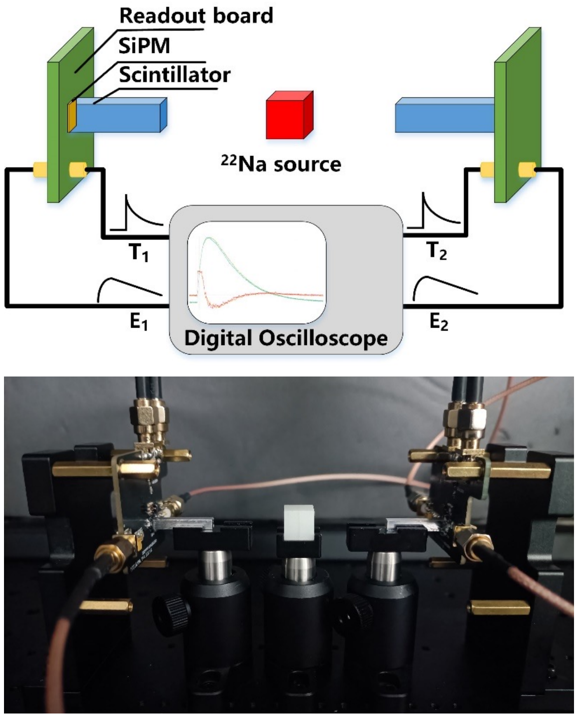


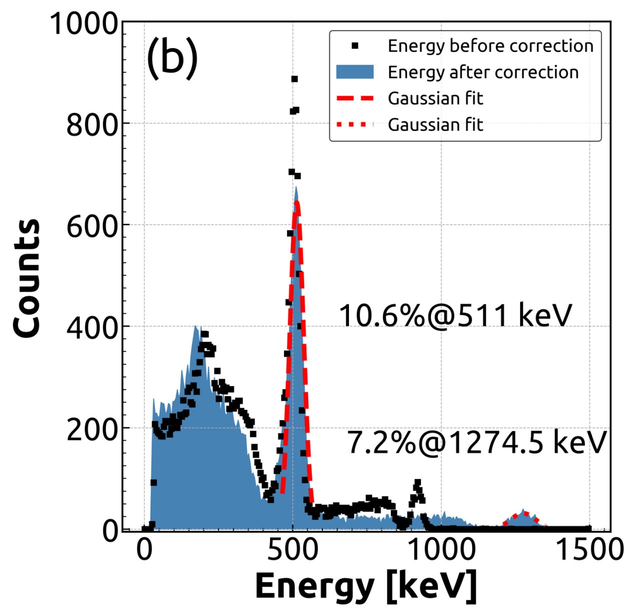


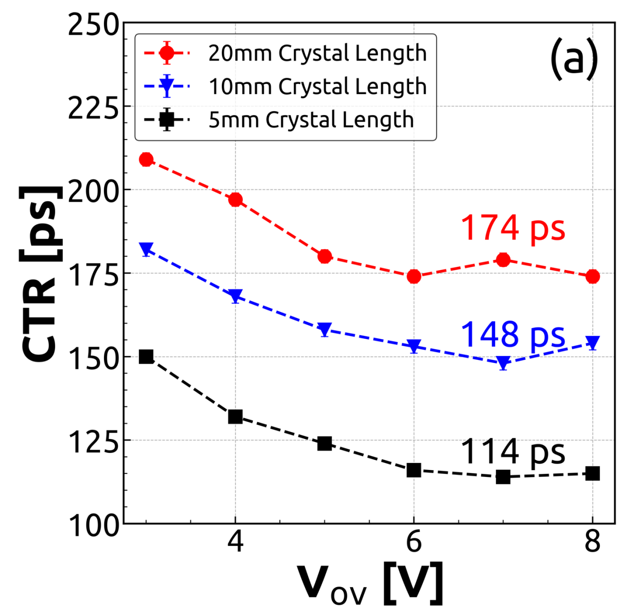
Approximatively 75 ps (FWHM) at 110 nm CMOS node

Application perspectives

Energy and time resolution of the devices are consistent with the requirements of PET







N. D'Ascenzo, submitted to IEEE TNS. , 2024

Overview of parameters

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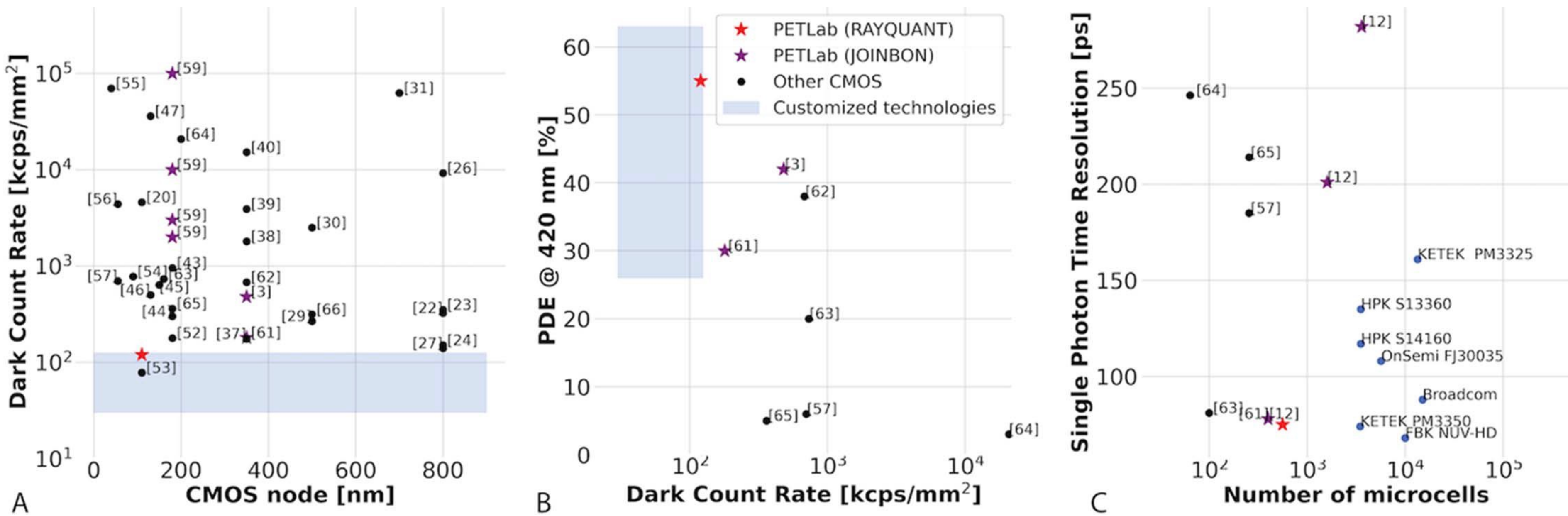
The obtained SiPM is competitive with commercial devices



N. D'Ascenzo, Chinese Optics Letters, 2024

Being obtained at a CMOS node, it is compatible with electronics on chip

Outline

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*The development of a performing digital SiPM is based on a solid CMOS process allowing a performant **analog SiPM***

A conservative digital circuit design

***Single photon counting** with high frame rate and dynamic range*

New Digital Signal processing approaches

Sensor design

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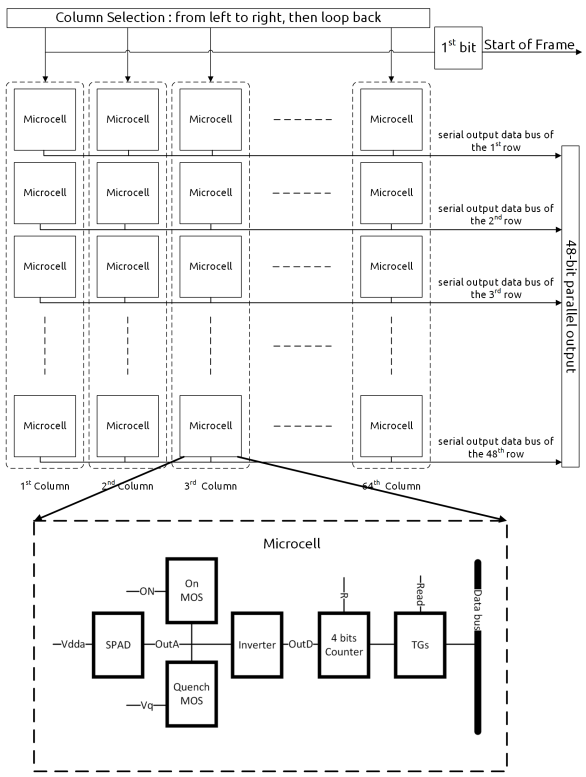
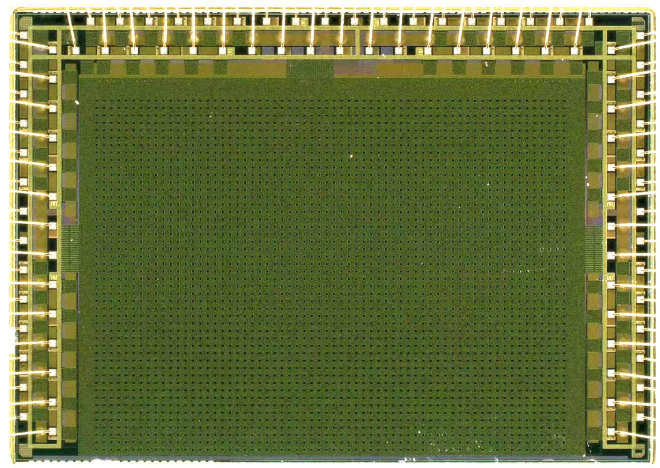
Array of digital SPAD with single pixel readout fabricated at 350 nm CMOS

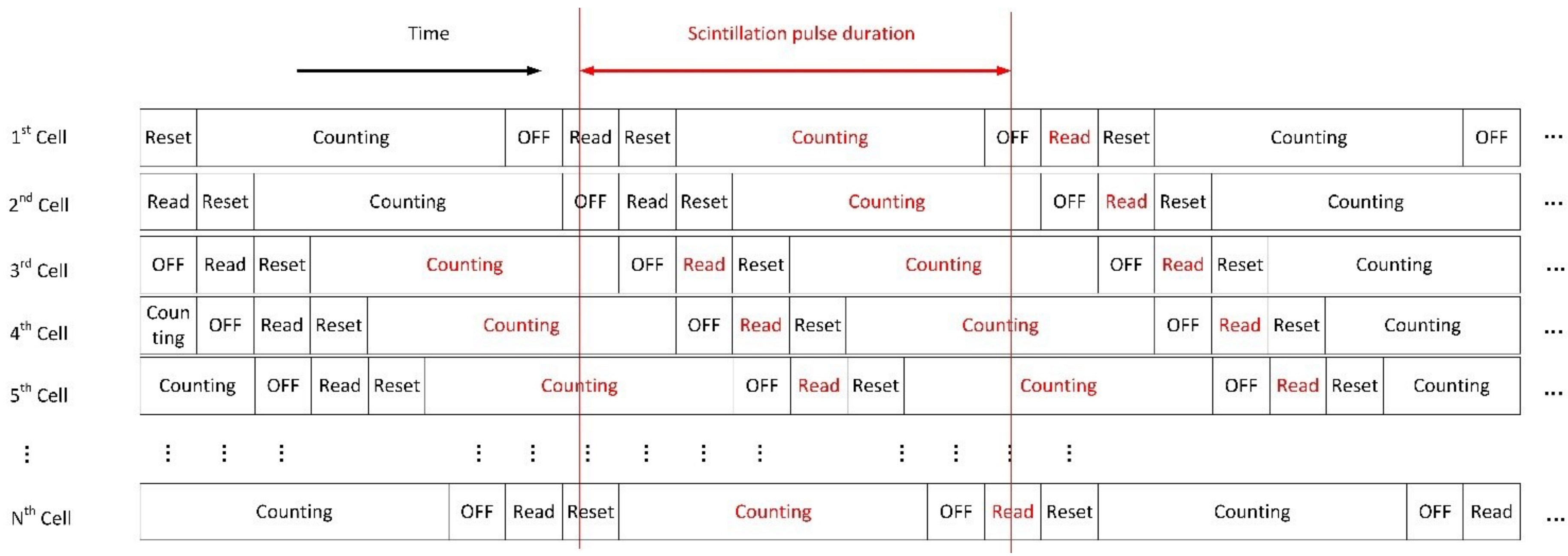




- **Pixel size:** 50x50 μm^2
- **Array size:** 48x64 (3072)
- **Die size:** 6.84x9.7 mm^2
- **Frame rate:** 4 MHz

Sensor design

The signal pulse train – a “scintillation light camera”



Important – note that the arrival time information is not yet included in this version of the sensor

Dark count rate

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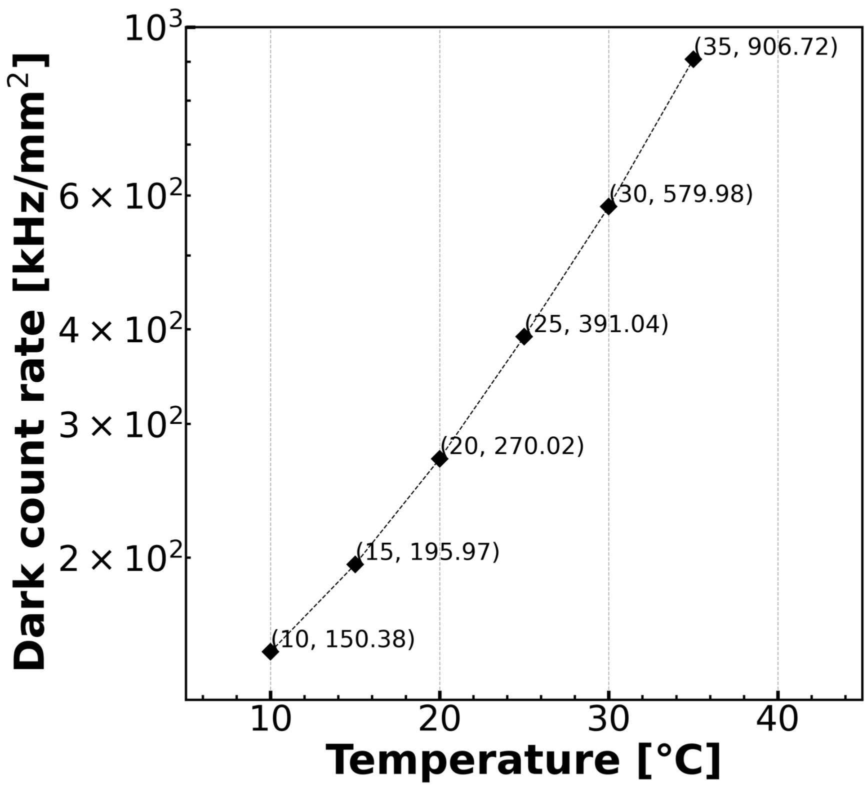
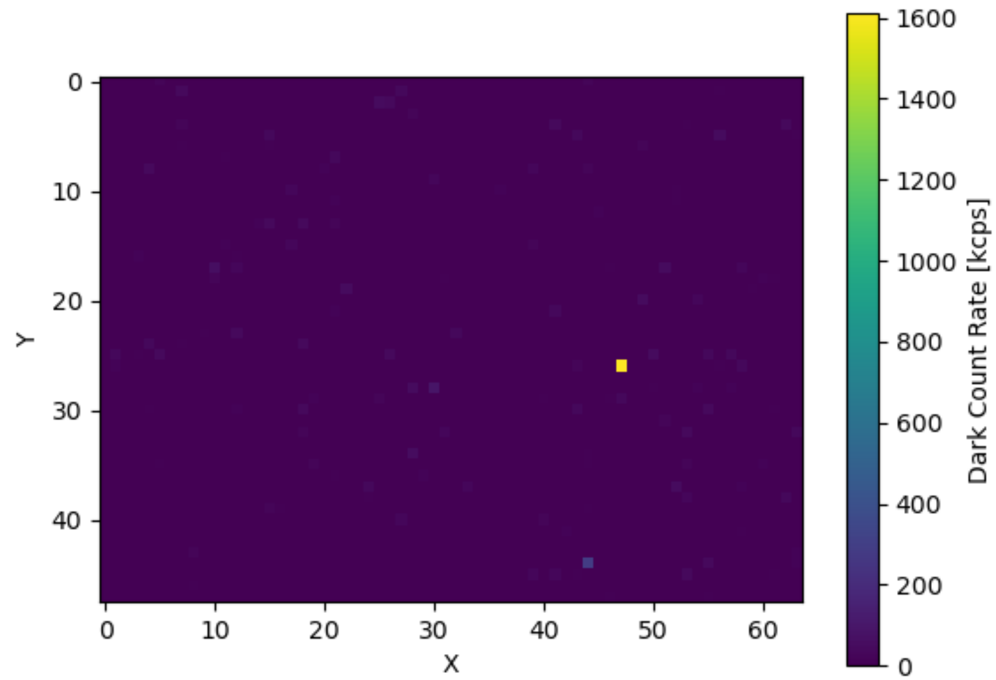
The dark count rate increases with temperature. The implementation of transistors slightly increases DCR





Scintillator readout

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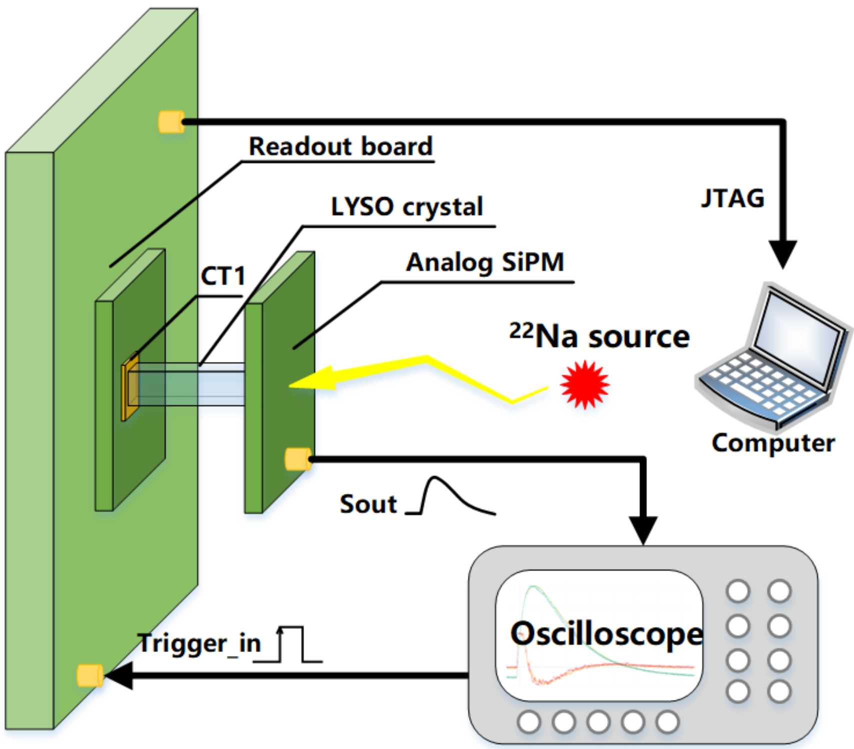
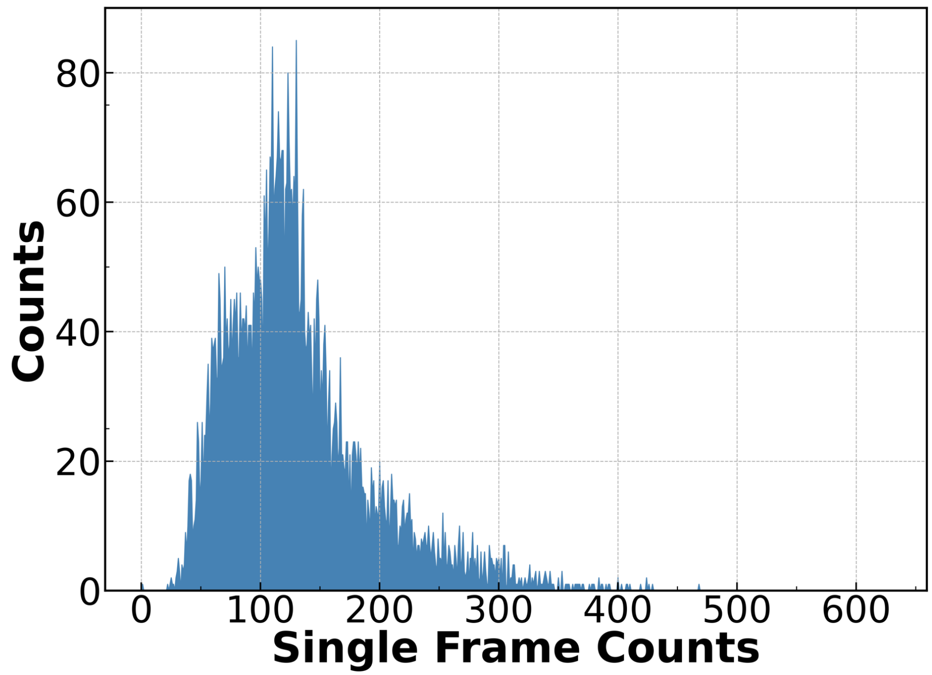
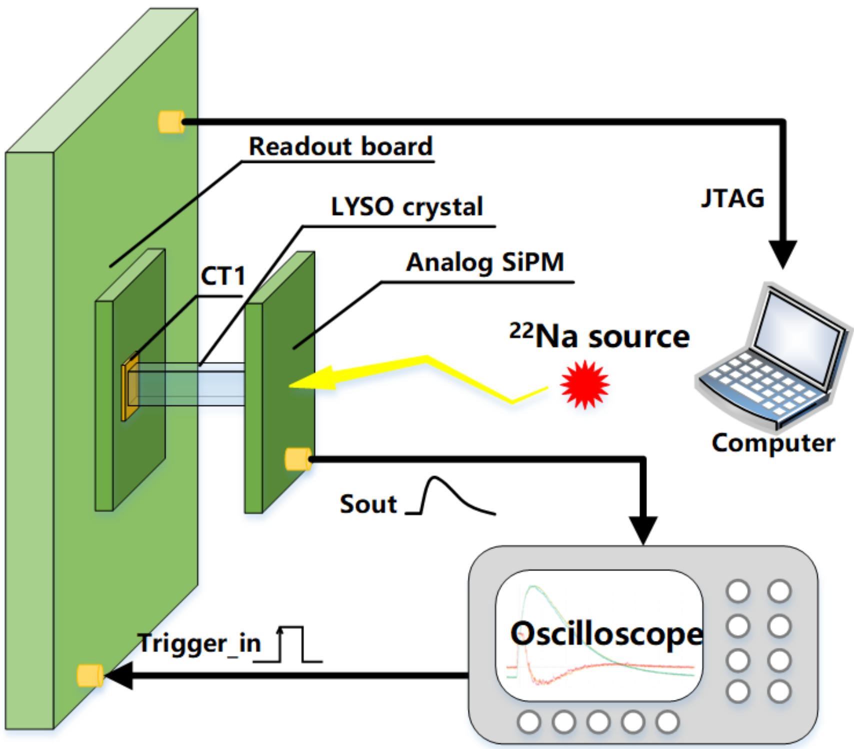
Read out the scintillation light produced by the detection of 511 keV optical photons in a 4x4 mm² LySO crystal

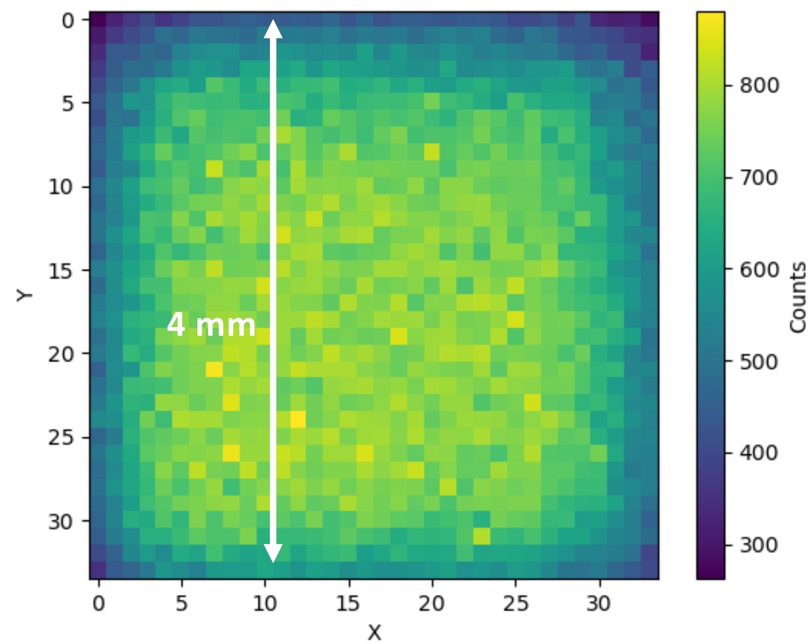




Scintillator readout

Visualize the scintillation light produced by the detection of 511 keV optical photons in a 4x4 mm^2 LySO crystal





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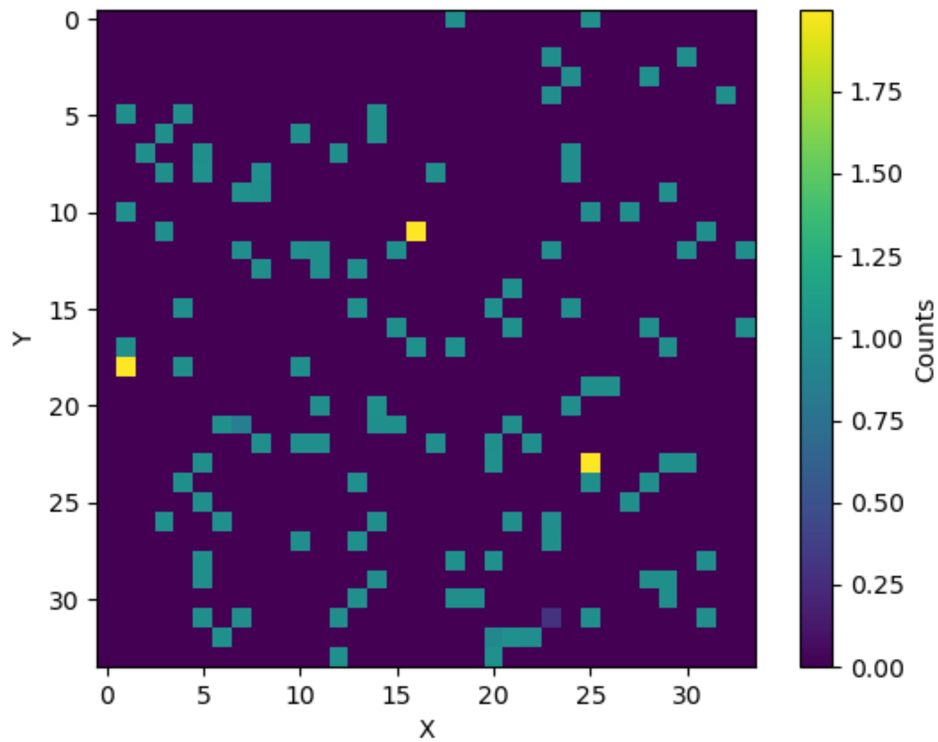

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New Digital Signal processing approaches

Reducing readout complexity** in order to reduce **power consumption** and **data storage for fast timing acquisition

Multi-threshold SiPM

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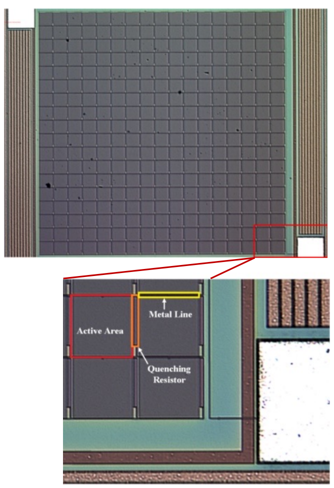
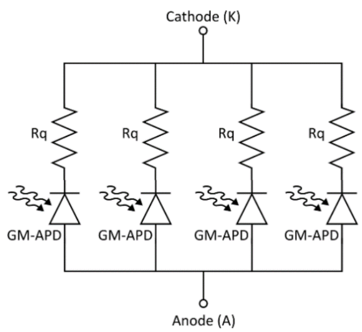
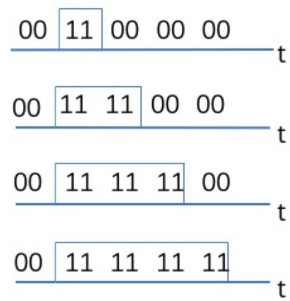
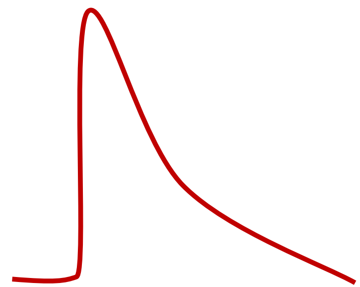
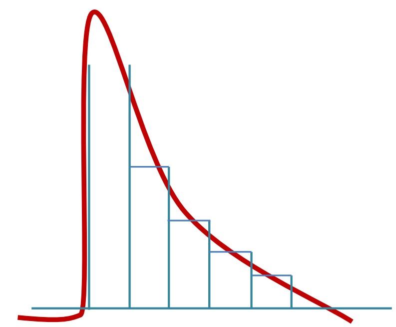
Multiple Analog-to-Digital Conversions Limit Current SiPM's Performance











MC working in Geiger mode → Hundreds of **digital** signals → Add to **analog** signal output → **Redigitalisation**

Digital to Analog

Analog to Digital

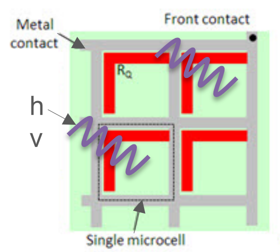
Challenges of SiPM Digitization

Direct digitization of SiPM is crucial

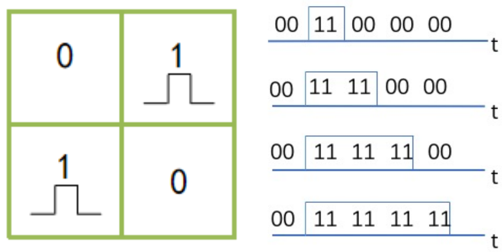
MT SiPM design

A new concept – sensors under production being delivered in November 2024

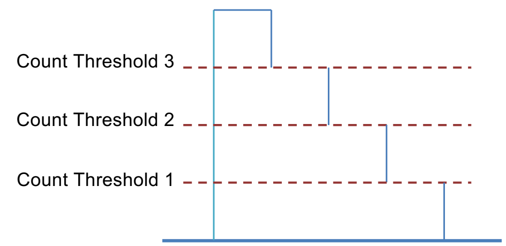
Real-time digitization at the signal source addresses the challenges of digital readout.



SiPM Receives Photons



Digitize from the Signal Source, Generating Multiple Digital Response Signals



Direct real-time Digitization

- Photon Counting Threshold Model Based on Prior Knowledge
- Digitize "count/time pair" signals to reconstruct photon timing information.
- Achieve direct real-time digitization of SiPM output signals to ensure signal integrity.

Significant leap in photodetection performance

- **Higher detection efficiency**
- **Extremely low dark count rate**
- **Faster time resolution**
- **Higher readout speed**

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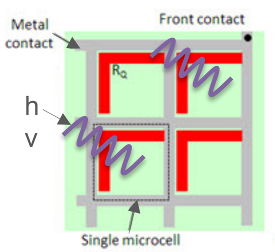

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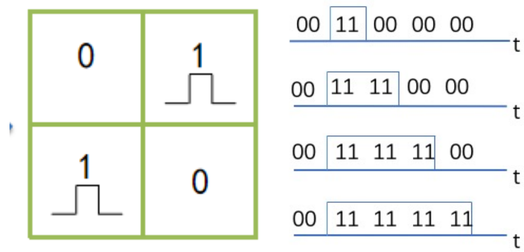

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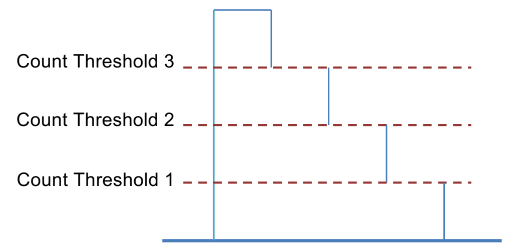

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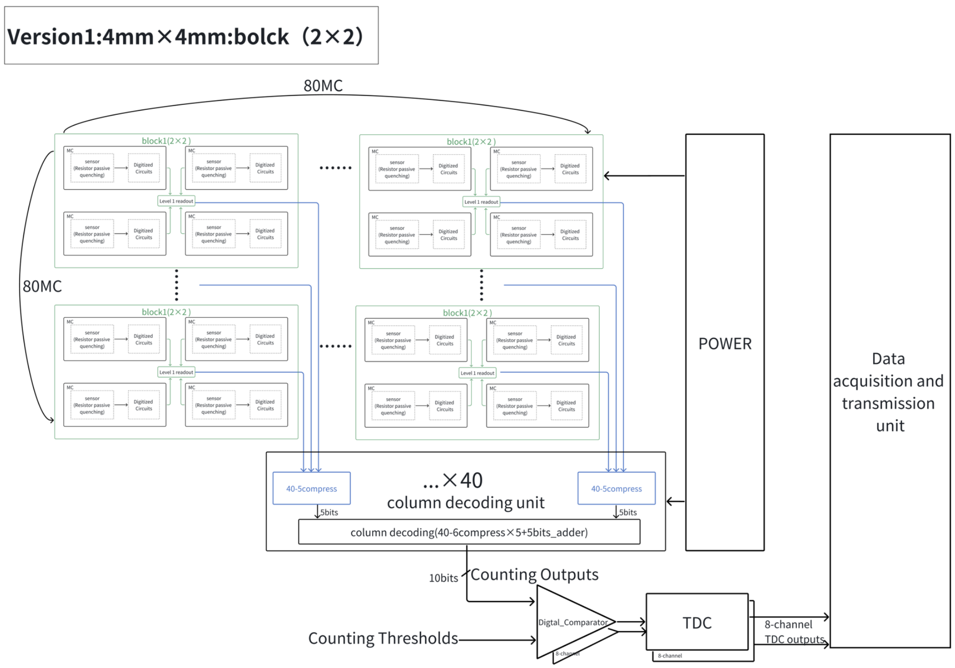
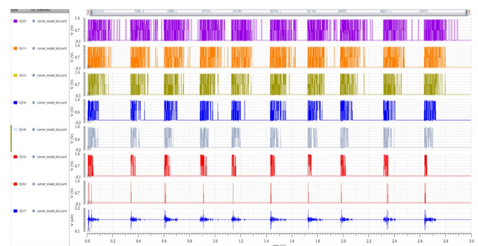
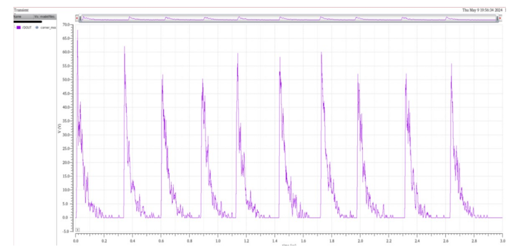
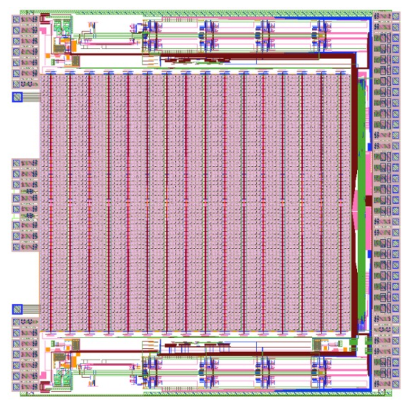
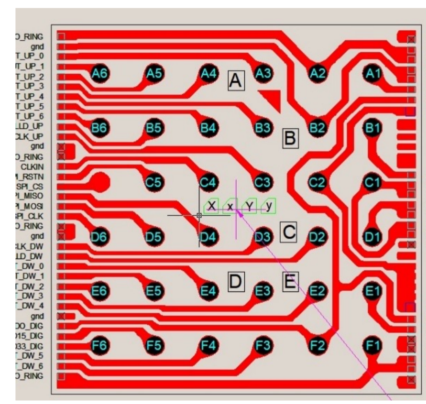
A PET system based on this chip will be available in 2025











Outlook

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- The high time and spatial resolution required in time dynamic agricultural PET necessitates the development of new digital CMOS SiPM devices
- The digital CMOS SiPMs will have a broad application to scintillator-based sensors
- Scintillator readout with digital SiPM devices will reveal unexplored possibilities in single photon digital signal processing


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Thankyou!!