Status and Perspectives of CMOS SPAD-based single-photon detectors

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- Advanced Quantum Architecture Laboratory

RICH2025, Mainz, Germany, 15-19 Sept. 2025

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Introduction – Analog vs digital SiPMs

SPAD: single-photon avalanche diode
SiPM: silicon photomultiplier

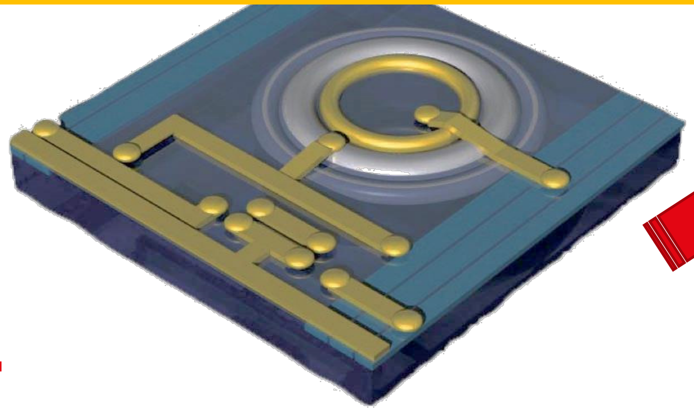
Single-photon Avalanche Diodes (SPADs) Metrics

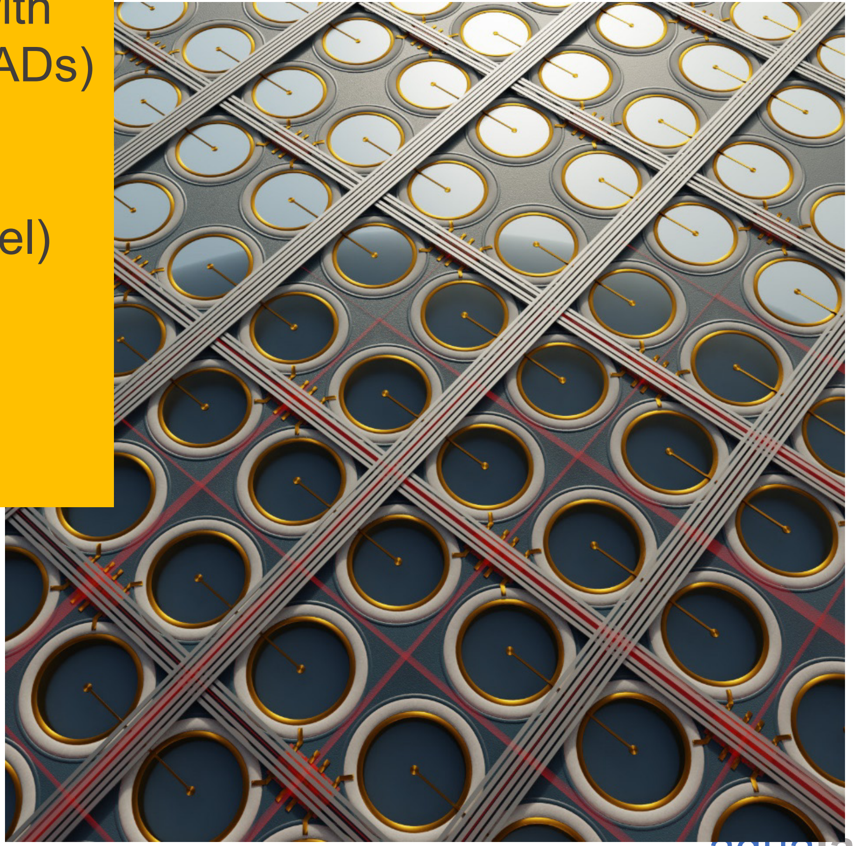
Detect/time-stamp single optical photons with CMOS Single-photon Avalanche Diodes (SPADs)

High sensitivity (up to 90% PDP)
Low noise (10-100 counts-per-second / pixel)

Excellent timing resolution (10-100 ps)

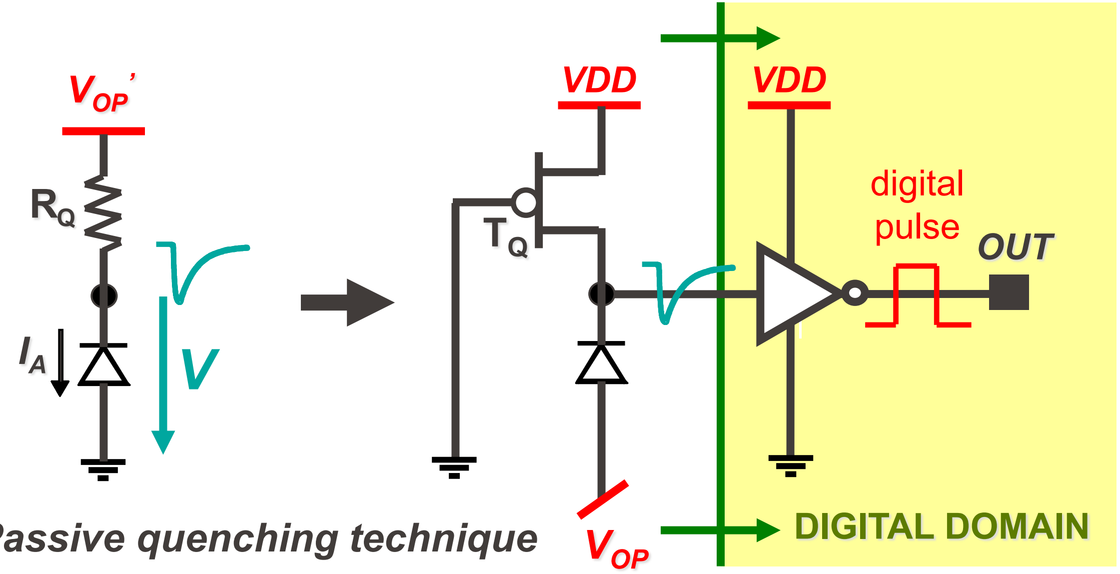
Increasing spatial resolution (kpx - Mpx)





SPADs as digital devices in CMOS

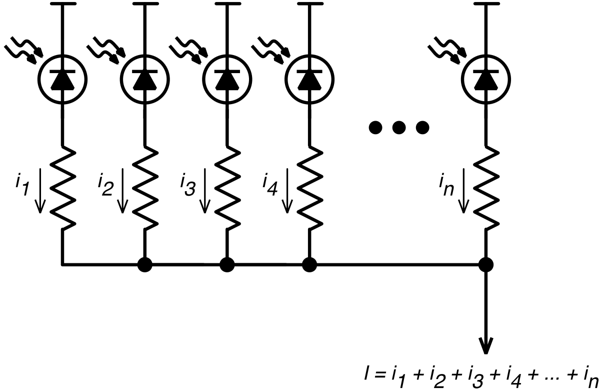
- The SPAD becomes like any other digital device but it is triggered by a photon!

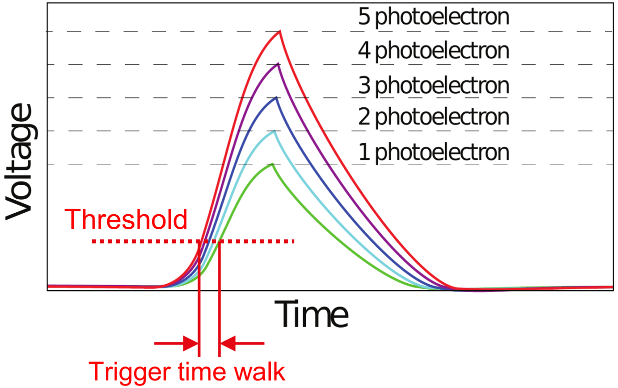


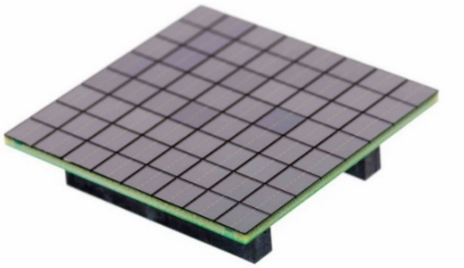
Passive quenching technique

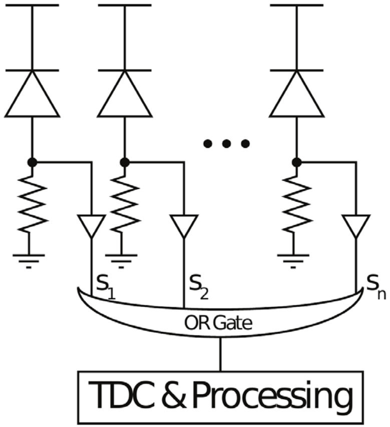
- With two more switches one can <u>gate</u> sensitivity

Analog vs Digital SiPMs

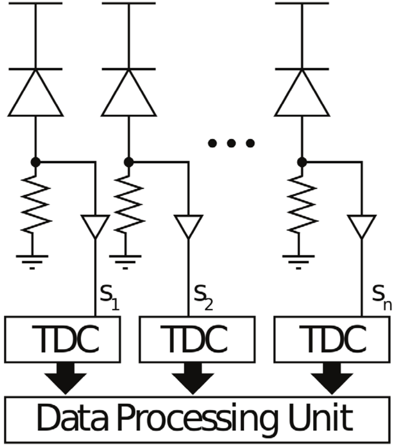








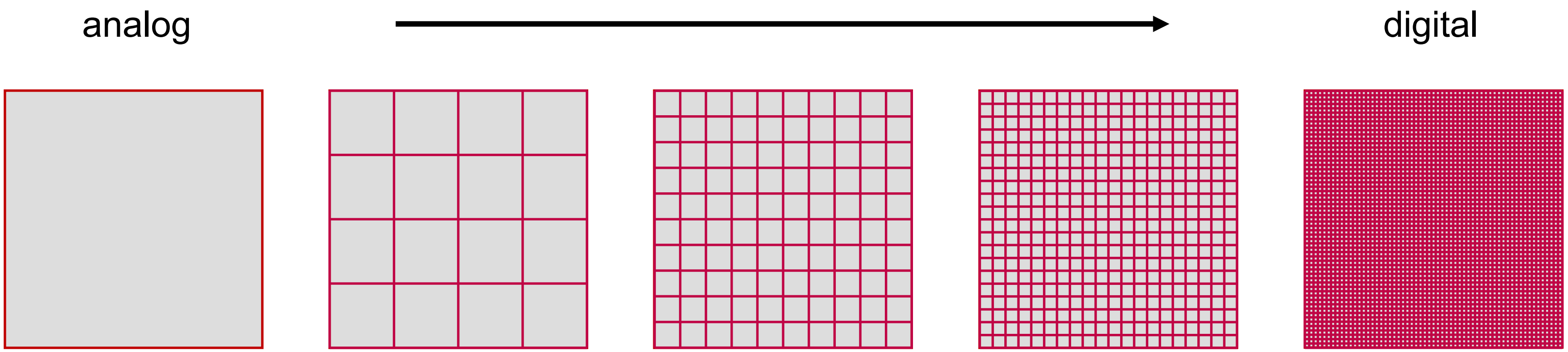
Standard dSiPM



Ideal (multi-channel) dSiPM

[S. Mandai & E. Charbon, NSS-MIC 2012; E. Venialgo, NSS-MIC 2016]

Transition from analog to digital

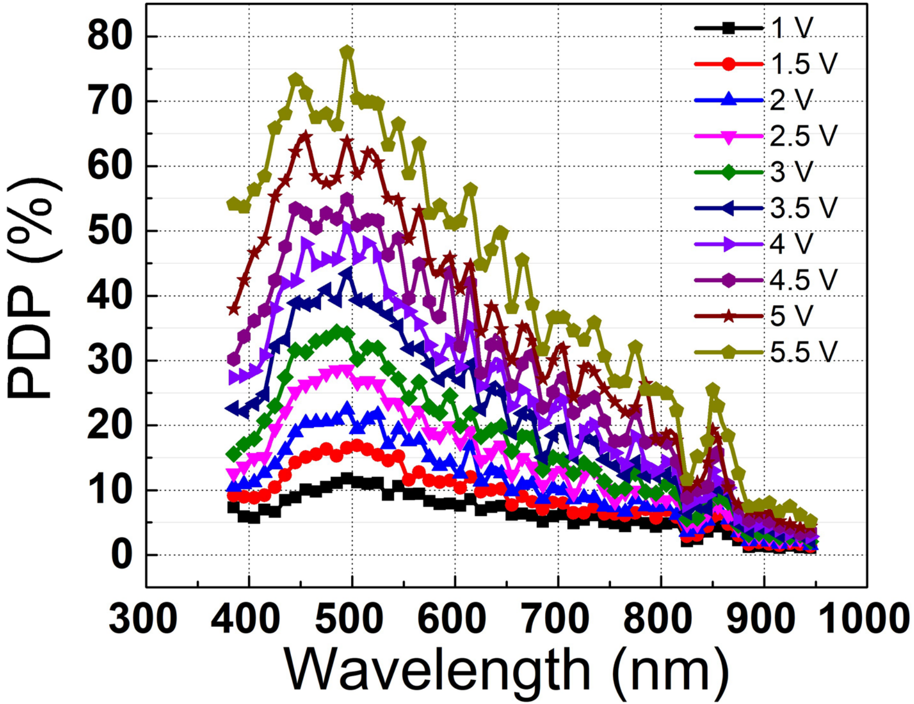


Is it necessary to go for a fully digital SiPM?

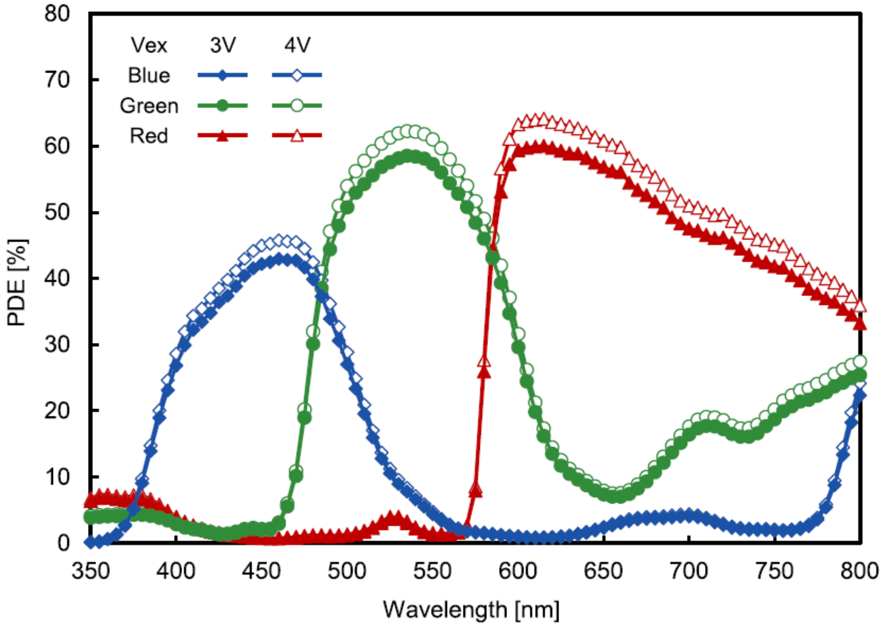
Physics of Molecular Imaging Systems Teaching and Research Unit
RWTH AACHEN UNIVERSITY

SPAD Metrics: recent Improvements & Trends

Photon Detection Probability (PDP): recent results



U. Karaca, et al, IISW 2023
FSI 110 nm (monolithic)

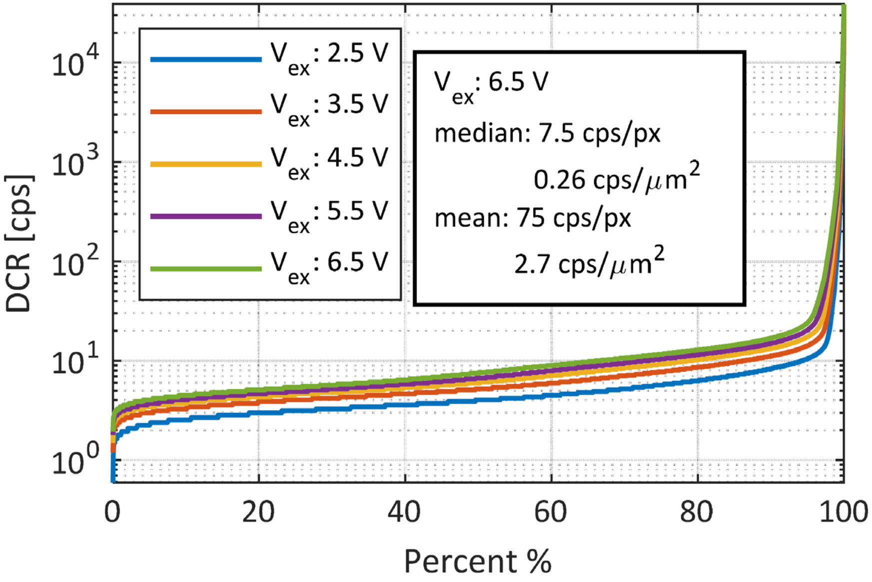


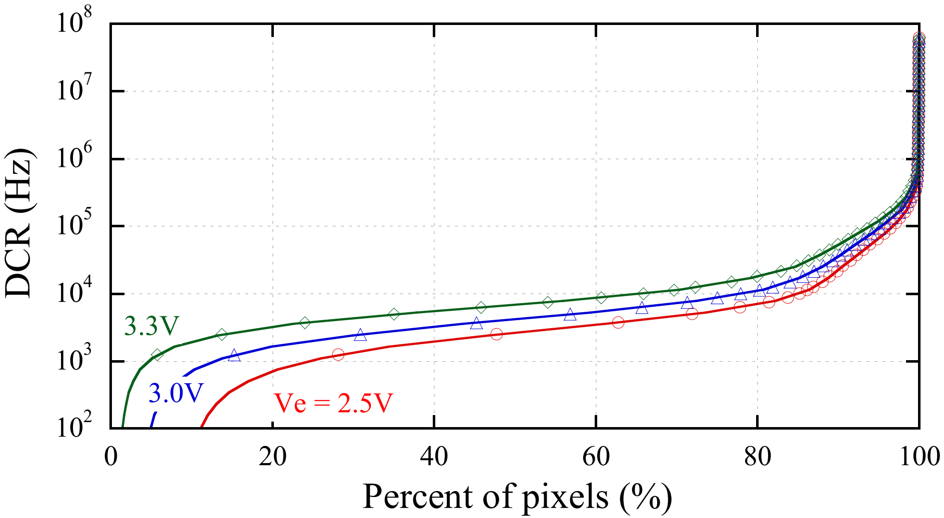
J. Ogi, et al, JSSC(56) 2021
Sony BSI 90 nm/40 nm (3D-stacked)

- Caveats: PDP vs PDE when moving from single pixel to array
- Trade-offs: microlens and product availability, isolated vs non-isolated pixels

Dark Count Rate (DCR)

- DCR (Dark Count Rate) population examples:
  - Left: SwissSPAD2 512x512px, 16.38 um pitch, 10.5% fill factor native -> reduced DCR and crosstalk
  - Right: older 0.35 μm node
- Process dependent – not easy to obtain the corresponding statistics (large population)





Courtesy: Yuki Maruyama

- A Ulku, et al., JSTQE 2019

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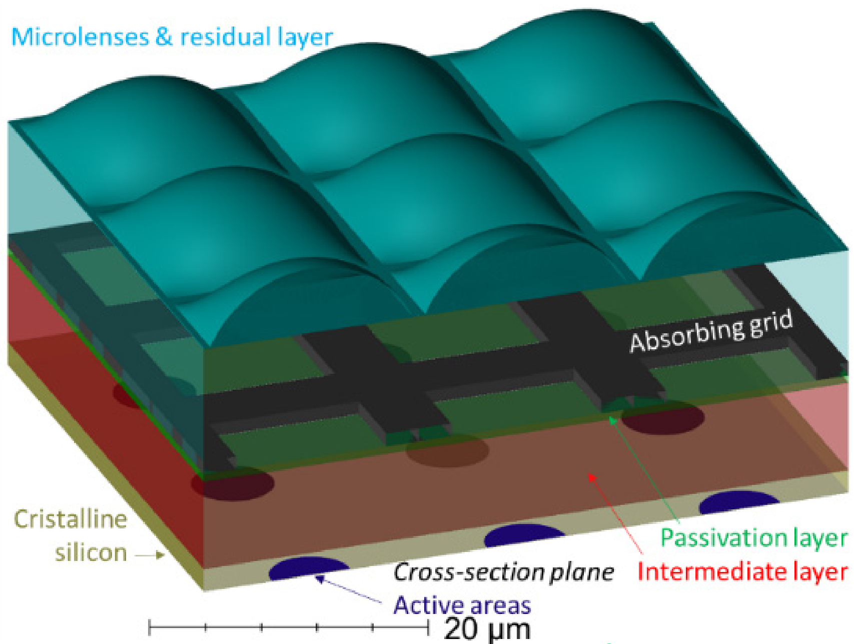
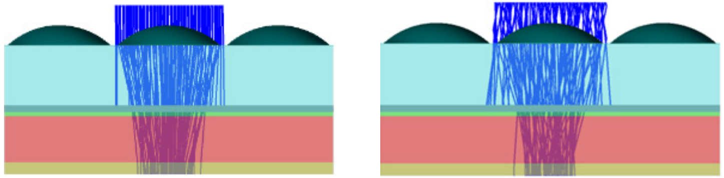
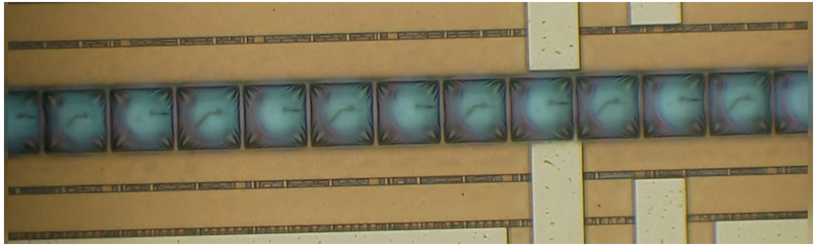
Fill Factor Recovery by means of Microlenses

- Alignment marks/crosses needed!
- Optimised imprints possible on small quantities (sag/residual height)





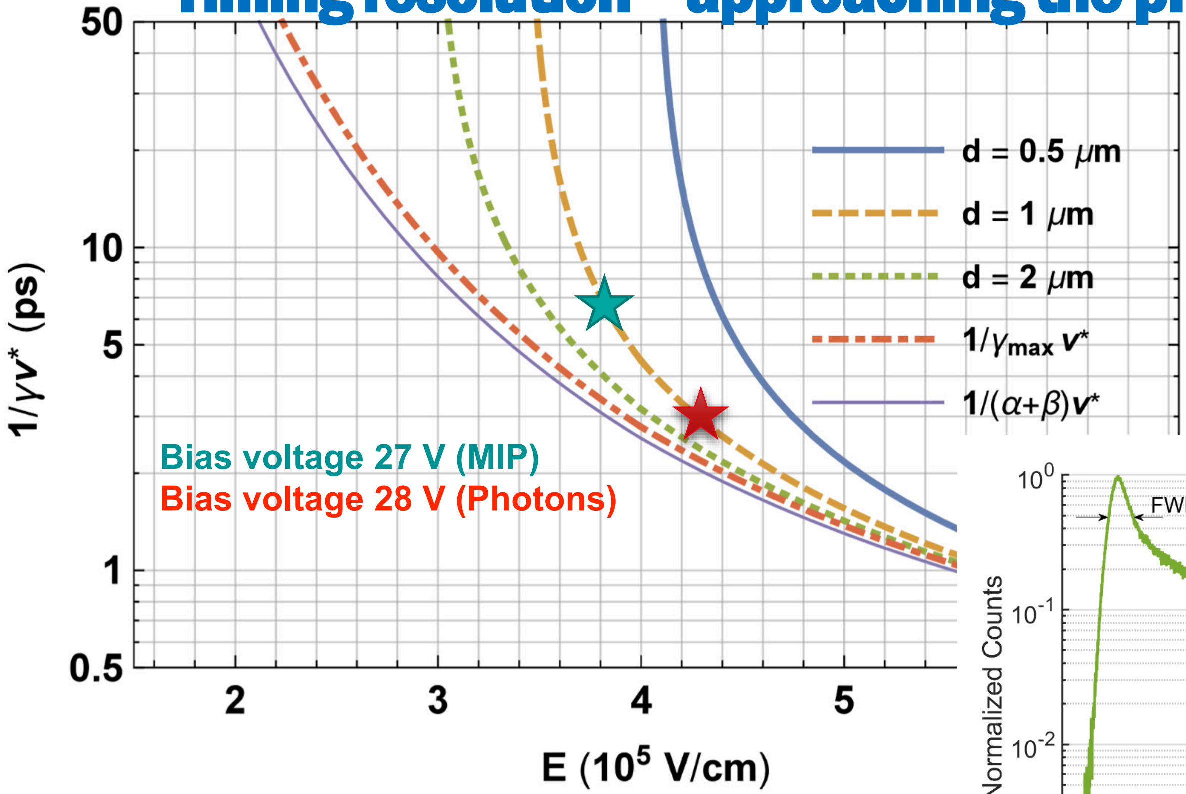
Low NA vs. high NA
→ Issues with scintillators!



R&D, die or reticle level, imprint

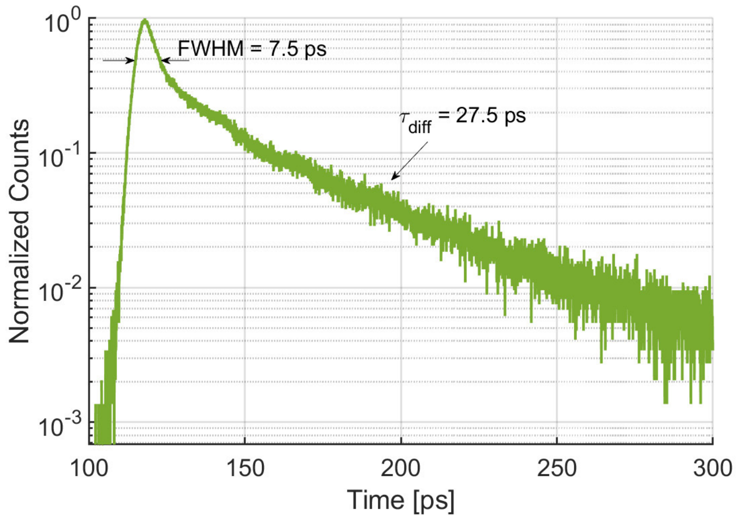
- [Bruschini et al., OpEx(31) 2023]

Timing resolution – approaching the physical limits



Bias voltage 27 V (MIP)
Bias voltage 28 V (Photons)

F. Gramuglia, et al., Frontiers in Physics(10) 2022



W. Riegler, P. Windischhofer, P. Time Resolution and Efficiency of SPADs and SiPMs for Photons and Charged Particles. *NIM A* (2021)

11

CMOS SPAD-based R&D and Products

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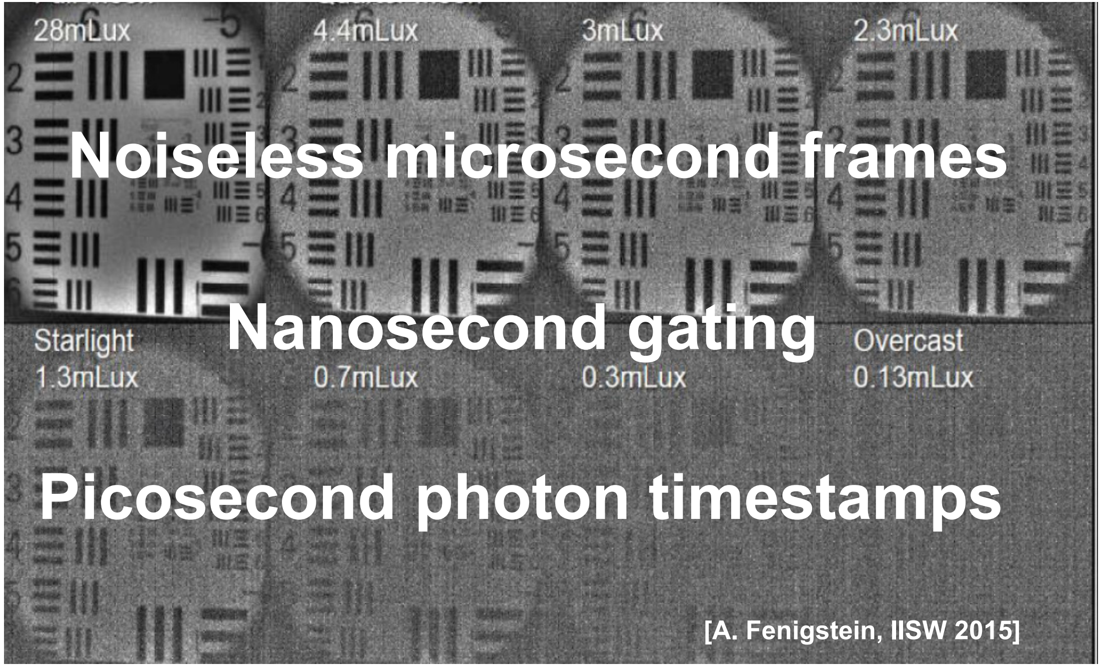
SPAD Arrays/Imagers Strengths



- [R. Henderson, IISW 2018]
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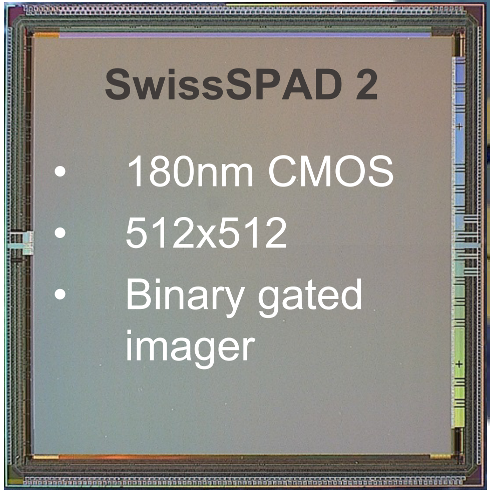
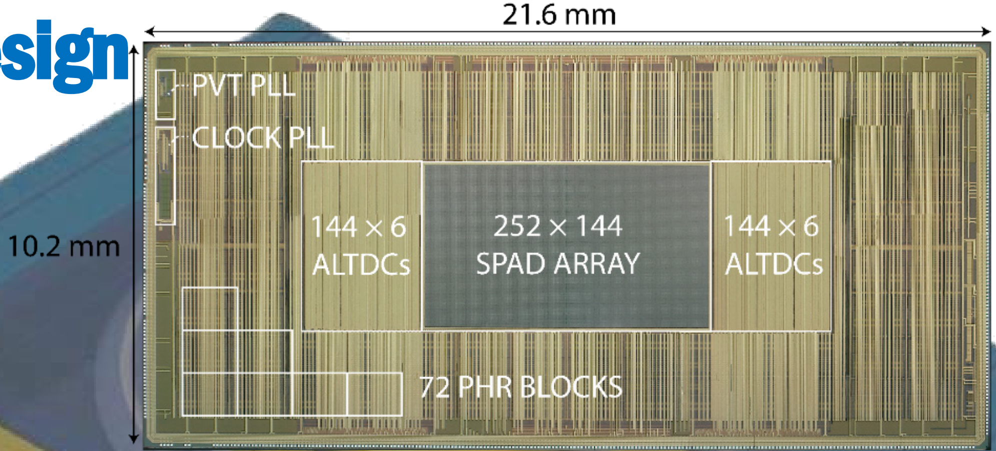
AQUA – SPAD Design Examples



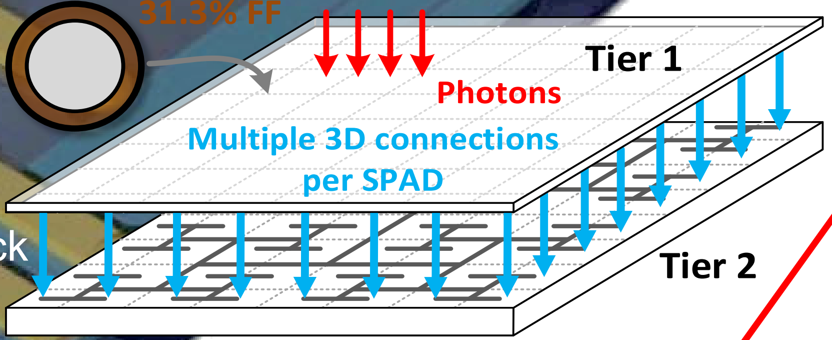
SwissSPAD 2

- 180nm CMOS
- 512x512
- Binary gated imager



- 180nm CMOS
- 11.2 Gbit/s output data bandwidth

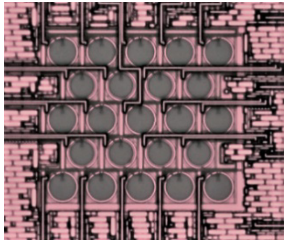
Mantis



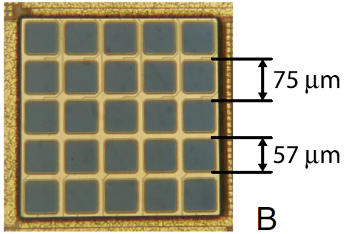
- 45nm/65nm CMOS 3D stack
- First 3D stacked direct time-of-flight sensor in CMOS

Examples of CMOS SPAD-based products

Async readout of individual pixels - excel in confocal applications

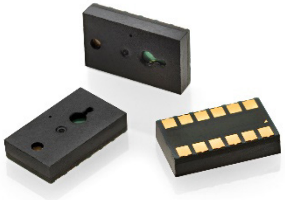


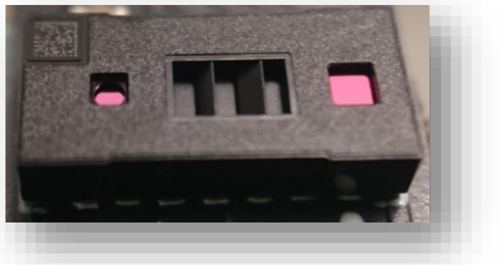
Antolović et al, OpEx 2018, FOM 2019 - 0.18 μm SPAD23 (Pi Imaging Technology)

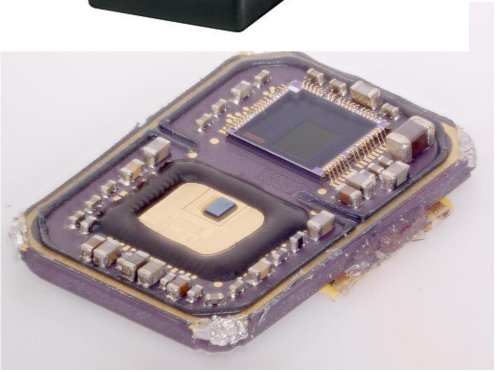


Buttafava et al, Optica 2020 0.16 μm BCD

Market "push"- available off-the-shelf







Sony iPhone 15 pro LiDAR Module /with optics removed ©2024 YoleSystemPlus

VL53L5, Compact Integrated Module

- Class 1 certified 940nm invisible VCSEL
- 61° diagonal, square FoV

Ranging Capabilities

- Up-to 64 (8x8) ranging zones
- Up-to 4m ranging per zone

[Mellot/Rae, STMicroelectronics, IISW 2018]

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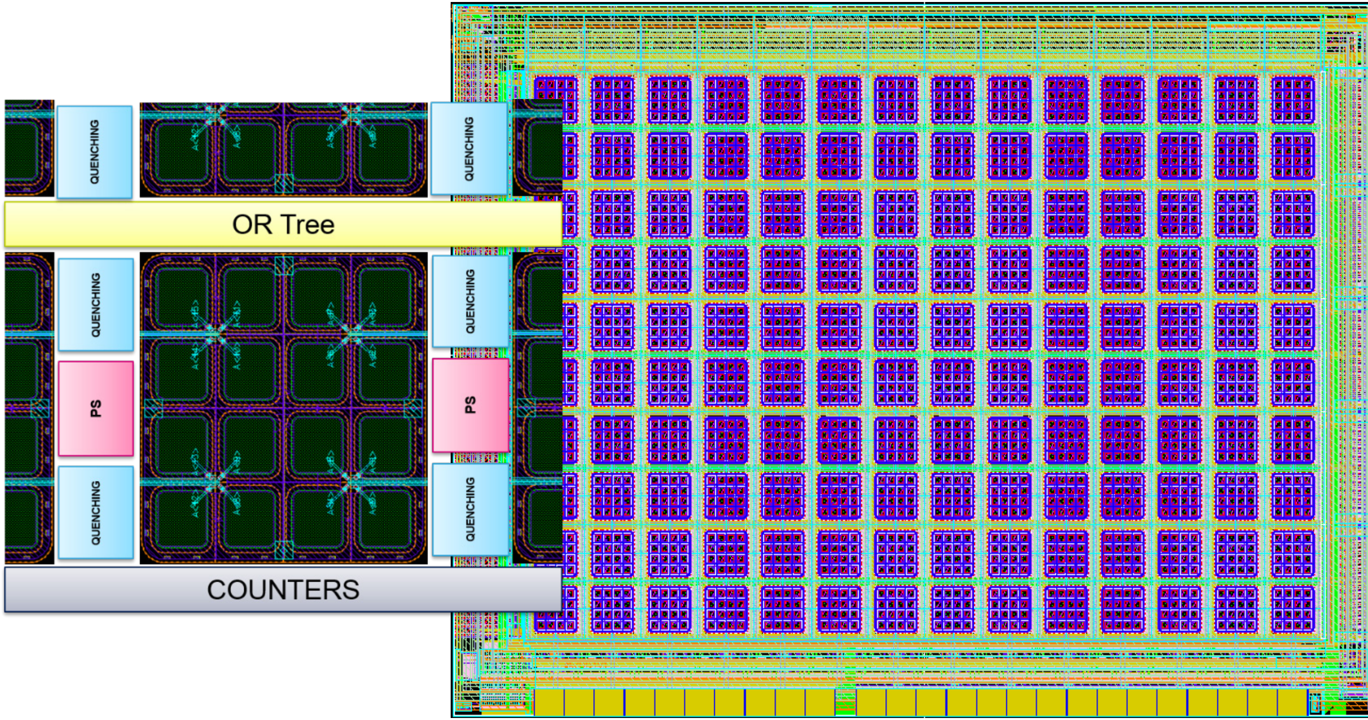
SPAD "Pixel" & Multi-Zone dSiPM Array

4 x 4 SPADs sharing NWELL

Logic

- individual quenching and enabling
- pulse shaper
- OR tree
- counters

Pixel fill factor ~ 40%



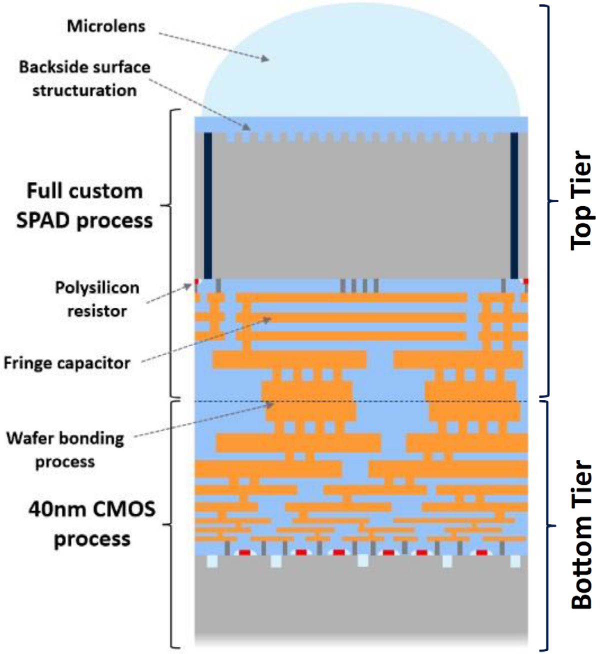
- [Source: S. Pellegrini, STMicroelectronics ISSW 2018]

Industrialised SPAD Example – Backside illuminated

2Bu
ToF Modules Shipped

3D stacked SPAD technology

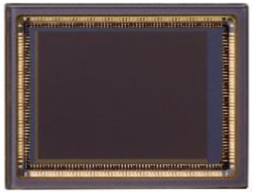
Optimized for high sensitivity, low DCR, low jitter and low power



Pixel performance	
Breakdown V	19.2V
Excess bias	2.5V
DCR at 60°C	800 cps
PDE @ 940nm	21.2%
Max Count Rate	88Mcps
Jitter (FWHM)	119ps
Charge Per Pulse	68fC

life.augmented

Low light Level Intensity Imaging



Canon MS-500 Backside Illuminated 3.2 Mpx

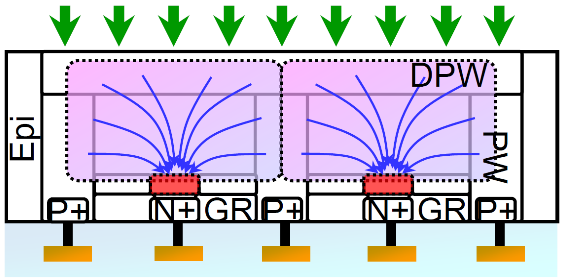
SPAD SENSOR

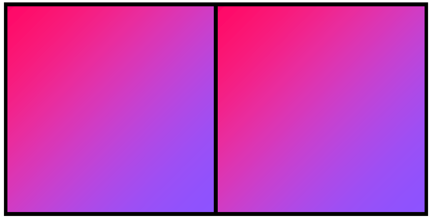
*Zoomed image of ship at 5km distance, captured at midnight

0.1%	0.4%	1.0%	0.4%	0.1%
0.4%	2.0%	4.0%	2.0%	0.4%
1.0%	4.0%	100%	4.0%	1.0%
0.4%	2.0%	4.0%	2.0%	0.4%
0.1%	0.4%	1.0%	0.4%	0.1%

Crosstalk

Charge focusing SPAD

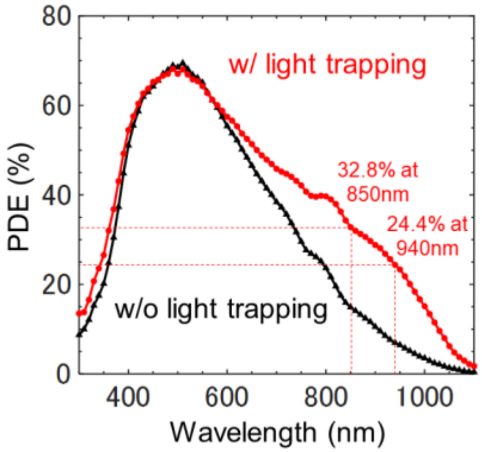


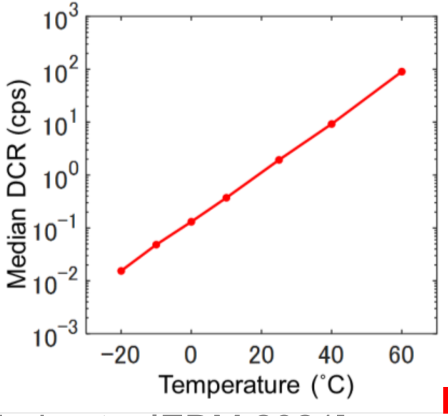


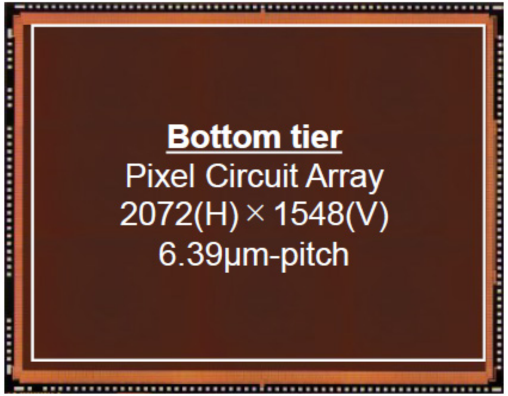
a.k.a. "electrical microlenses"

- [K. Morimoto, Image Sensors Europe 2024]

Low light Level Intensity Imaging

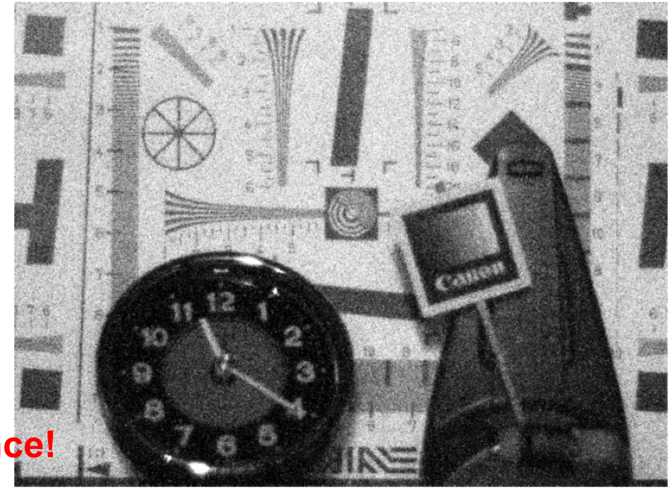






Canon MS-500
Backside
Illuminated
3.2 Mpx

2 mLux



- [K. Morimoto, IEDM 2021]

Power consumption at high illuminance!
Here: clocked recharging

Example of technology development: SPAD test structures@110 nm

L. Ratti, Univ. Pavia

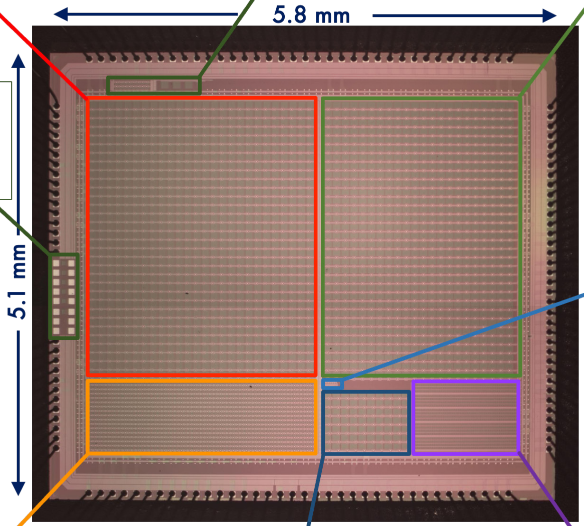
Array 1 (A1)
100 μm pitch
32x26 pixels
80x84 μm^2 active area
67% fill factor

Array ASSTI
2x8 pixels
30x40 μm^2 active area

Array APXT
4 pixels with
different active area

Array 2 (A2) -10 bit
100 μm pitch
32x20 pixels
90x72 μm^2 active area
64% fill factor

Single SPAD sensors with different active area



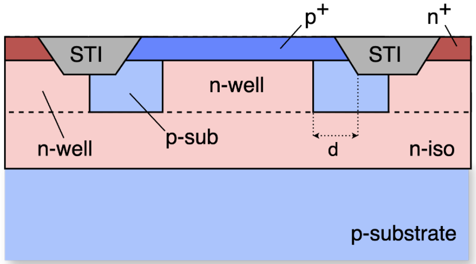
10b/20b TDC and ring oscillator

Array 3 (A3)
50 μm pitch
16x52 pixels
30x40 μm^2 active area
48% fill factor

Mini(4x4)-dSiPM Array (ASiPM)
160 μm pitch
5x12 dSiPMs
41% fill factor

Array 4 – Active Quenching (AAQ)
100 μm pitch
7x10 pixels
67% fill factor

SPAD CROSS-SECTION



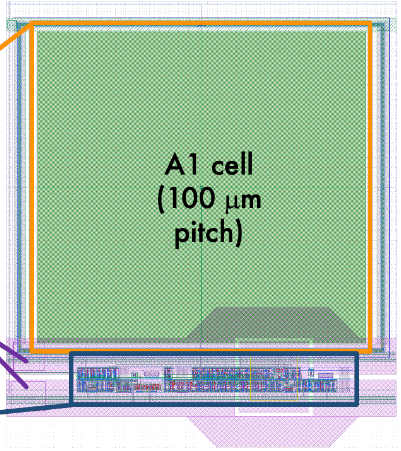
d≠0 only in ASSTI

ELEMENTARY CELL LAYOUT

SPAD active area

ground and power lines

front-end electronics



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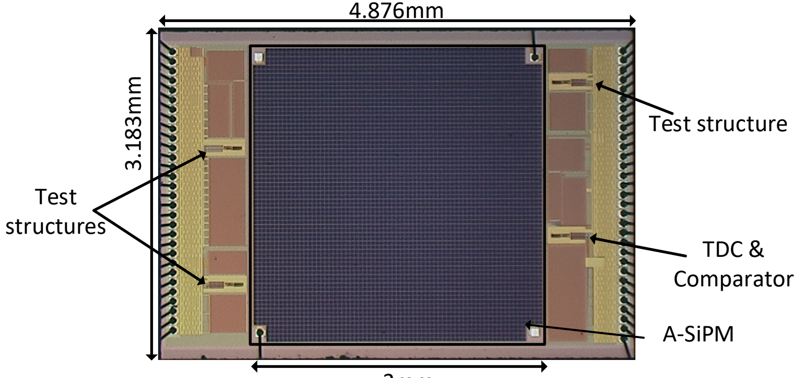
Examples of R&D Systems for HEP & PET

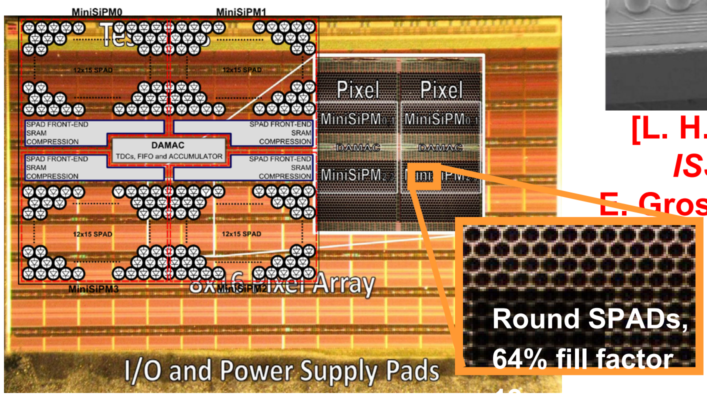
Examples of R&D Systems

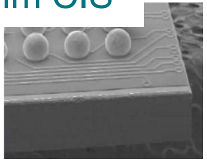
Blumino digital analog SiPM SensL, 350nm



[A. Muntean et al., IEEE TRPMS(5) 2021]

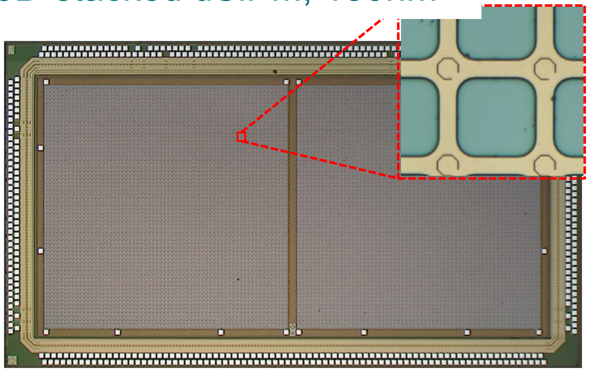
SPADnet dSiPM for TOF-PET, ST 130nm CIS

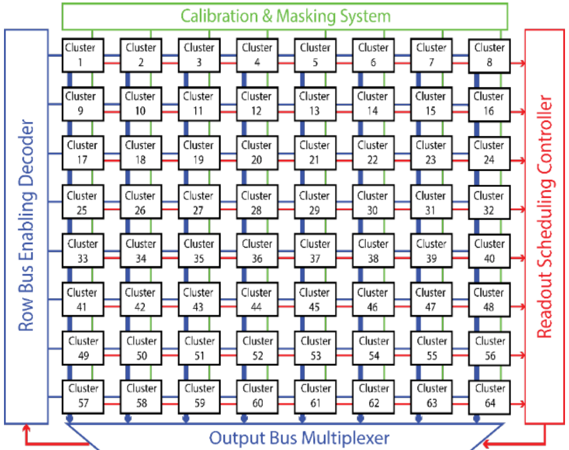




[L. H. Braga et al., *ISSCC* 2014, E. Gros d'Aillon, NDIP 2014]

Blueberry FSI 3D-stacked dSiPM, 180nm





[F. Gramuglia, et al, NSS-MIC 2021, IISW 2021]

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spadRICH

EPFL, JSI – R. Dolenec, R. Pestotnik:
monolithic dSiPMs for future RICH detectors

Swiss National Science Foundation

Institut "Jožef Stefan" Ljubljana, Slovenija

aris Slovenian Research and Innovation Agency

weave Research funding without borders

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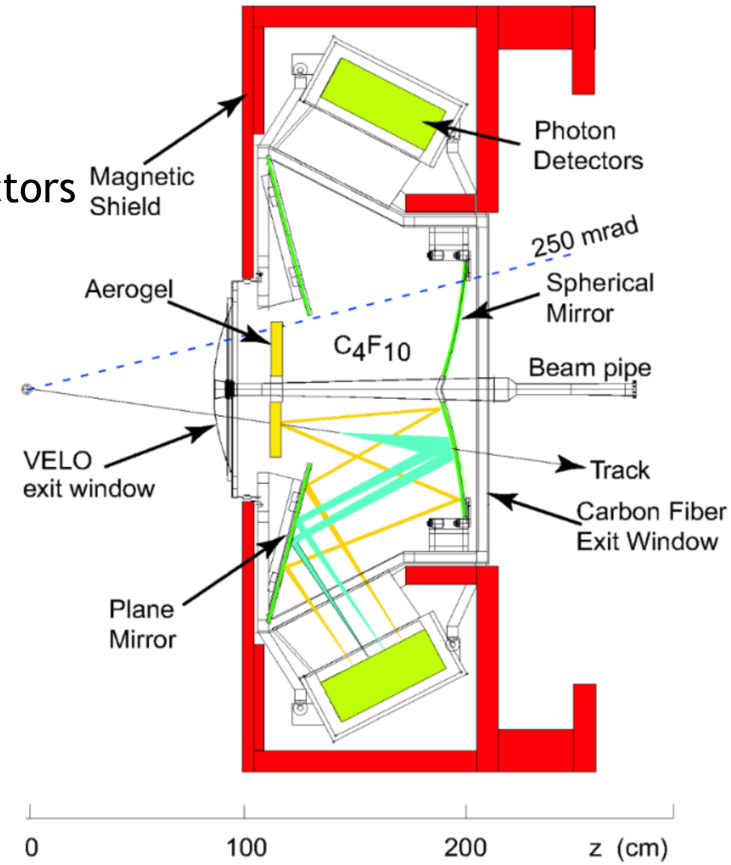
Project background

- Planned upgrades of Ring Imaging Cherenkov (RICH) detectors
  - **LHCb**, Belle II, ALICE3
- High performance requirements for photodetectors used
  - magnetic field
  - timing resolution
  - Cherenkov angular resolution → small channel size
  - channel occupancy
  - background radiation
- **Silicon Photomultiplier (SiPM)**
  - main candidate
  - main issue: **neutron radiation damage**

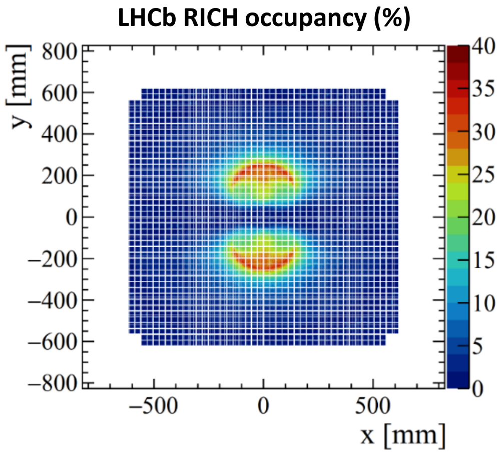
LHCb RICH1:

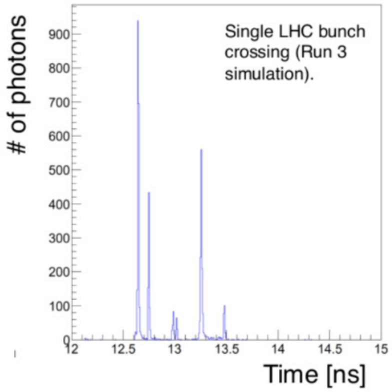


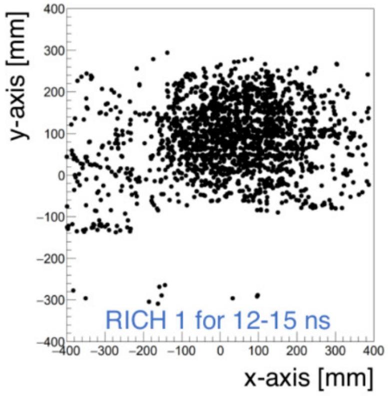
LHCb RICH upgrade photodetector requirements

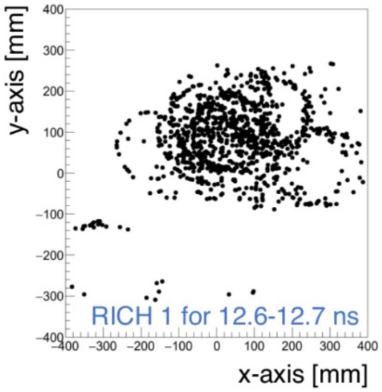
- Fast timing
  - Nanosecond front-end gate – background and data throughput reduction
  - Picosecond hit timestamps – reduce combinatorial background
- Cherenkov angle resolution
  - High granularity ~1x1 mm^2 – also to reduce photon occupancy
  - Enhanced sensitivity in green – enable chromatic error reduction

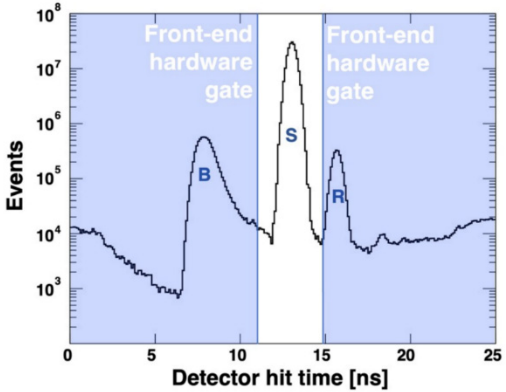
Occupancy: 1-photon hit probability/channel/bunch crossing (25 ns)



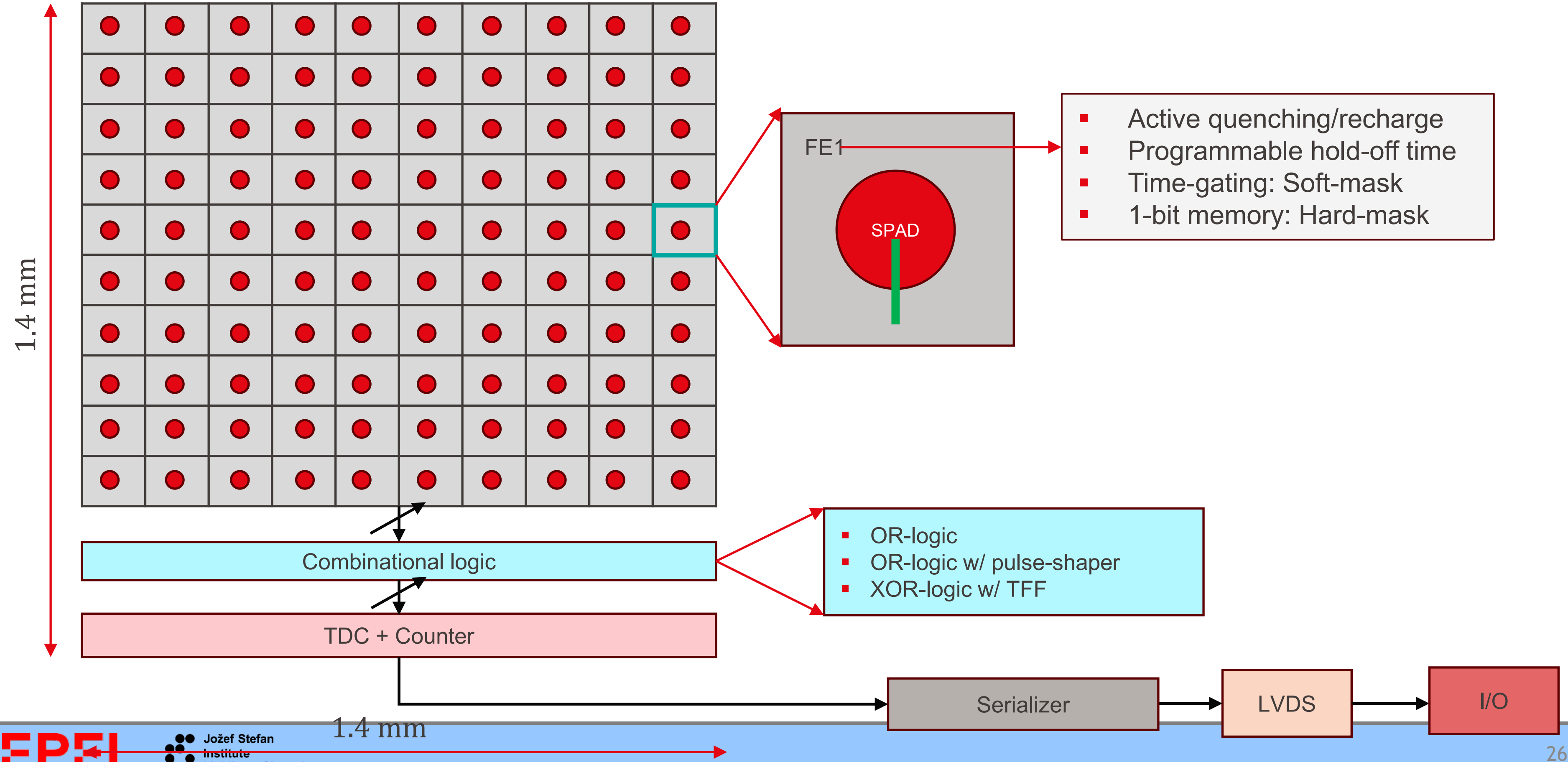






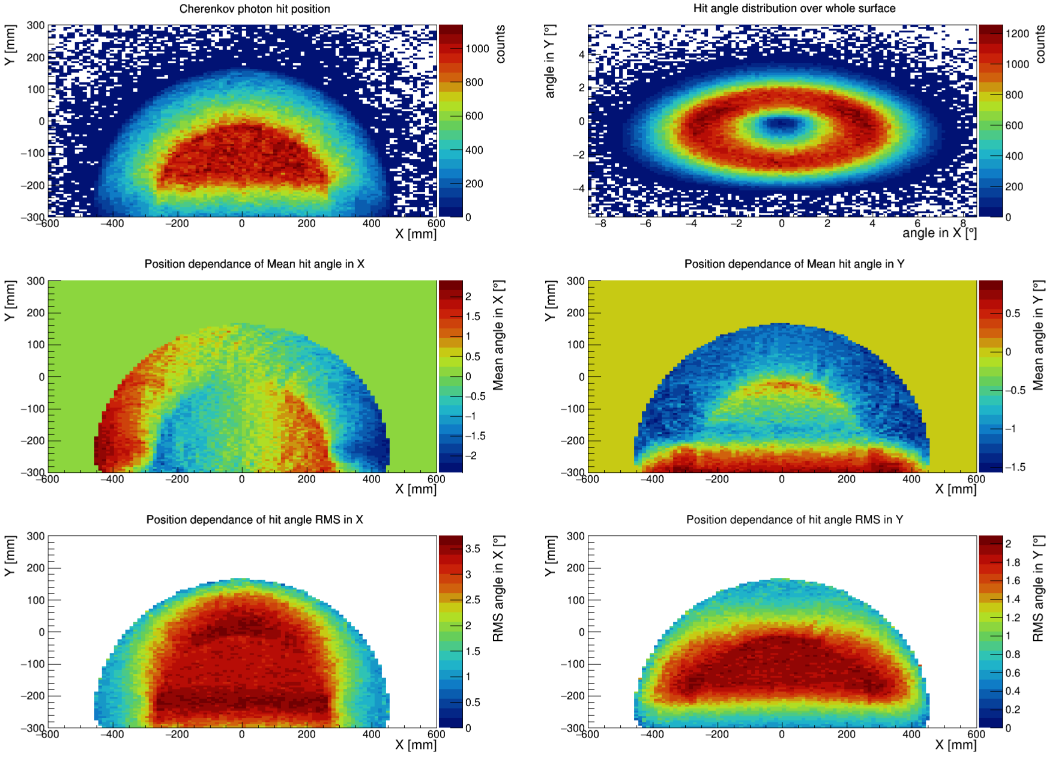


spadRICH Architecture (preliminary)



RICH specific optimizations: Microlenses

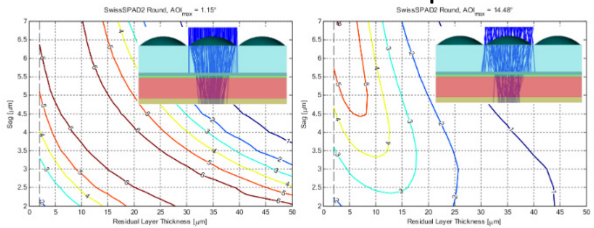
- Small SPAD area → improved radiation hardness, microlenses → recover effective active area
- Simulated photon hit distributions in LHCb RICH (upper detector):



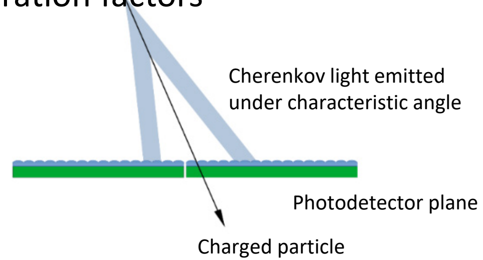
Maximum required micro-lens acceptance half angle ≈ 6°

→ Relatively modest NA ≈ 0.1 / f ≈ 5

→ Good concentration factor possible



Possible position dependent optimization of microlenses to further improve concentration factors



spadRICH: Summary & Conclusions

spadRICH: monolithic dSiPM for future RICH detectors

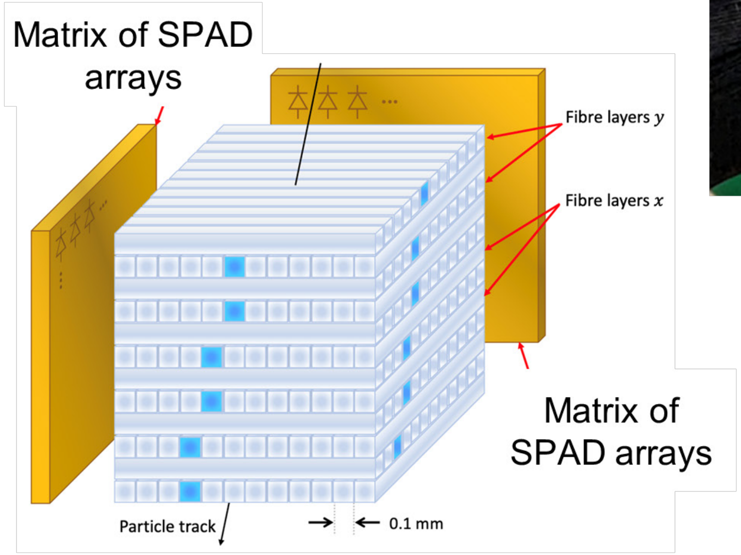
- Constraints:
  - Granularity down to 1x1 mm^2
  - Timing precision ~100 ps, 40 MHz trigger (25 ns), few ns gating
  - Switching off hot pixels, 30% occupancy
  - Radiation hardness ($2x10^{13}$ 1-MeV neutron equivalent/cm^2)
- ~Collimated light -> use of microlenses to recover fill factor and reduce radiation damage looks feasible
- Possible cryogenic operation, but afterpulsing challenge in irradiated detectors
- Initial activities:
  - Radiation hardness measurements (neutrons up to 10^{12} neq/cm^2 @TRIGA) in 180 nm (actively quenched SPADs), GF 55nm BCD and 110 nm
  - Operation at cryogenic temperature (starting)
  - Microlenses: radiation hardness measurements and cryogenic operation

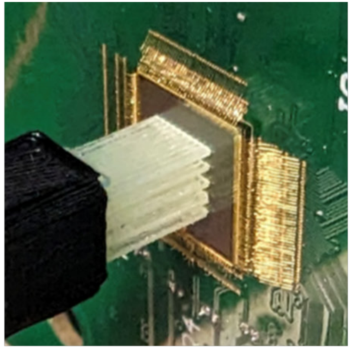
PLATON

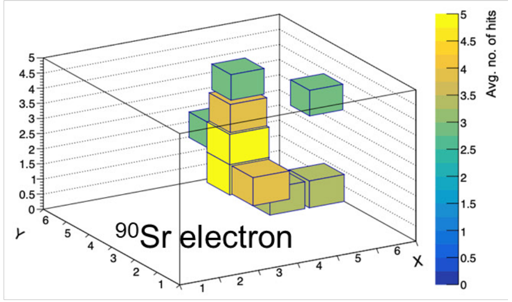
ETH (D. Sgalaberna), EPFL:
neutrino tracking / scintillating fibres, monolithic dSiPMs

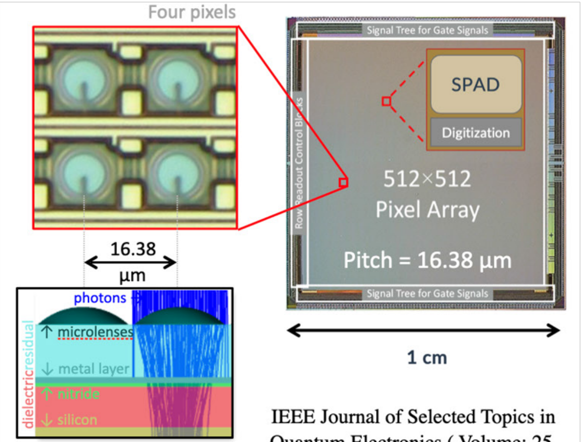
SciFi: tracking with scintillating fibres

Goal for future neutrino near detectors is tracking low-momentum protons









modified from (C. Bruschini, et al. 2023)

IEEE Journal of Selected Topics in Quantum Electronics (Volume: 25, Issue: 1, Jan.-Feb. 2019)

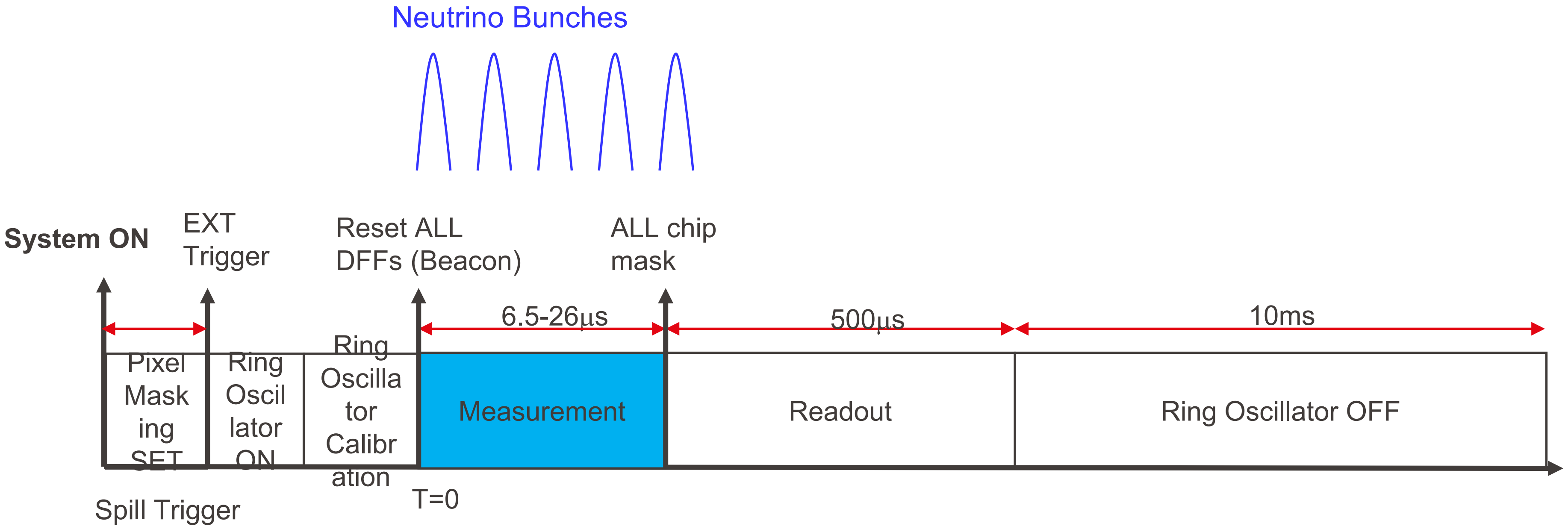
- The concept has been proven w/ SwissSPAD2
- Developing novel SPAD sensor (see later)

Eur.Phys.J.C 84 (2024) 2, 202

D. Sgalaberna

EPFL ETH zürich FNSNF aqualab

Event structure of neutrino beam trigger @T2K/HK

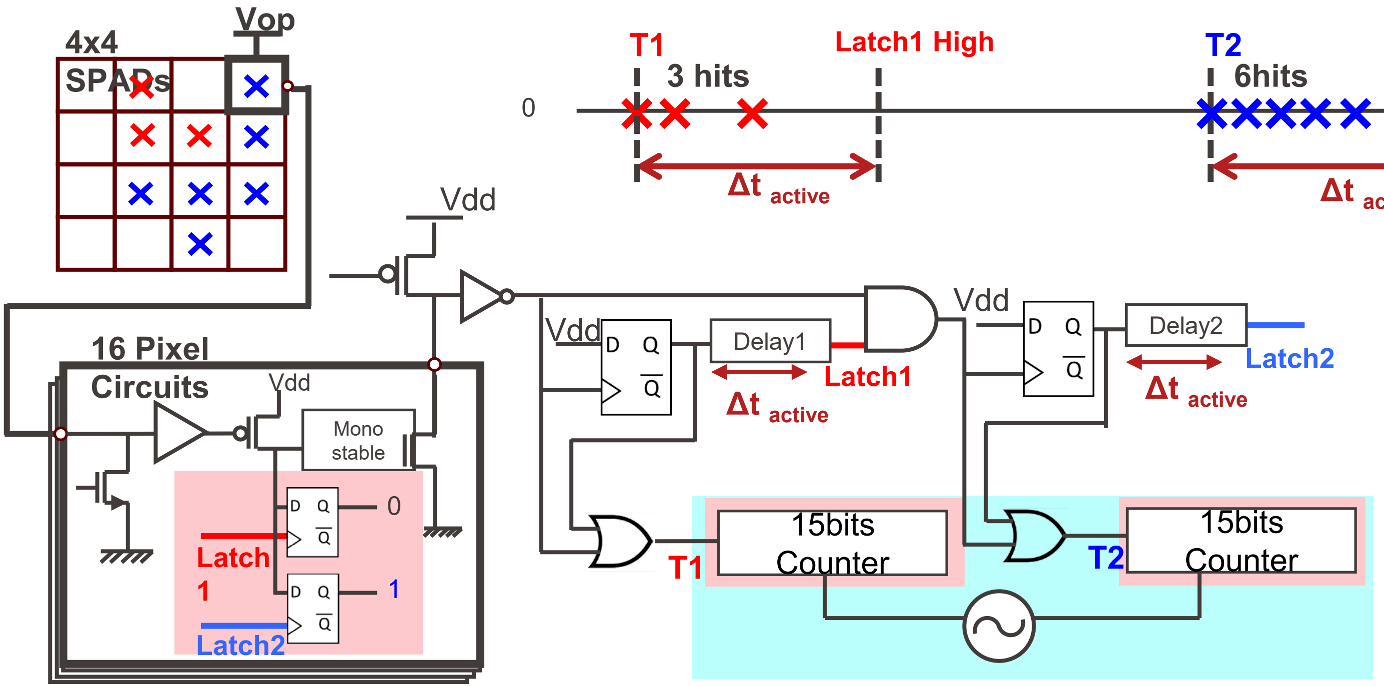


- Next cycle: 1 second later → ample time for read-out vs parallelisation
- Ring oscillators can be switched off in-between spills (→ power saving). Need however to be recalibrated before each measurement.

PLATON Pixel Architecture / 1

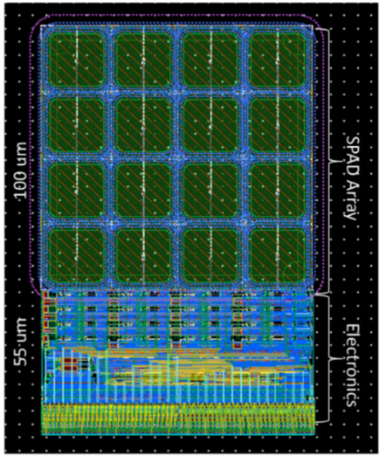
4*4 SPAD array with TDC

- Asynchronous TDC for event driven architecture
- Taking 2 sub-images per spill



2. Multiple counters for spatial map

1. Asynchronous TDC



aqualab

- Kodai Kaneyasu (EPFL)

DIGILOG

EPFL, RWTH – V. Schulz & S. Gundacker, FBK:
3D-stacked FSI digital analog-SiPM for ToF-PET

DIGILOG 1010 0111000001110011

EPFL

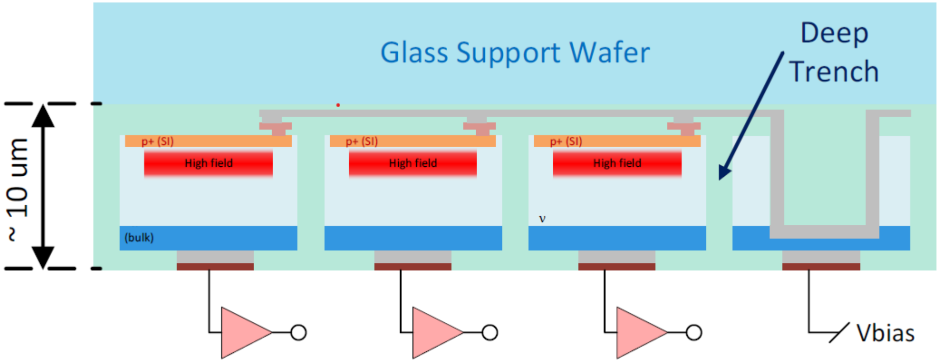
ExMI PMI Physics of Molecular Imaging Systems Teaching and Research Unit

RWTH AACHEN UNIVERSITY

FBK CENTER FOR SENSORS & DEVICES FONDAZIONE BRUNO KESSLER

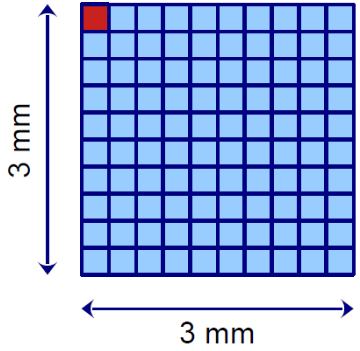
aqualab

DIGILOG: Segmentation and 3D stacking

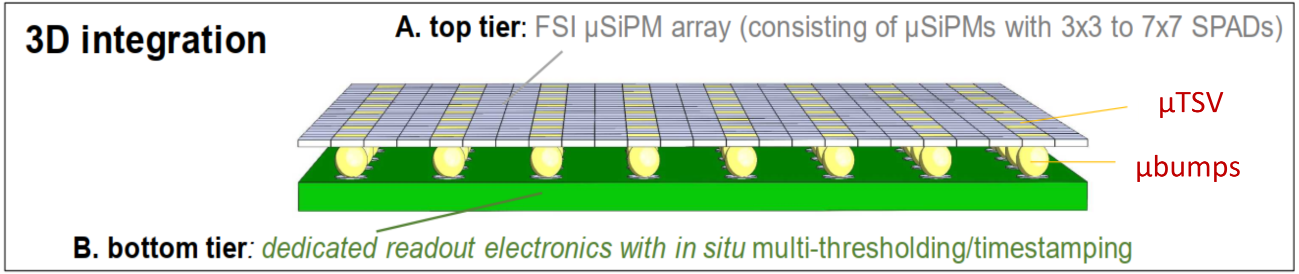


FONDAZIONE BRUNO KESSLER — CENTER FOR SENSORS & DEVICES

SiPM: 3x3 mm²
SPAD: 50 x 50 µm²
10x10 µSiPM array
(36 SPADs per µSiPM)



Lower capacitance C → higher electrical signal → possible to detect the 1st photon
Smaller SiPM size → better SPTR
Single Cell TSV: Backside contacts + RDL (redistribution layer)



Gundacker, S et al. (2023). "DIGILOG: A digital-analog SiPM…", *IEEE NSS-MIC.*
Gola, A et al. (2024). FBK roadmap towards the next-generation of 3D-integrated SiPM and SPAD technologies.

EPFL

dSiPMs for other HEP/nuclear applications

- Univ. of Sherbrooke (Canada, S. Charlebois, J.-F. Pratte): dSiPMs for HEP and related applications – PDC platform →

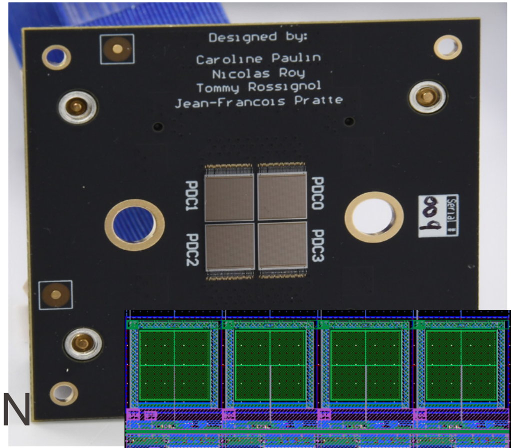
- I. Diehl, DESY (Hamburg, Germany)

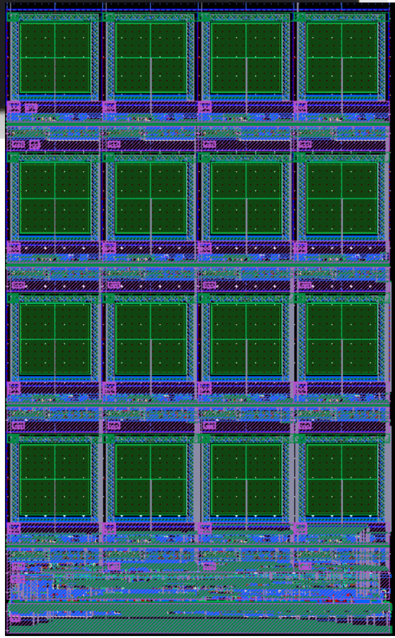
- P. Fischer, M. Keller, Univ. of Heidelberg (Germany) – DARWIN

- Fabrice Retière (TRIUMPF, Canada)

- FERMIlab – DUNE collaboration

- L. Ratti (Pavia, Italy) & colleagues: stacked SPAD arrays for HEP tracking (coincidence detection) & dSiPMs (ASPIDES INFN) →





Summary & Conclusions

Final Considerations

- SPAD products do exist either for volume (e.g. ranging, low light level imaging) or for specific applications (e.g. microscopy/scientific)
- Analog vs digital vs "hybrid" - Design life cycles (more demanding in fully digital approaches)
- Foundry access still a very important item
  - Multi-project wafer vs. full (dedicated) runs
  - Focus on NIR for certain applications (e.g. LIDAR)
- No "one size fits all" device → harder to assemble a critical design/sponsoring mass?
- Exploit applications where there is an added value from the digital circuitry
  - Higher granularity, spatial and/or temporal
  - Added functionality, like switching off noisy SPADs, or control hold-off time
  - "Ultimate" performance (e.g. timing)
- Tiling is still a specific requirement of HEP/nuclear physics (and PET…)

Acknowledgments

- *Edoardo Charbon & the whole aqualab Team!* →
- *Special thanks: Serge Charlebois, Catherine Pepin, Jean-François Pratte, Univ. de Sherbrooke*
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- Alberto Gola, Stefano Merzi, Maria Ruzzarin, Laura Parellada Monreal (FBK)
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- Lodovico Ratti, Univ. di Pavia