SWIR/NIR SPAD Image Sensors for LIDAR and Quantum Imaging Applications

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Acknowledgements

Swiss National Science Foundation
European Commission, STW/NOW

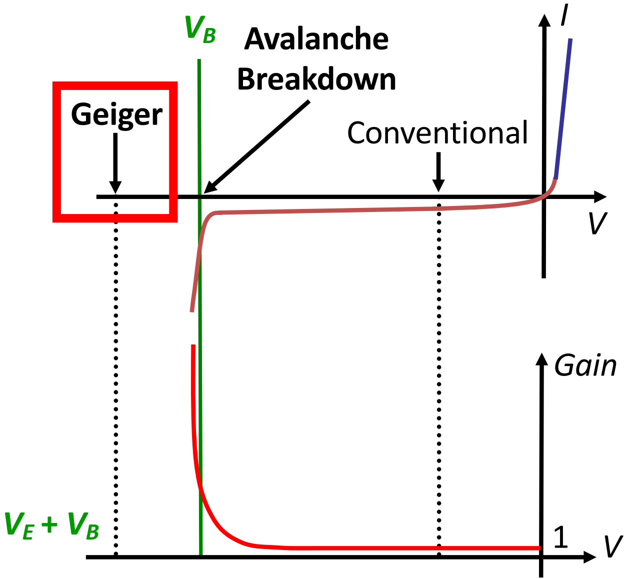
Global Foundries, Canon, and many others.

Solid-State Photon Counting

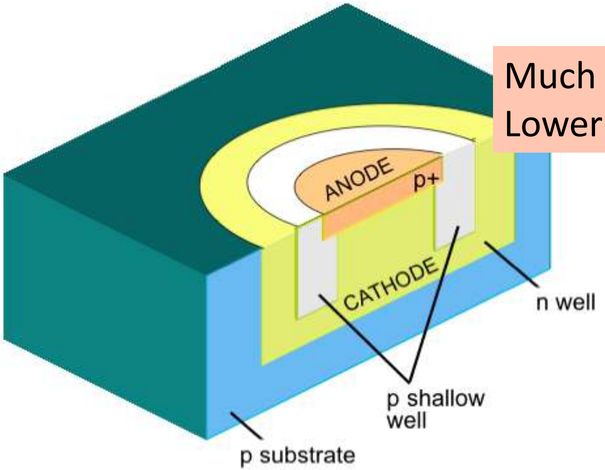
Single-photon detectors over time

- Electron multiplication in vacuum
  - Photomultiplier tube (PMT)
  - Microchannel plate (MCP)
- CMOS APS, sCMOS
- Electron multiplied charge-coupled device (EMCCD)
- Avalanche photodiode (APD)
- Geiger-mode APD (GAPD) or Single-photon avalanche diode (SPAD)
- Silicon photomultiplier (SiPM)

SPAD or Geiger-Mode APD



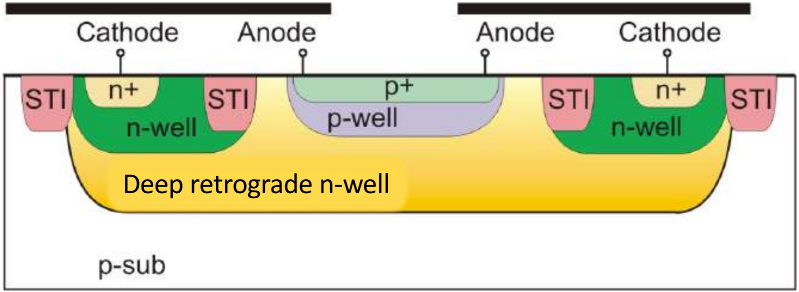
Planar implementation of a SPAD



Much smaller structure
Lower voltages involved

The CMOS SPAD Revolution

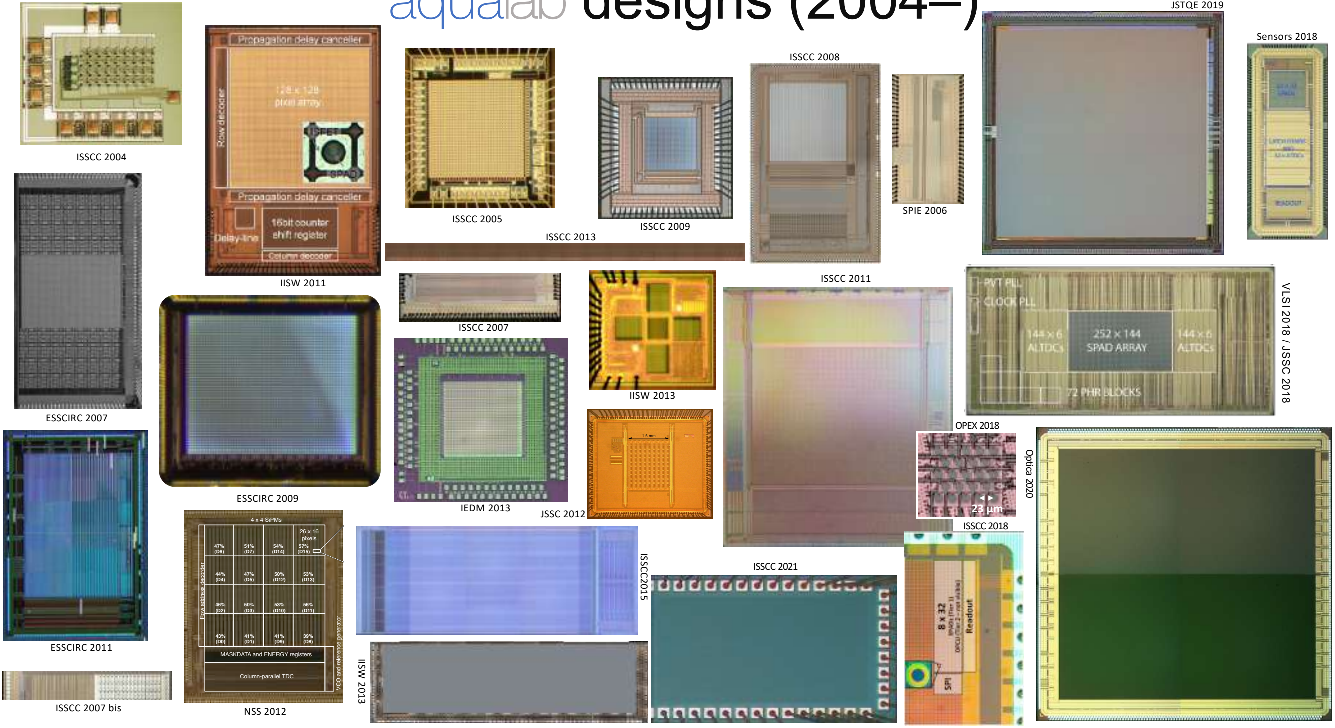
CMOS SPADs



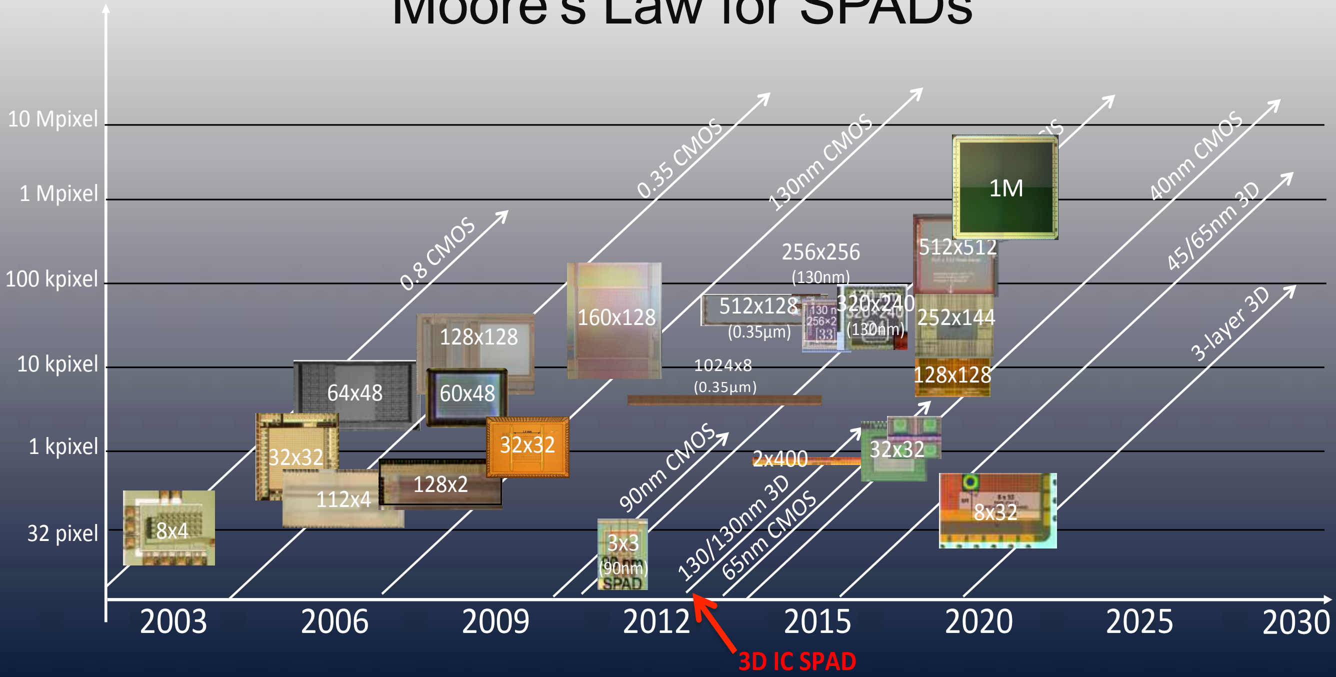
Reproducibility, reliability, miniaturization

We can go from single-sensor photon counting to single-photon IMAGING

aqualab designs (2004–)



Moore's Law for SPADs



The phenomenal SPAD performance evolution

- Timing resolution (100ps → 7.5ps)
- Sensitivity
  - Photon Detection Probability (PDP) (10% → 78%)
  - Fill-factor (1% → 80%)
- Dead time (100ns →1.5ns)
- Dark counts (kcps → cps → mcps)
- Afterpulsing (10% → 0.1%)

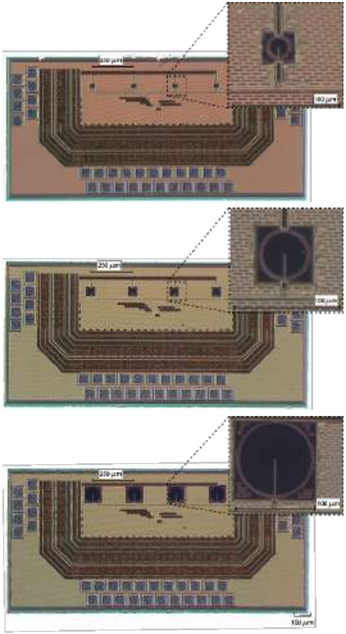
cps = counts per second
kcps = 10^3 cps
mcps = 10^{-3} cps

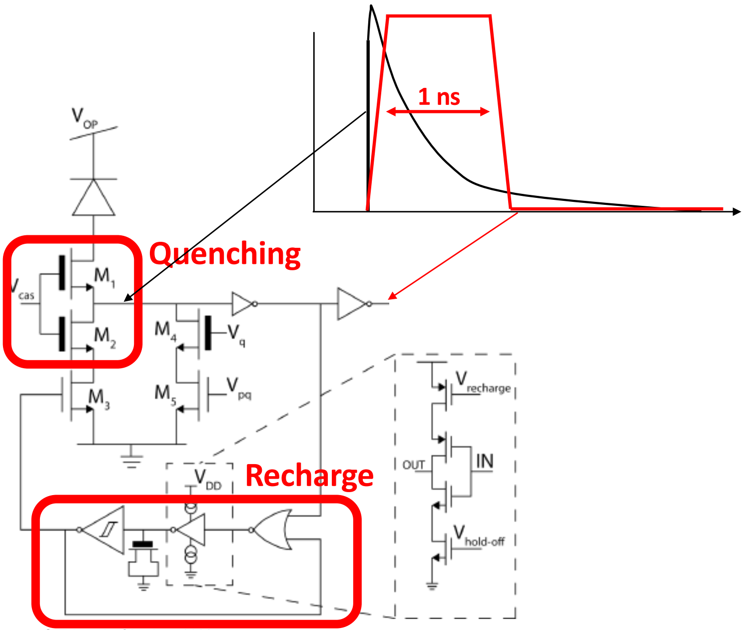
The power of integration

25µm

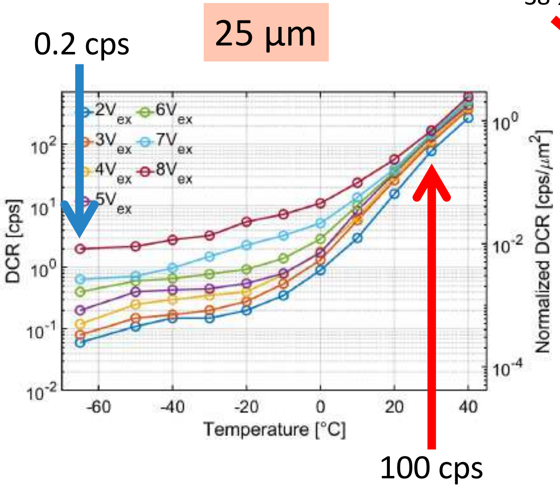
50µm

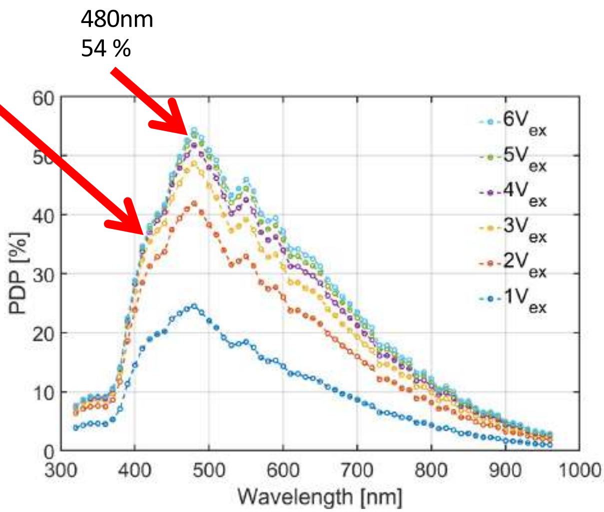
100µm





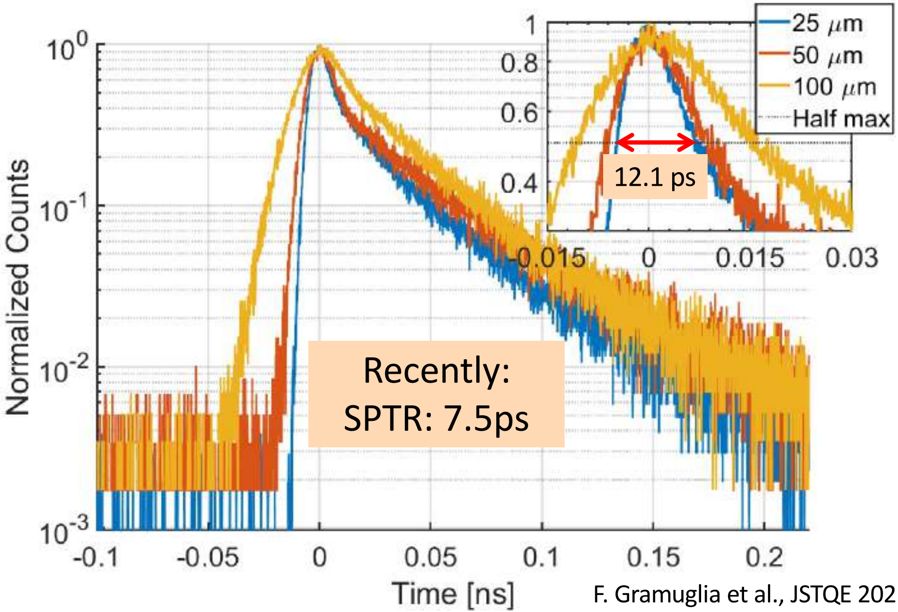
Sensitivity (PDP) and noise (DCR)





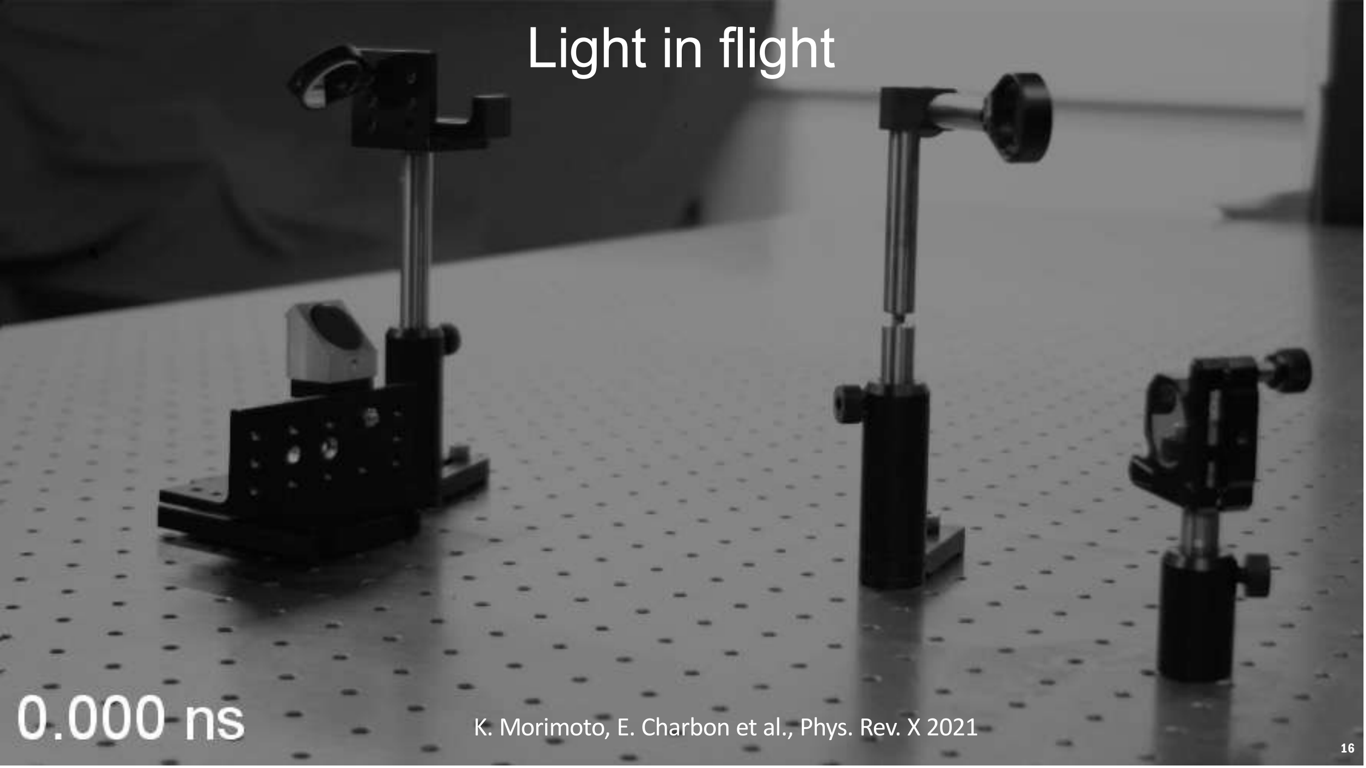
F. Gramuglia et al., JSTQE 2021

Timing resolution (SPTR)



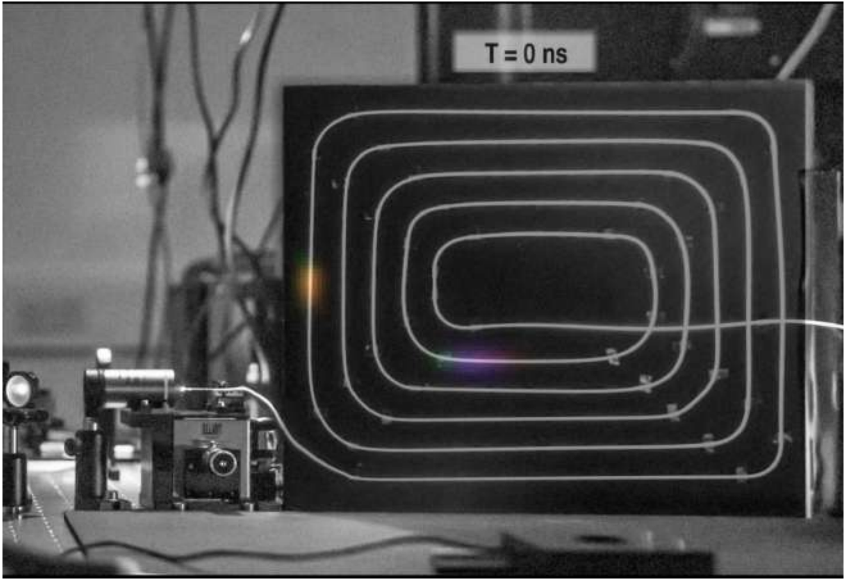
F. Gramuglia et al., JSTQE 2021
F. Gramuglia et al., Frontiers in Physics, 2022

Light in flight



K. Morimoto, E. Charbon et al., Phys. Rev. X 2021

Observe light dispersion in real time



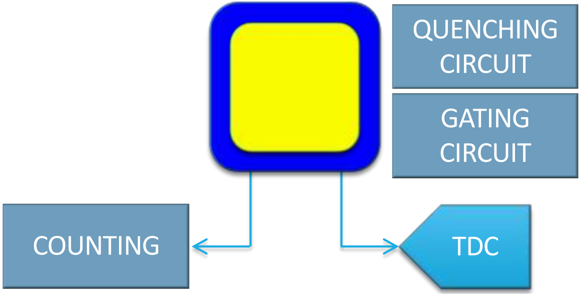
R. Warburton et al., Sci. Rep. 7, doi: 10.1038 2017

LiDAR

Source: Velodyne

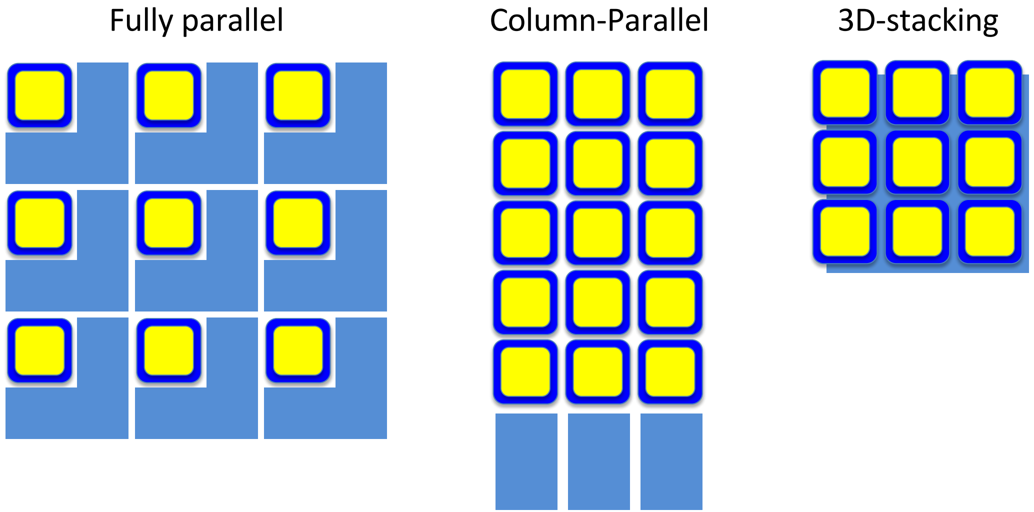
How to Build a LiDAR from a SPAD?

First, the SPAD pixel



TDC = time-to-digital converter

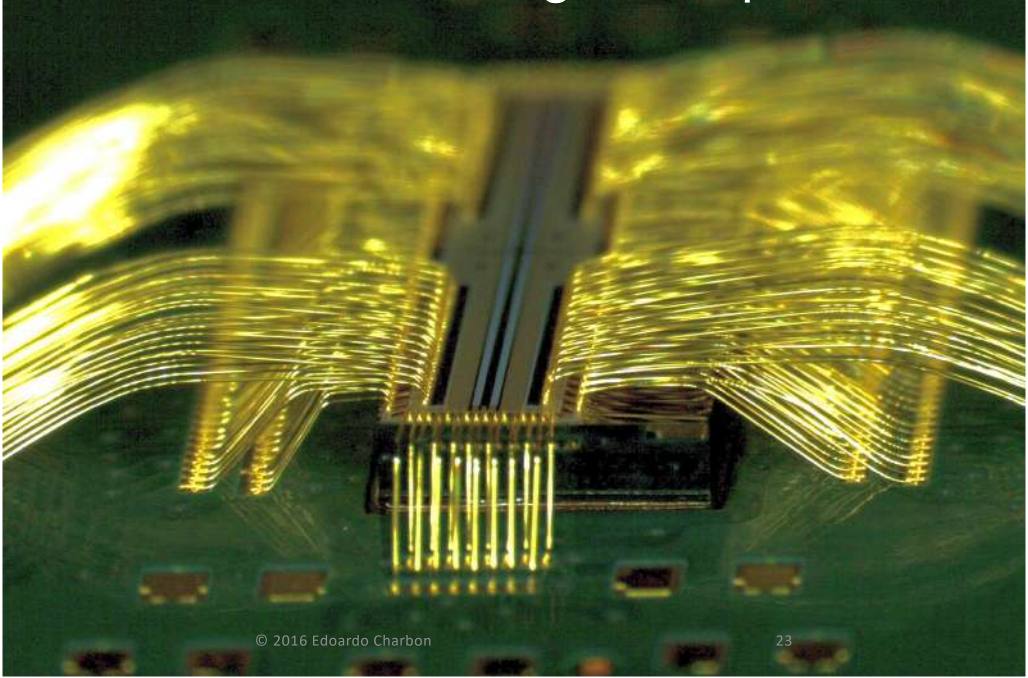
2D arrays



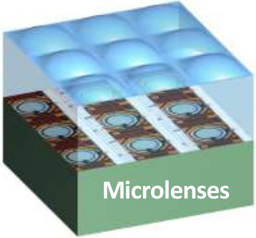
Readout

- Frame-based
- Event-based or event-driven
- Reconfigurable

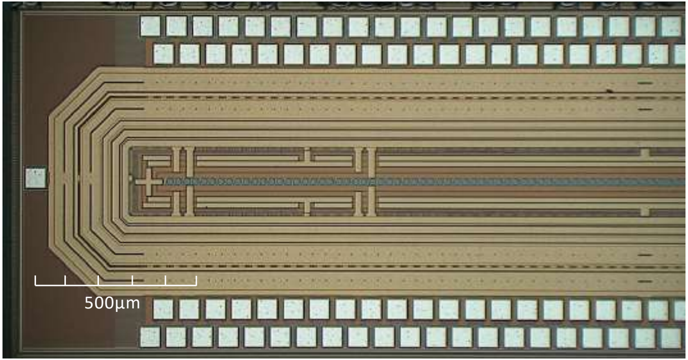
LinoSPAD: reconfigurable platform



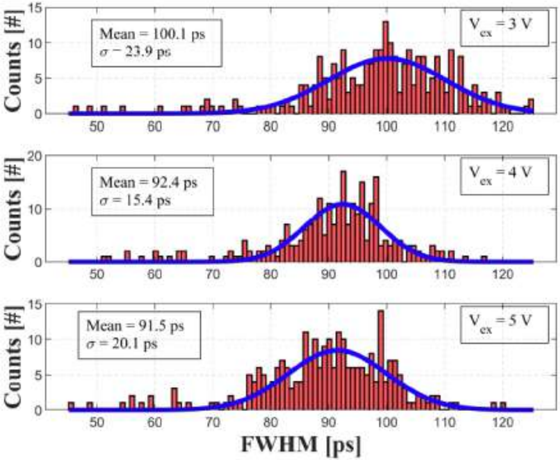
LinoSPAD2: a reconfigurable SPAD array



- SPAD output redirected to an FPGA for processing
- On-demand resource allocation, functionality, speed
- Embedded pulse shrinking, TDC, etc.
- Microlenses

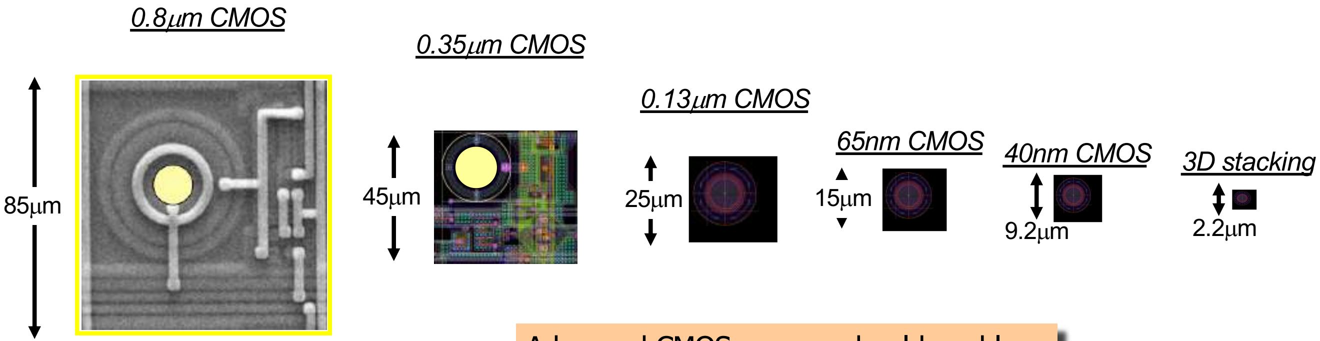


C. Bruschini et al., SPIE 2023



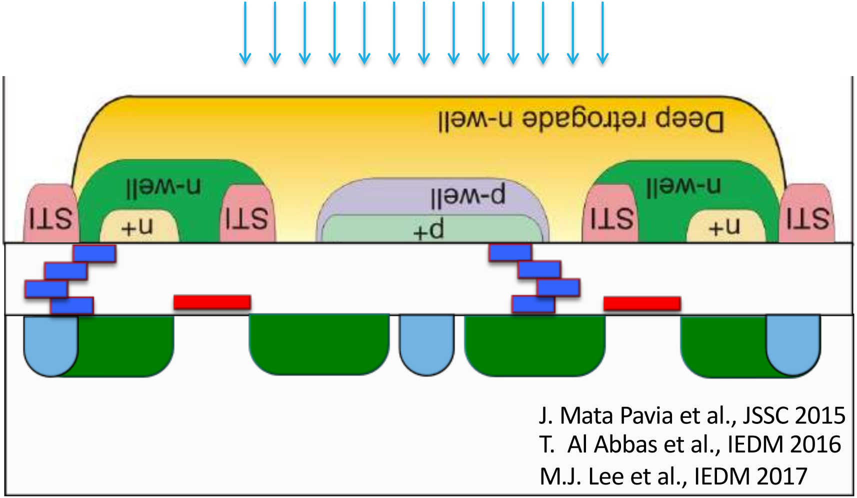
Scaling Up

2D SPAD scaling



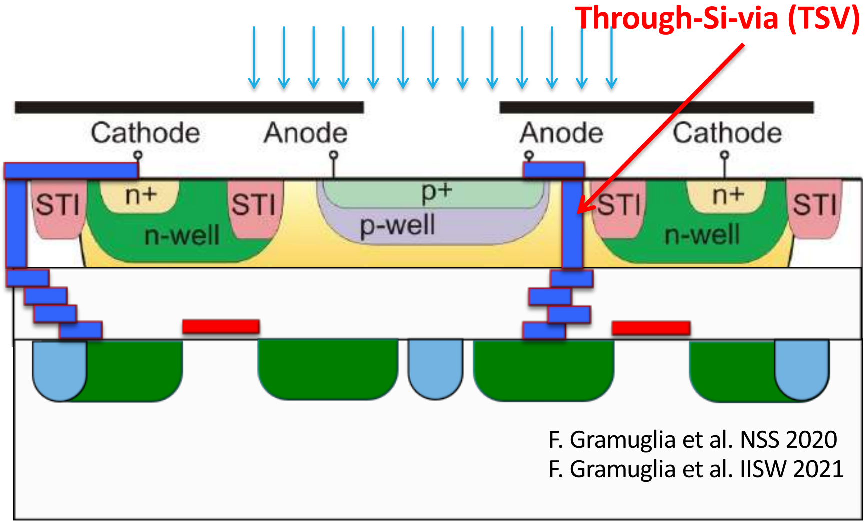
Advanced CMOS process should enable:
- low pitch
- high performance
- high fill factor

3D stacking (backside illumination – BSI)

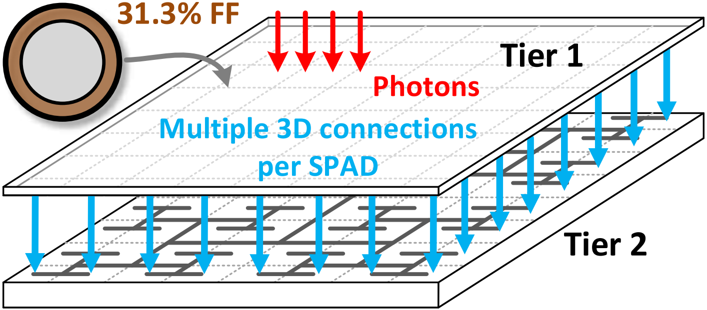


J. Mata Pavia et al., JSSC 2015
T. Al Abbas et al., IEDM 2016
M.J. Lee et al., IEDM 2017

3D stacking (frontside illumination – FSI)



The potential of 3D stacking

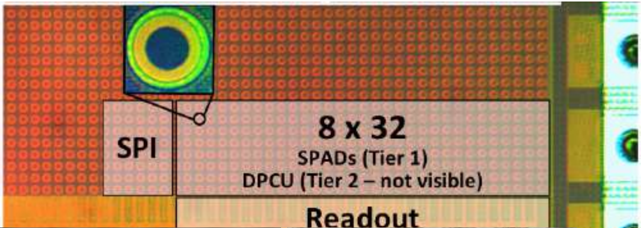


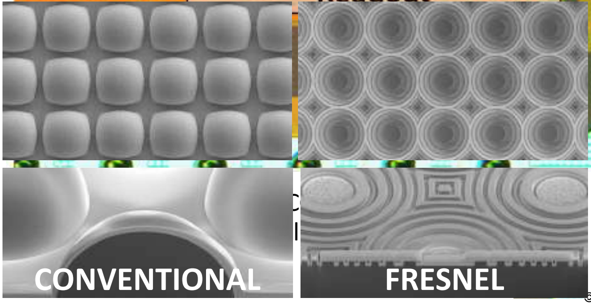
M.J. Lee, A.R. Ximenes, P. Padmanabhan, Y. Yamashita, D.N. Yaung, E. Charbon, IEDM 2017

- Tier 1: SPADs + microlenses
- Tier 2: quenching, recharge, TDCs, multi-core, memories, communication unit, I/O

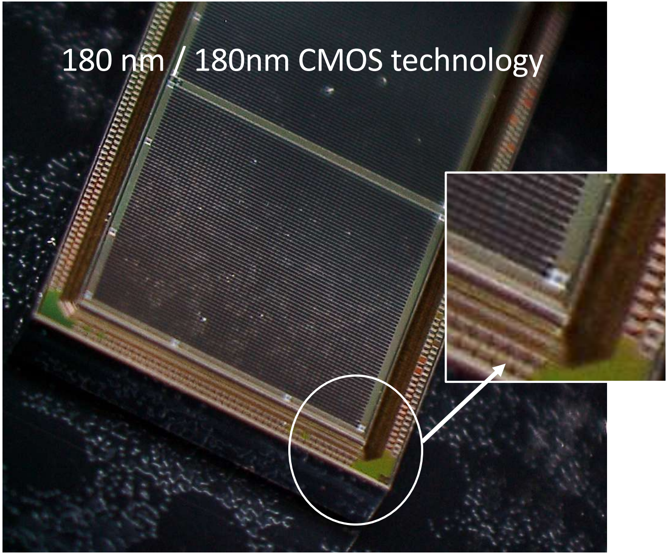
3D-stacked BSI & FSI chips

45 nm / 65nm & 22nm TSMC technology



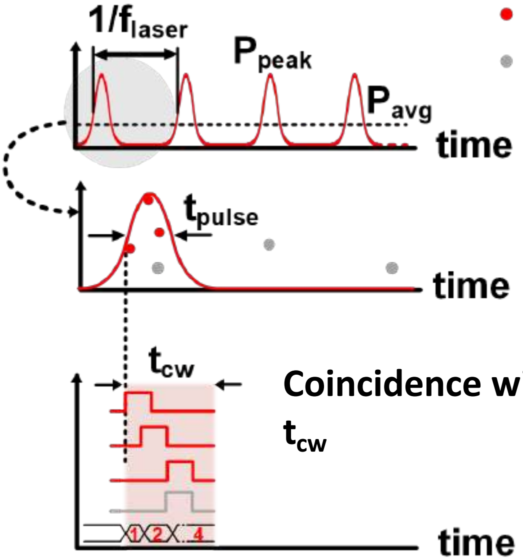


180 nm / 180nm CMOS technology



F. Gramuglia et al. NSS 2020 / IISW 2021

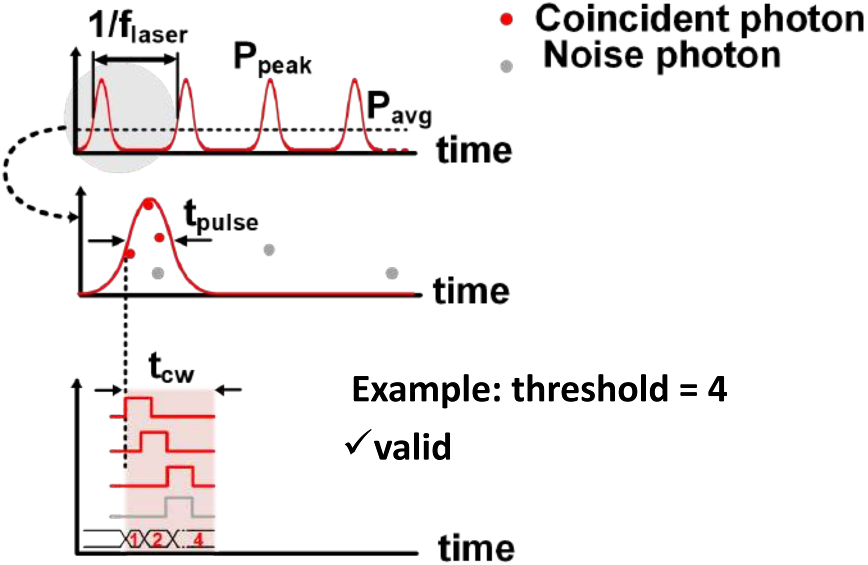
Small digression: coincidence detection



- Coincident photon
- Noise photon

Coincidence window, t_{cw}

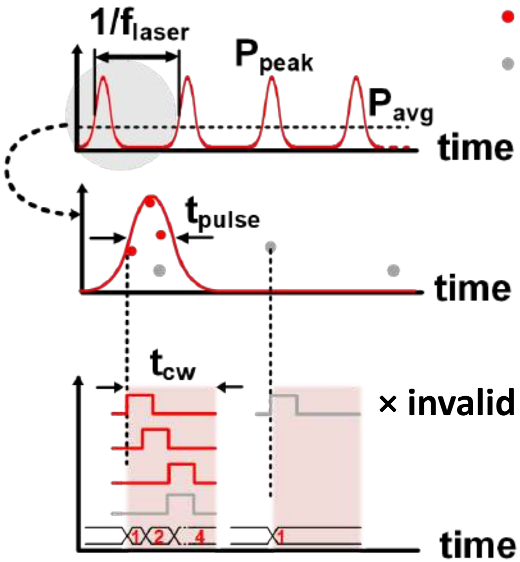
Coincidence detection

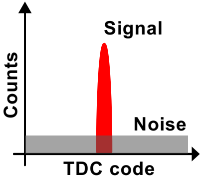


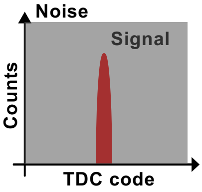
Example: threshold = 4

✓valid

NIR Coincidence detection





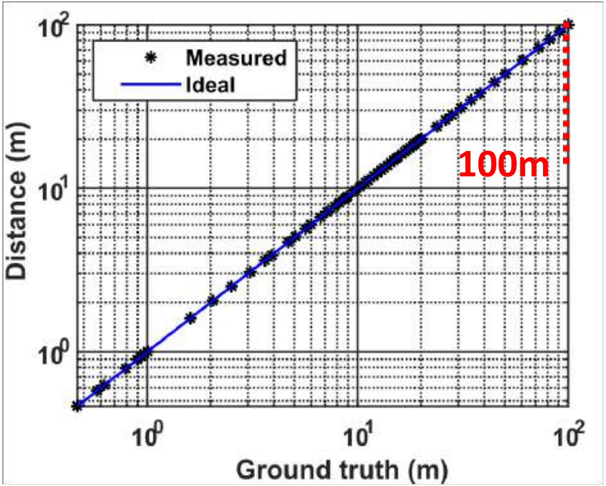


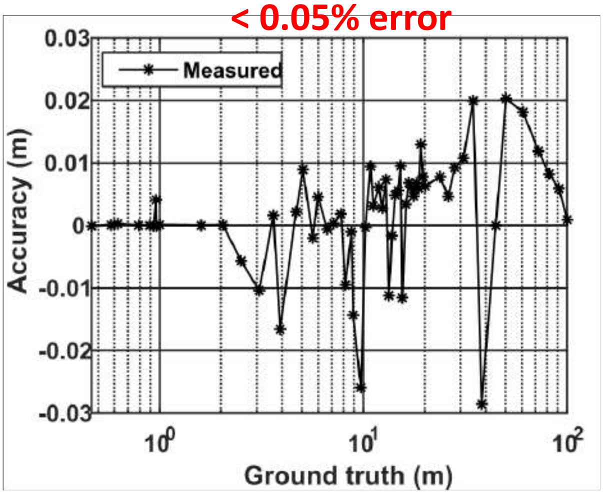
Outdoor:
8 klux

EPFL campus, Lausanne

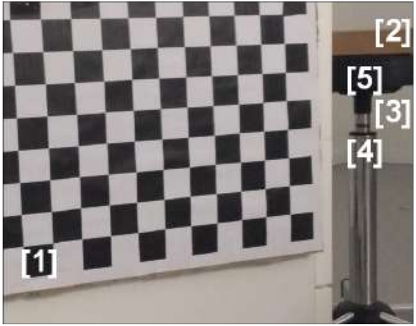
FLASH time-of-flight measurement

50% reflective target

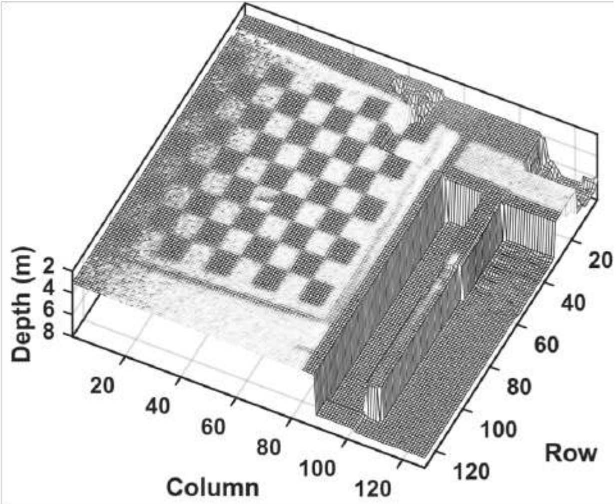




FLASH time-of-flight measurement



Various target reflectivities
[1] Checkerboard 10 – 50%
[2] Cardboard box 20%
[3] Wall 60%
[4] Roller stand 40 – 45%
[5] Roller seat 10%



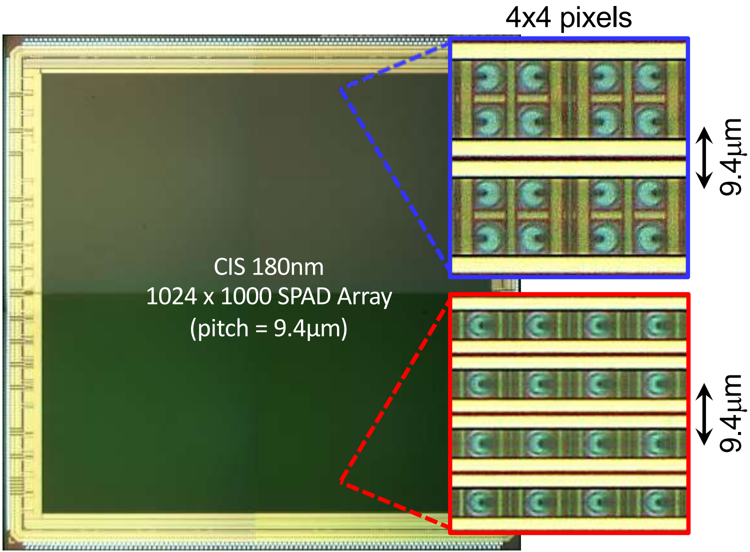
- **1ms exposure, flash**
- **Objects between 2 – 8m**

Large Format Cameras

MegaX: the first SPAD megapixel camera

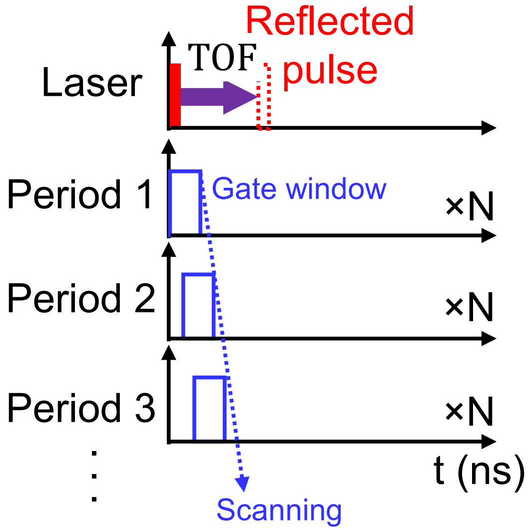
Features

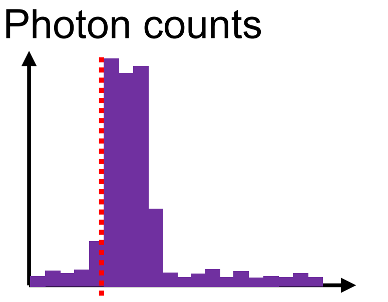
- 1024 x 1000 pixels
- 9.4µm pitch
- 3.8ns gating
- 24,000 fps
- 24.5Gb/s
- VDD: 1.8V
- VBD: 24.7V



K. Morimoto et al., Optica 2020

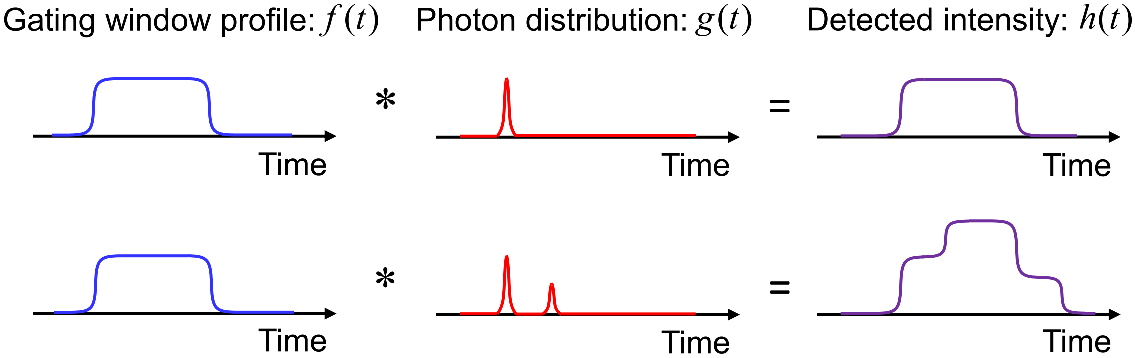
To keep pixels small: time gating



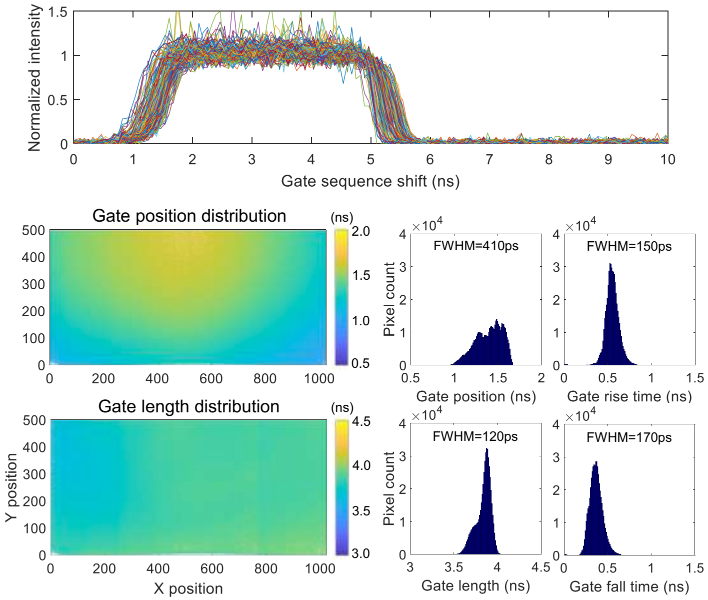


$$\mathrm{TOF} = \frac{2d}{c}$$

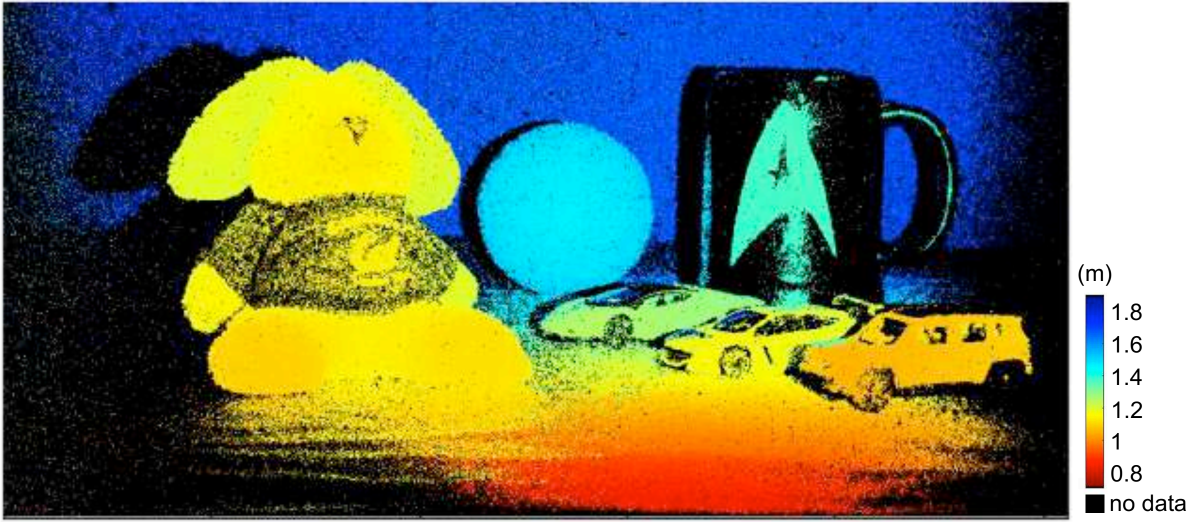
Multiple reflections



Time gating profile



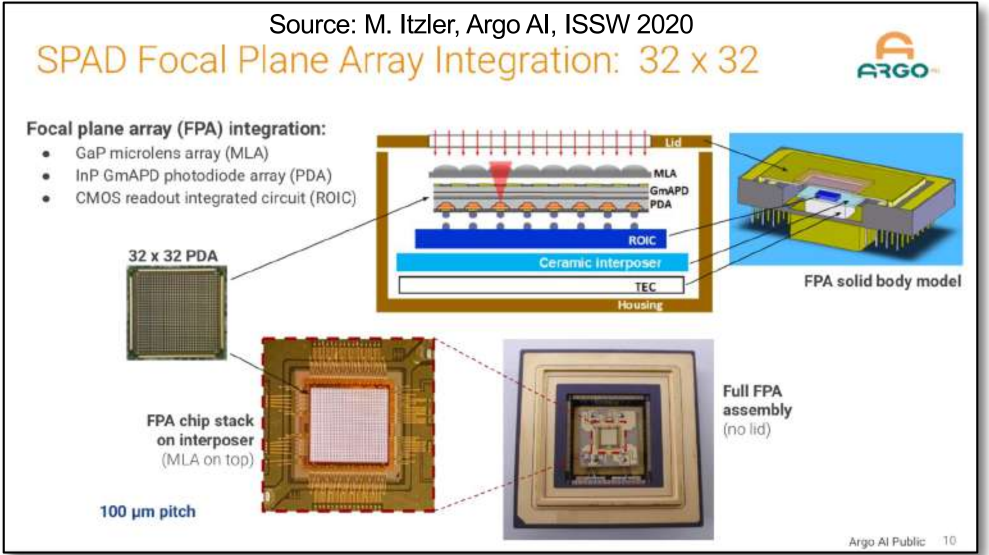
MegaX LiDAR

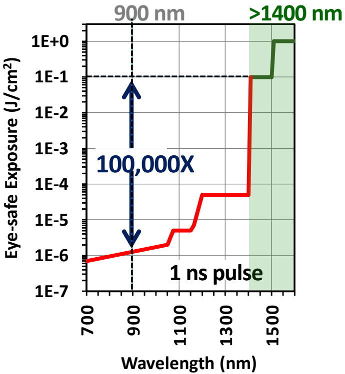


K. Morimoto et al., Optica 2020

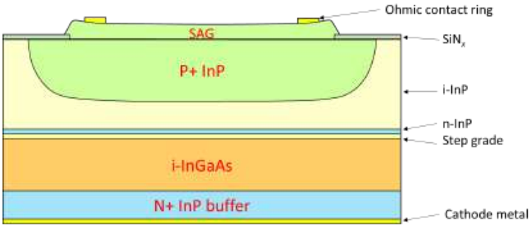
Outlook for NIR/SWIR SPAD

1. Hybrid 3D integration

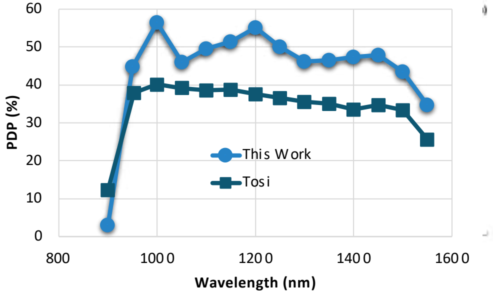




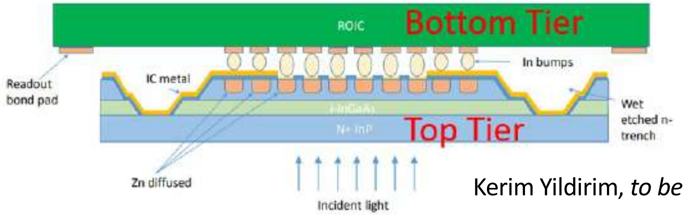
InGaAs-InP SPADs



SAG = Selective area growth
Ekin Kizilkan et al., JSTQE, 2022

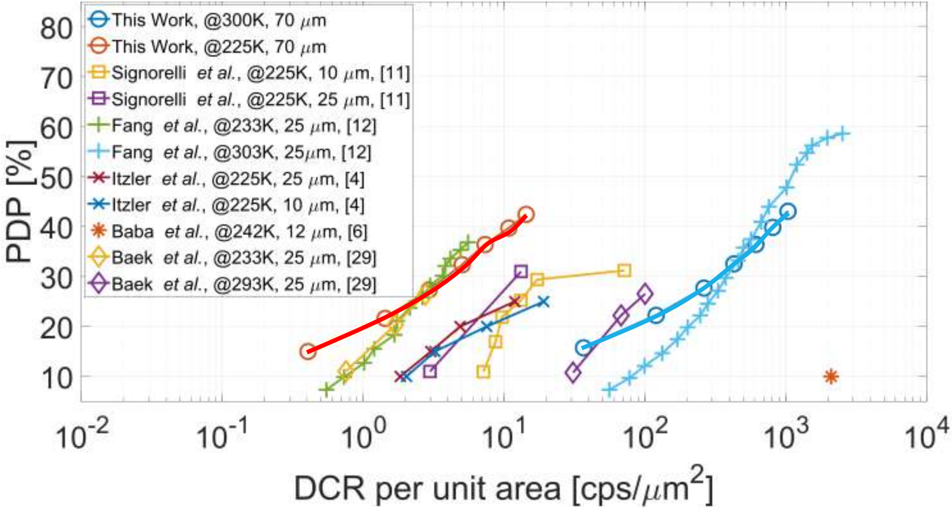


96 x 96 InGaAs SPAD pixel array

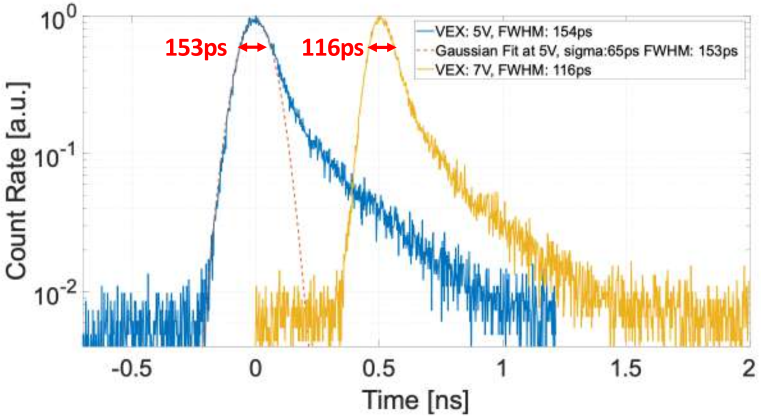


Kerim Yildirim, *to be published*, 2022

InGaAs-InP sensitivity vs. noise

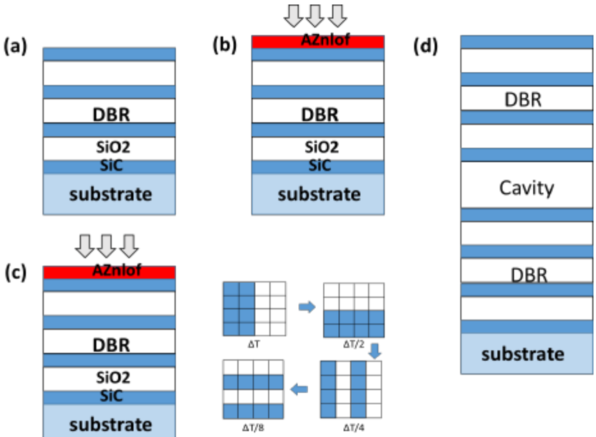


InGaAs-InP jitter

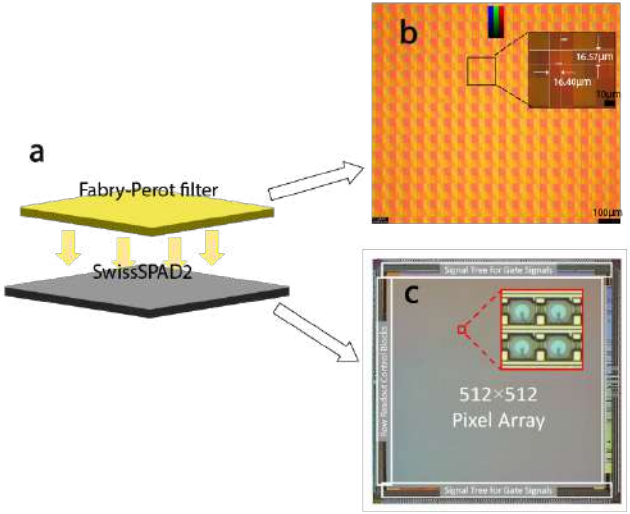


2. Hyperspectral single-photon imaging

- SiC/SiO_2 DBR Fabrication process



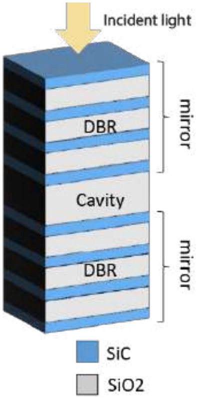
ΔT, ΔT/2, ΔT/4, ΔT/8 is 120nm, 60nm, 30nm and 15nm

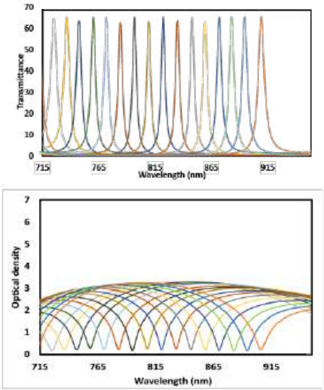


Chufan Zhou et al., *to be published*, 2023

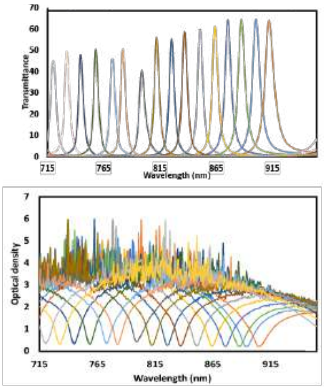
Measurements and modeling

- 2^{nd} resonance FP structure which contains 3.5 pair DBR made up of SiC/SiO_2 multilayers.
- Optimized thickness of SiC and SiO_2 in the DBR layer is 150nm and 80nm.
- The thickness of cavity range from 450nm to 675nm.With 15nm one step.





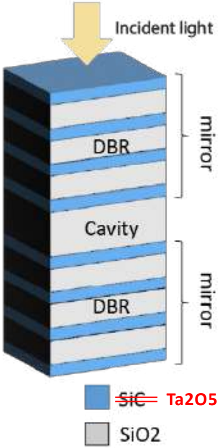
Simulation

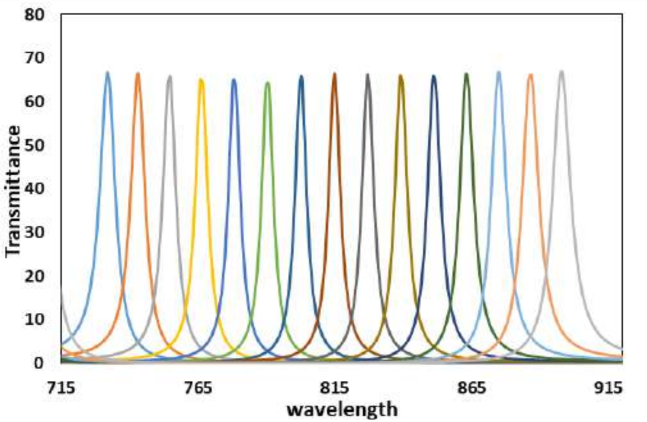


Measurement

Chufan Zhou, *to be published*, 2023

Ta_2O_5/SiO_2 DBR simulation and measurement



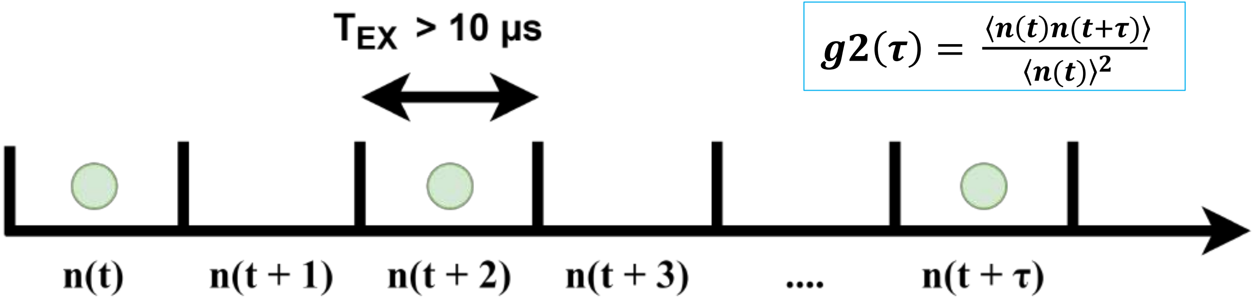


Chufan Zhou et al., *to be published*, 2023

- Change 80nm ***SiC*** to 80nm ***Ta_2O_5***.
- Keep rest parameters same as previous.

3. Coincidence & real-time g2 computation

$$g2(\tau) = \frac{\langle n(t)n(t+\tau)\rangle}{\langle n(t)\rangle^2}$$



With optimized FPGA design, g2 is continuously calculated for every one of SwissSPAD3's 250,000 pixels, for 15 correlation bins, ***in real time***.

Example: g2 imaging for real-time oxygenation

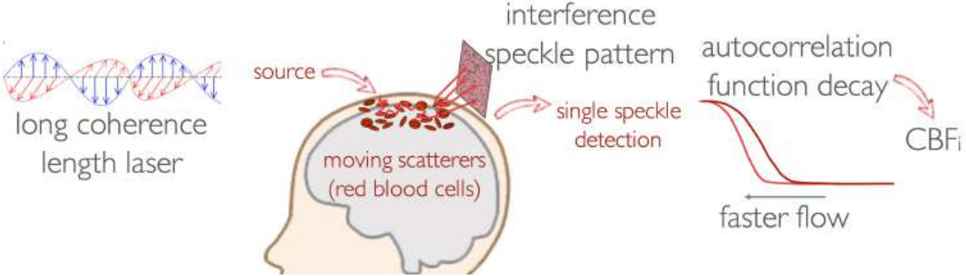
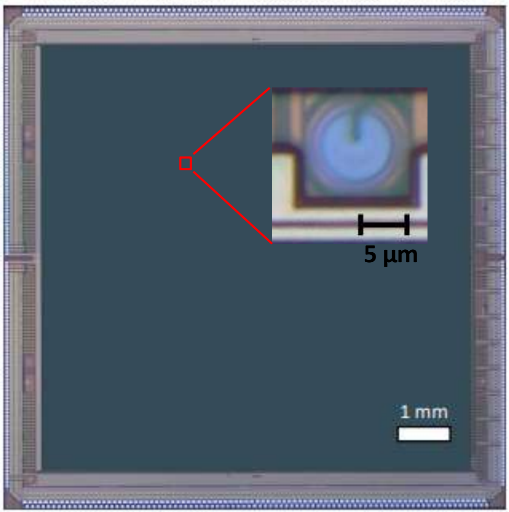
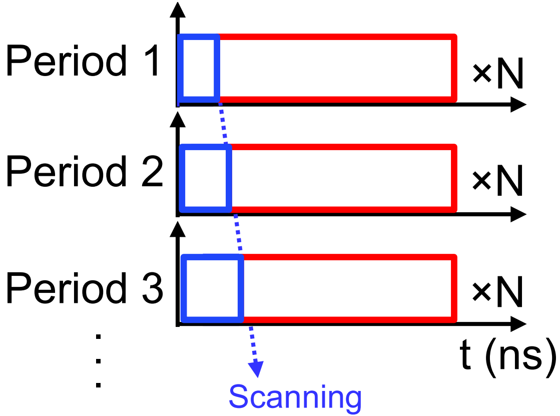


Image from https://optics.martinos.org/research/imaging-modalities/

- By measuring the temporal changes in correlations of scattered light, changes in blood flow can be detected in a non-invasive manner.
- Past work used single SPADs (very noisy, long integration time) or smaller arrays (32 x 32) to improve performance. Extremely computationally intensive.

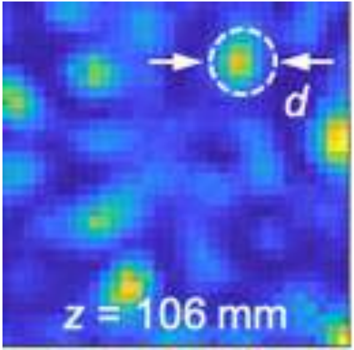
SwissSPAD3 – dual-gate SPAD camera

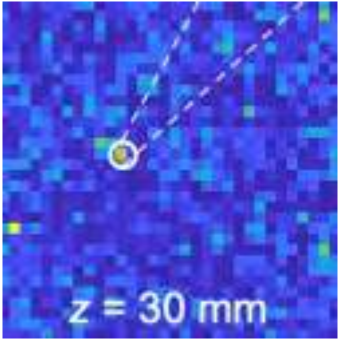


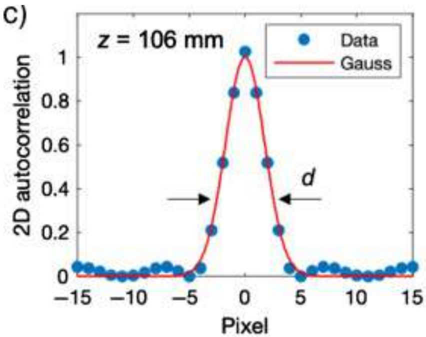


M. Wayne, A. C. Ulku, A. Ardelean, P. Mos, C. Bruschini, E. Charbon, Trans. el. dev., 2022

Optimizing information content





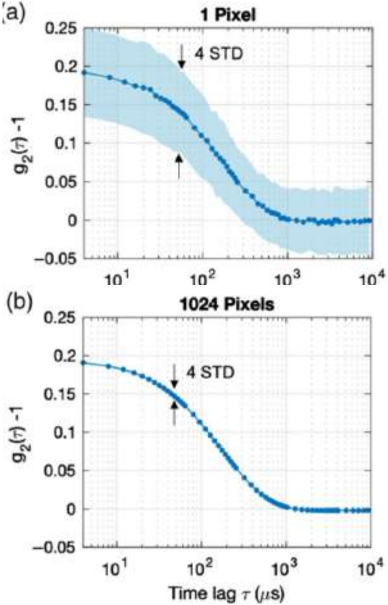


To maximize the parallelization, each pixel must measure an independent speckle.
Calibrate so average speckle diameter ≈ SPAD pixel pitch.

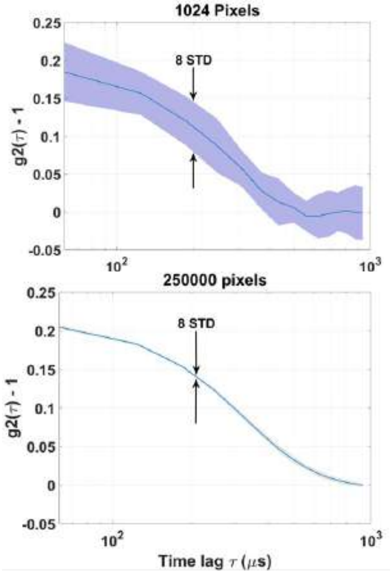
Michael Wayne

Images from Sie, E., et. al. "High sensitivity multispeckle diffuse correlation spectroscopy", Neurophotonics **7**(3), 2020.

More pixels = lower error and integration time

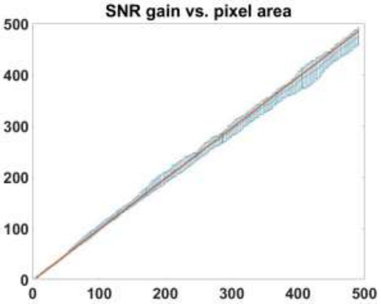


Integration Time = 8 s



Integration Time = 50 ms!!

- 500 x 500 pixels results in ≈ 500 gain in SNR!



- g2 precision ≈ 1 x 10^{-5} in 50 ms.
- Reveal extremely small effects.

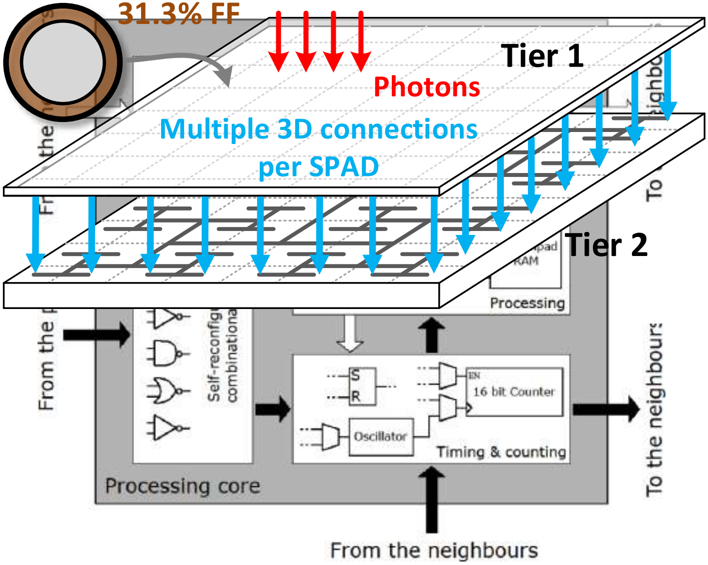
Michael Wayne et al., Biomed opt. exp. 2023

4. Embedded computation – computational imaging

- On ASIC
- On FPGA
- On processor

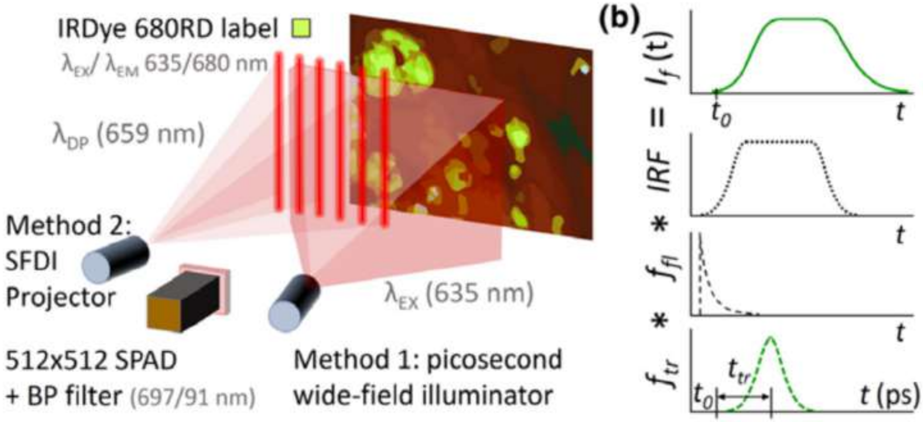
*Ultra*Phase: multi-core ASIC for SPAD imagers

- 18 processing cores in 16nm 3D-stacking CMOS technology
- 4x4 SPADs per core
- Each core:
  - Reconfigurable front end
  - 140 MIPS
  - Max 256 instructions per program
  - 128x32bit RAM
  - Support for subroutines
  - Support for pointers
  - Timing module LSB 430ps/2.4ns



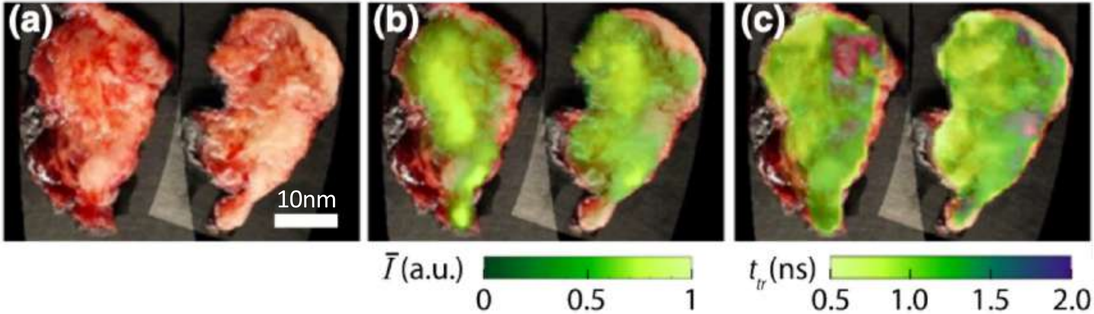
Andrei Ardelean et al., *Thesis*, 2022

Example1: LiDAR + fluorescence detection



P. Bruza et al., Optica 2021

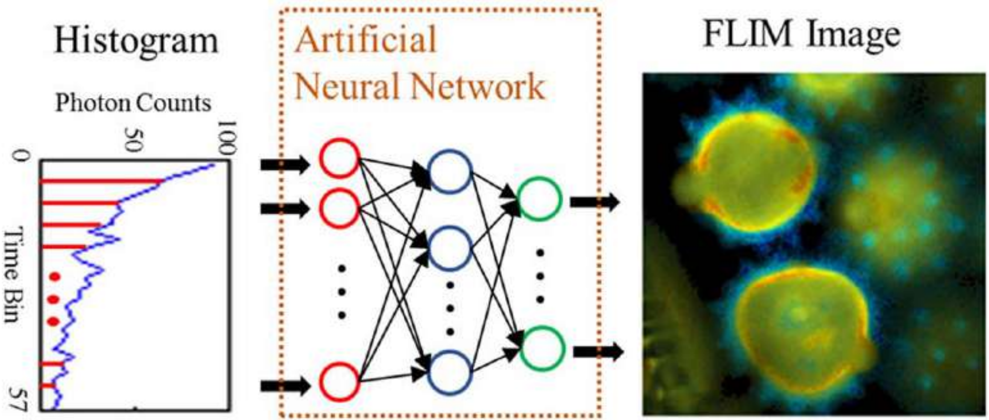
Sub-surface cancer detection



Aligned composite of H&N tumor specimen photographs (a) overlaid with (b) standard (steady-state) fluorescence signal I and (c) map of fluorescence propagation time t_{tr}.

P. Bruza et al., Optica 2021

Example2: Artificial Neural Networks for FLIM



Wu, Gang; Nowotny, Thomas; Zhang, Yongliang; Yu, Hong-Qi; Li, David Day-Uei (2016): Artificial neural network approaches for fluorescence lifetime imaging techniques. In Optics Letters 41 (11), pp. 2561–2564. DOI: 10.1364/OL.41.002561.

Building Synthetic Datasets

- To accurately model a real FLI system, we take **fluorescence decay**, **instrument response**, **background noise**, and **dark counts** into account.

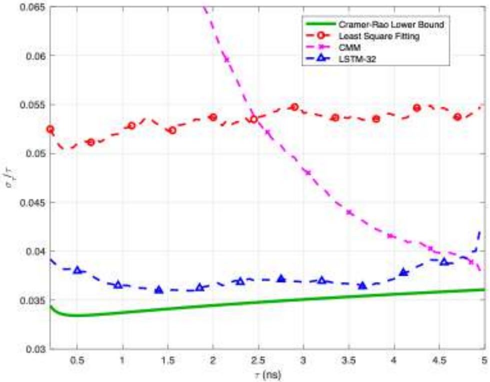
$$t = \sum_{i=1}^{N-1} \mathbf{1}_{k=i}\left(t_{fluo_i} + t_{irf}\right) + \mathbf{1}_{k=N} t_{bg}$$

- Given a set of parameters, we can generate timestamps to construct the dataset.
  - 500,000 samples in one dataset
  - Each sample contains 1,024 timestamps.

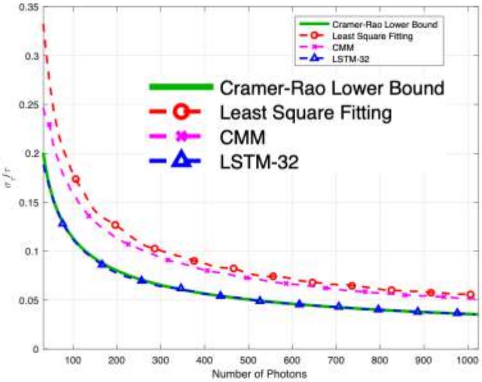
Cramér-Rao Lower Bound Analysis

$$Var(\hat{\theta}) \geq \frac{f'(x;\theta)^2}{J(\theta)} \quad \text{, where } J(\theta) = n\mathbb{E}_\theta\left[\left(\frac{\partial}{\partial\theta}\ln f(x;\theta)\right)\right]$$

Number of photons is 1024
(5% background noise)

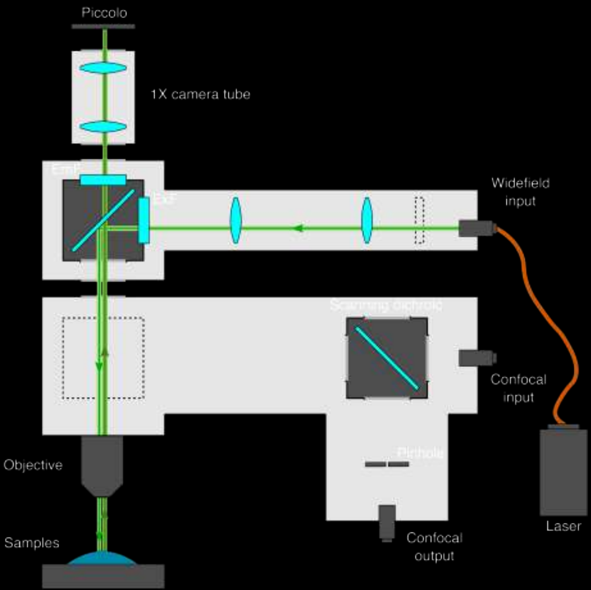


Lifetime is 2.5 ns
(5% background noise)

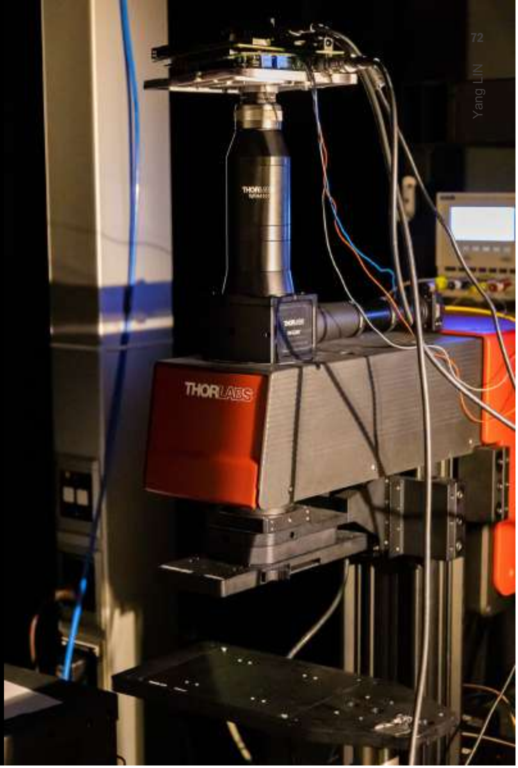


Yang Lin et al., Focus on Microscopy, 2023

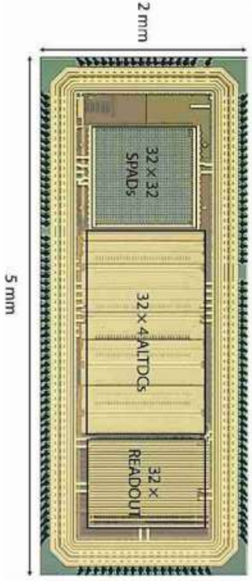
ANN FLIM Setup

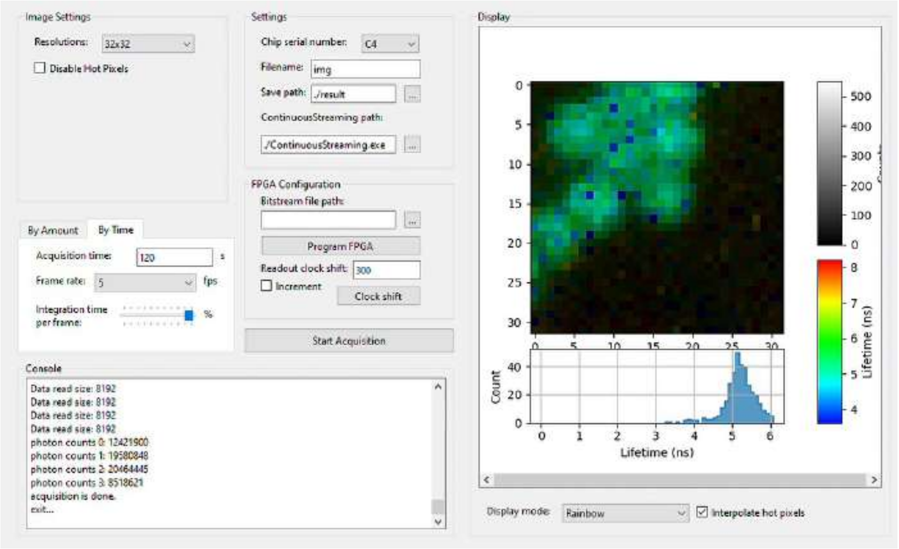


Credit: Andrei Ardelean, AQUA lab, EPFL



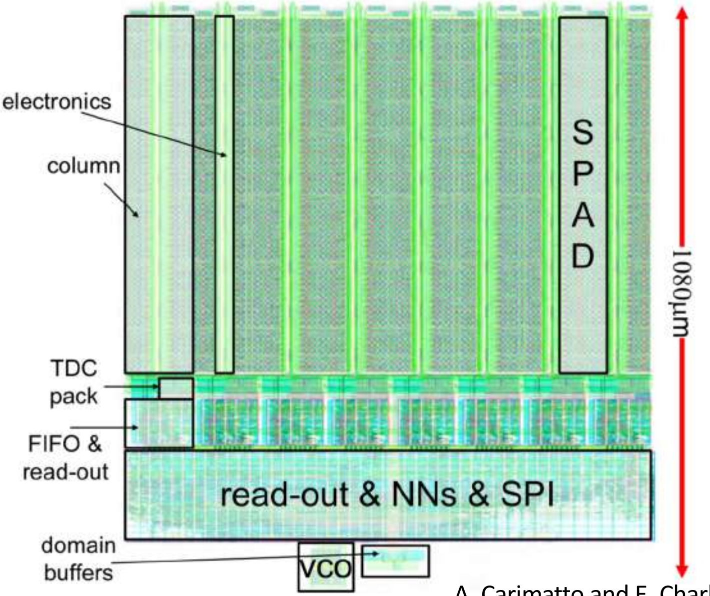
FPGA gated recurrent unit (GRU)





Yang Lin et al., Focus on Microscopy, 2023

Mindhive: an architecture with embedded ANNs



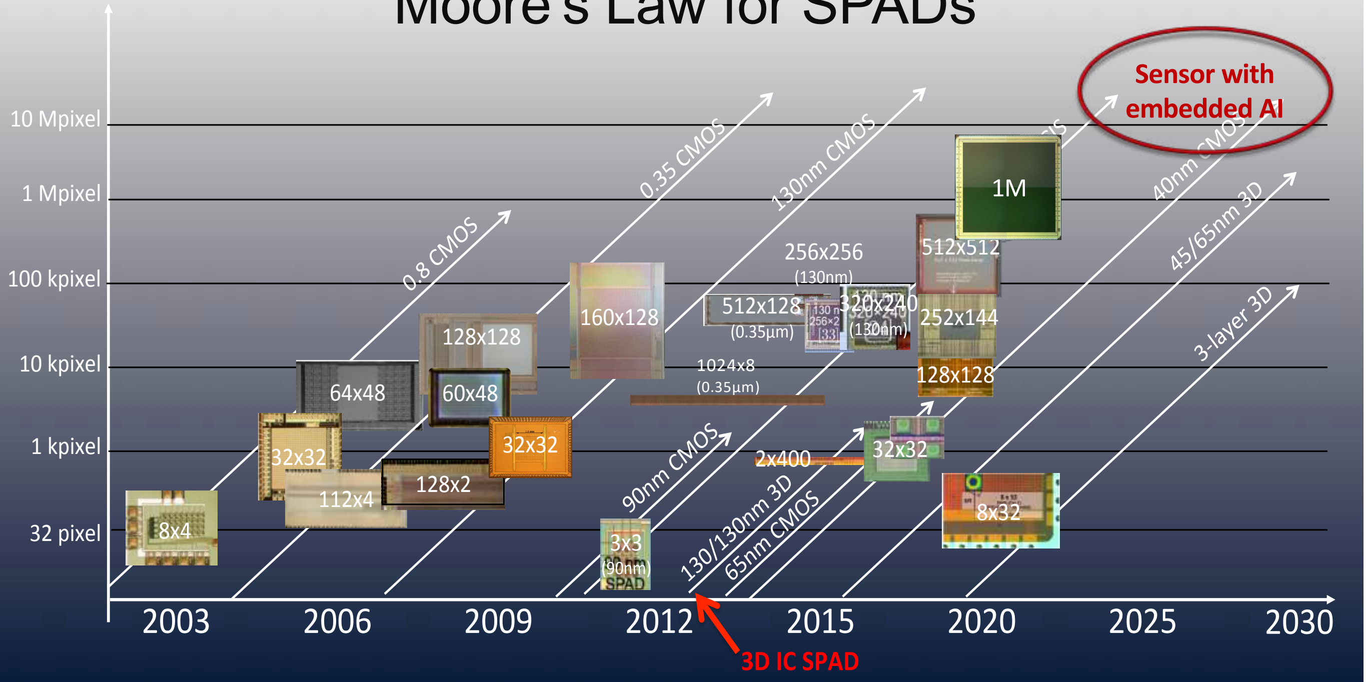
A. Carimatto and E. Charbon, *SPIE Photonics West* 2021
A. Carimatto, *Thesis*, November 2020

Conclusions

Emerging quantum imaging

- Quantum LiDAR
- Ghost imaging
- Quantum (ultra-fast) spectroscopy
- Quantum Raman spectroscopy
- Quantum distillation
- Quantum state tomography
- Quantum holography
- Quantum super-resolution
- Quantum plenoptic cameras
- Quanta burst photography

Moore’s Law for SPADs



Take-home messages

- Single-photon detection in SWIR/NIR domain using SPADs
- SWIR/NIR takes advantage of 3D-stacking to improve FF and functionality
- Photon counting with embedded ANNs are ideally suited for LiDAR, FLIM, and quantum imaging applications


Thank You
http://aqua.epfl.ch
1st User Group Meeting, Les Diablerets, 2022