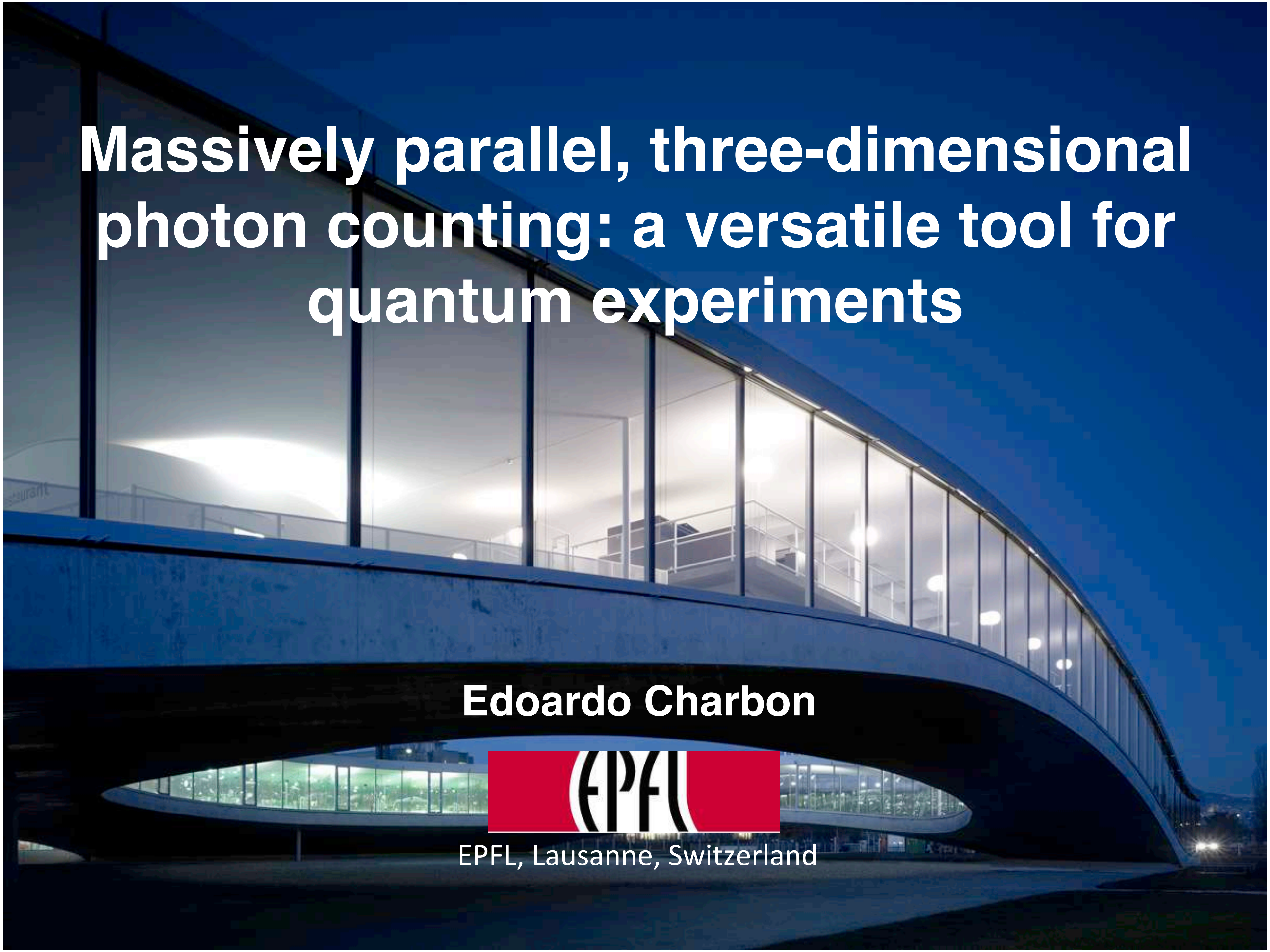


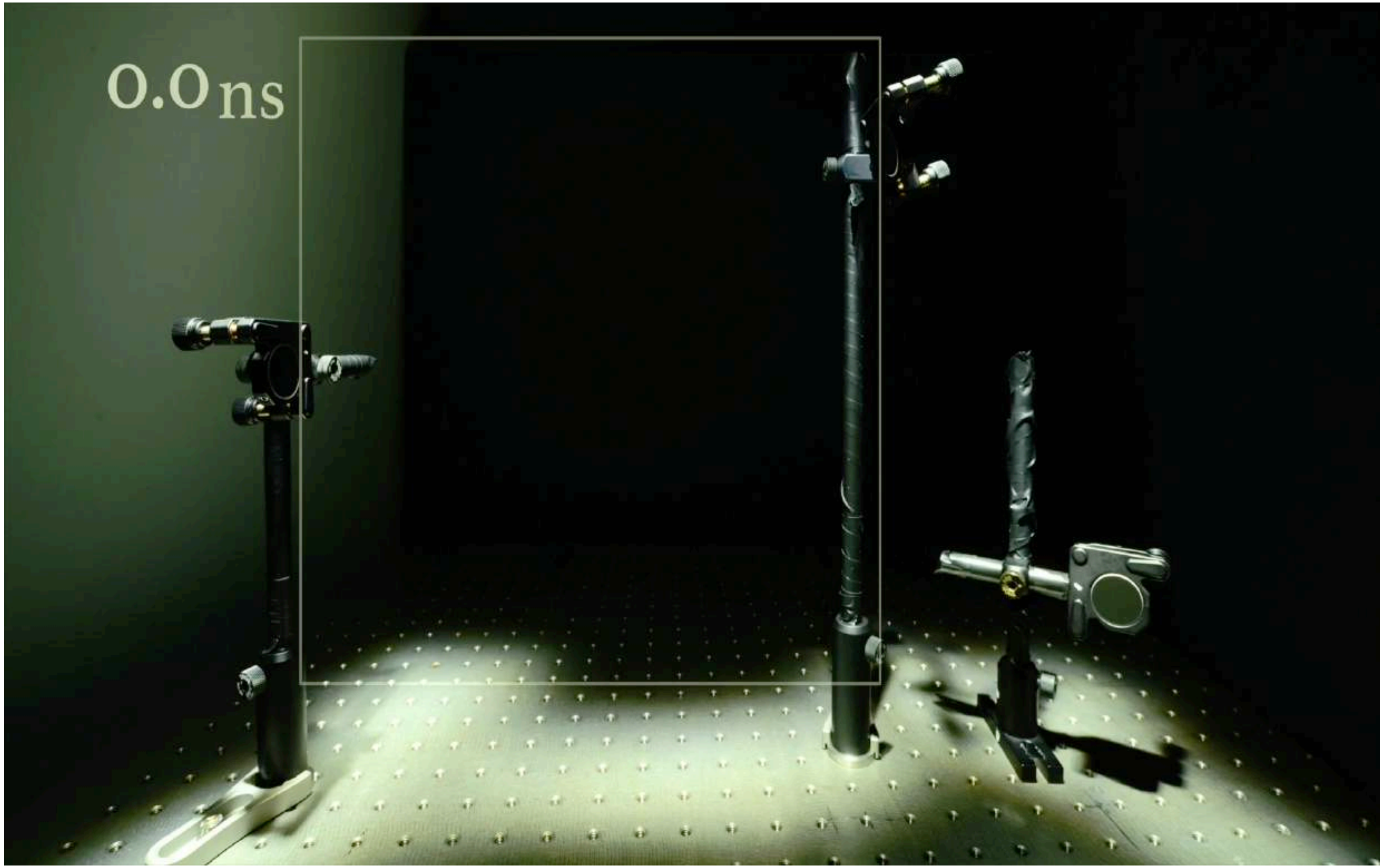
Massively parallel, three-dimensional photon counting: a versatile tool for quantum experiments

Edoardo Charbon

EPFL, Lausanne, Switzerland

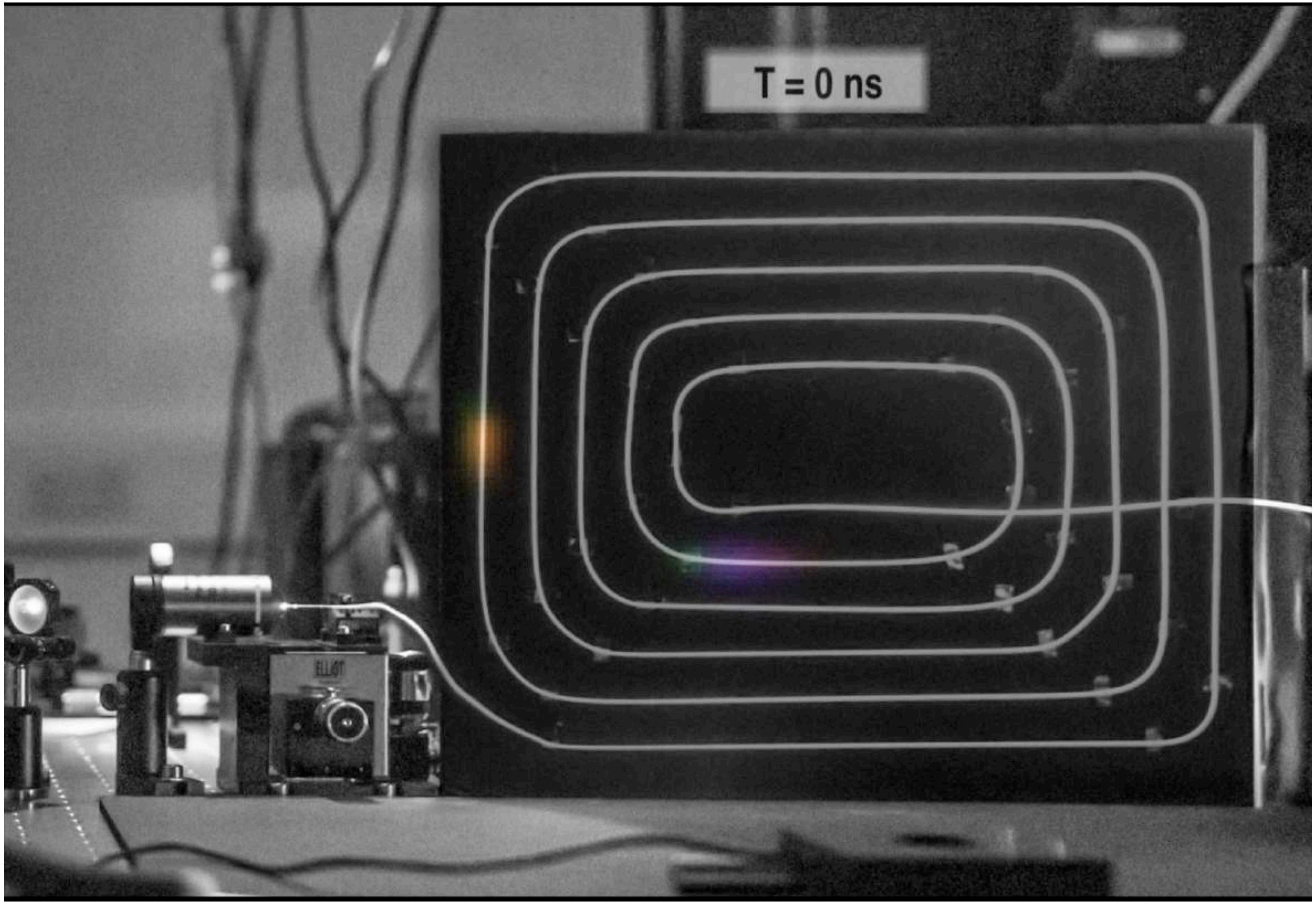
Photon Counting

Experiments Requiring Photon Counting



G. Gariepy et al., Nature Communications 6:6021 doi: 10.1038 2015

Experiments Requiring Photon Counting



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

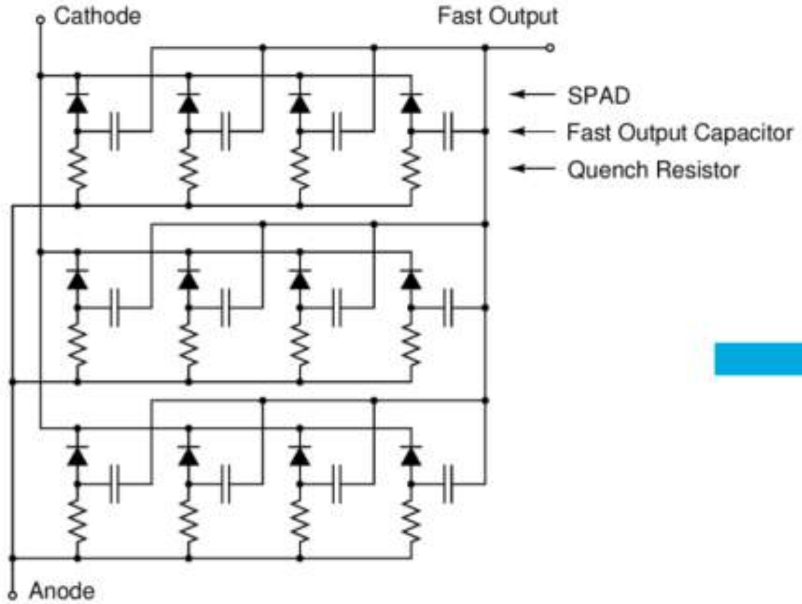
Other Applications in a Consumer Space

Photon Counters

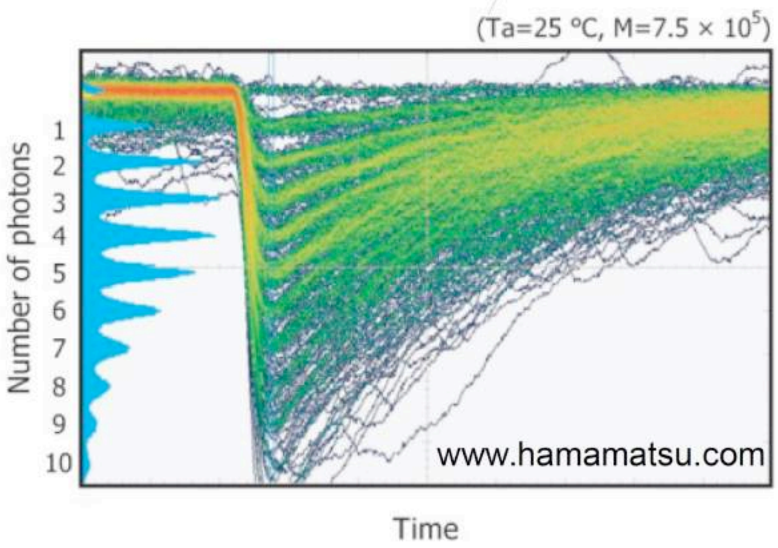
Photomultiplier Tubes (PMTs)

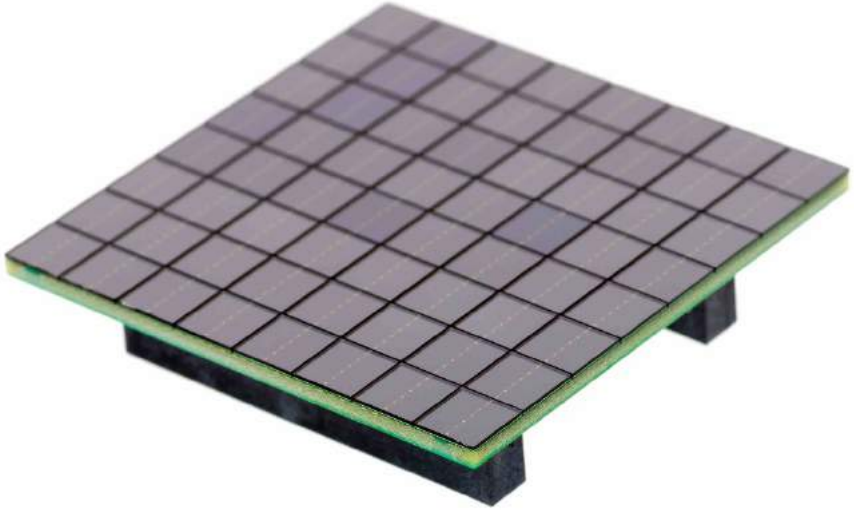
Source: Hamamatsu

Silicon Photomultipliers (SiPMs)

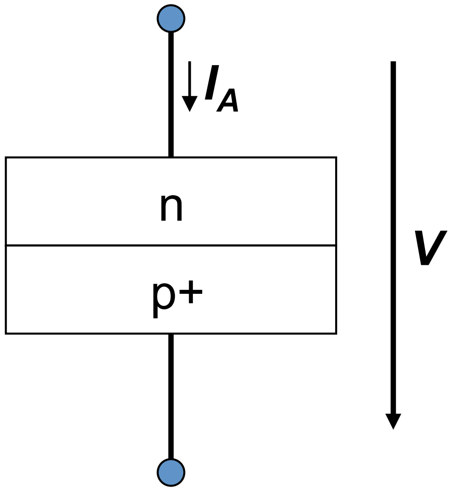


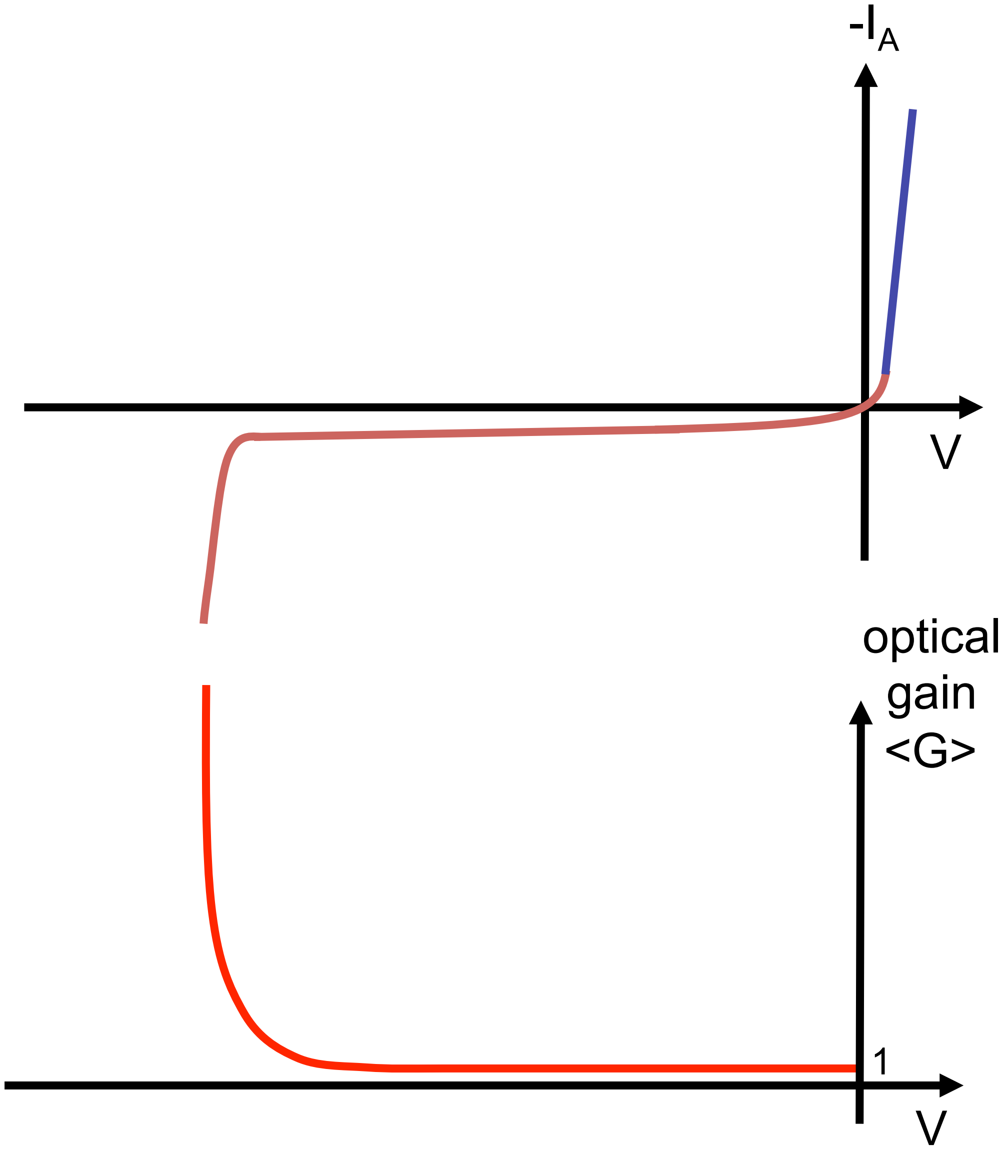
Example of 12 microcell/SPAD SiPM





What is a SPAD?





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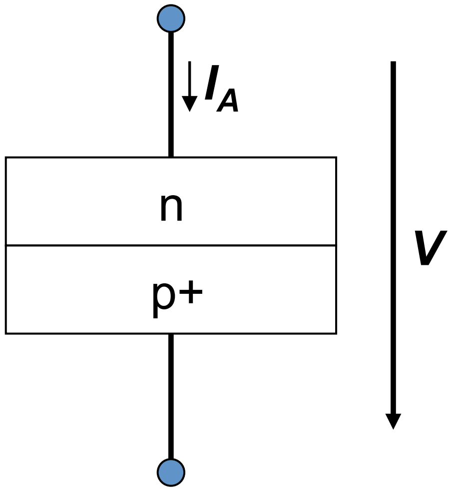

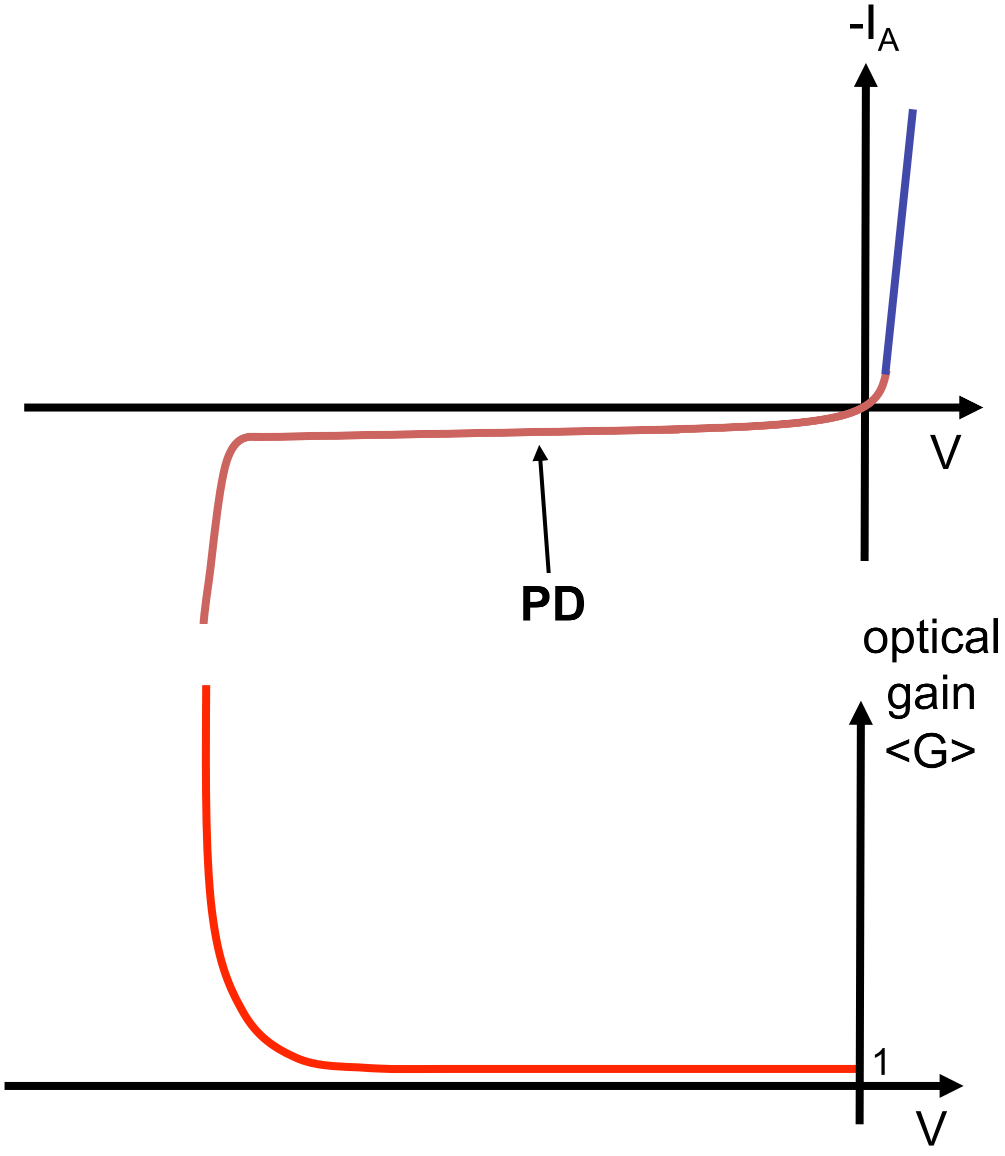

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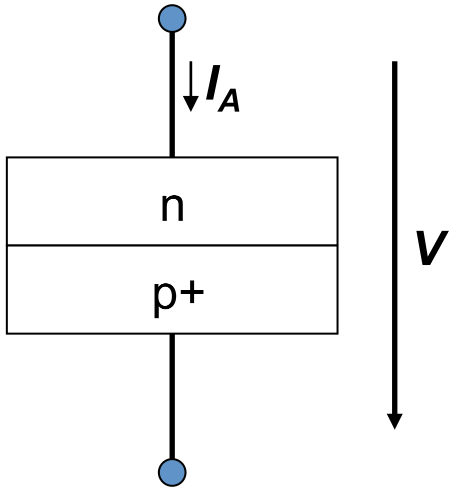
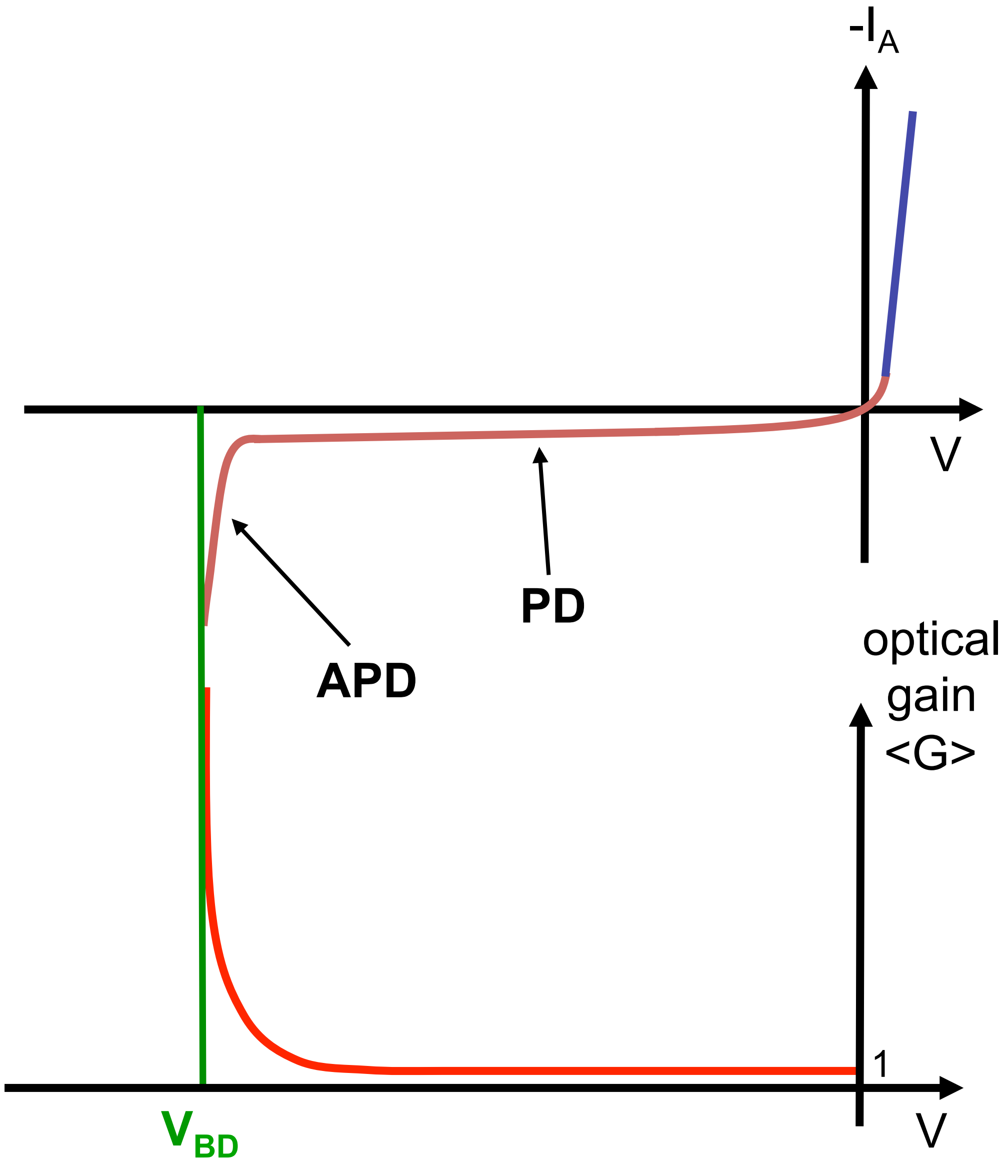
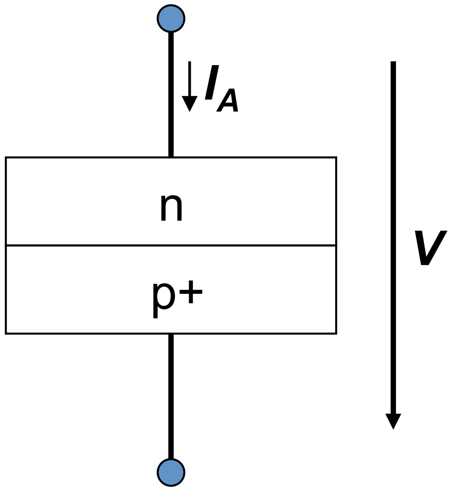
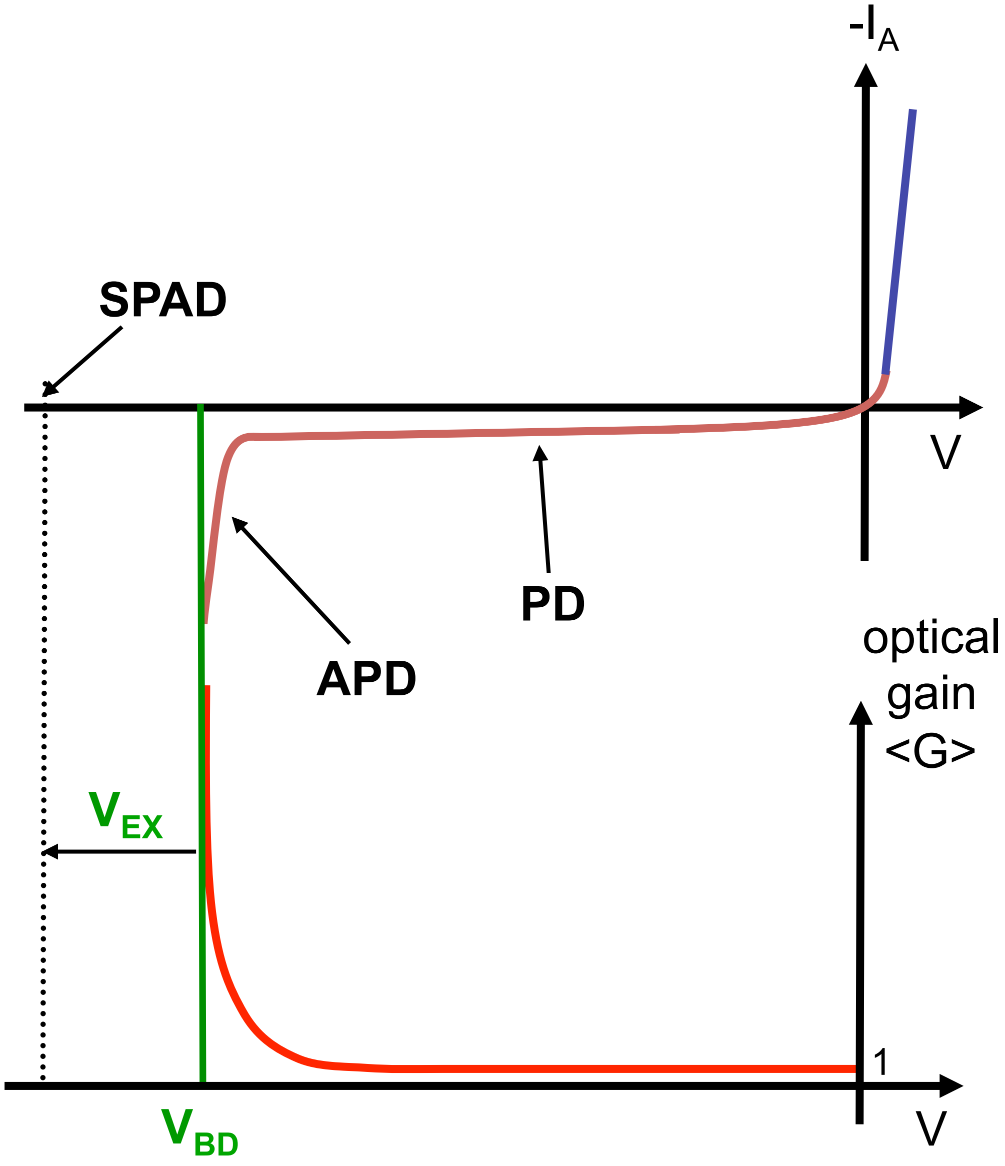


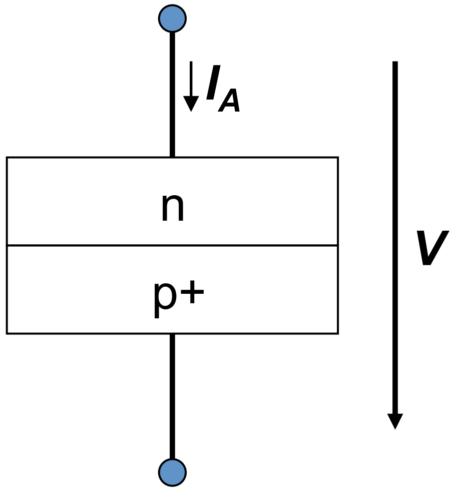


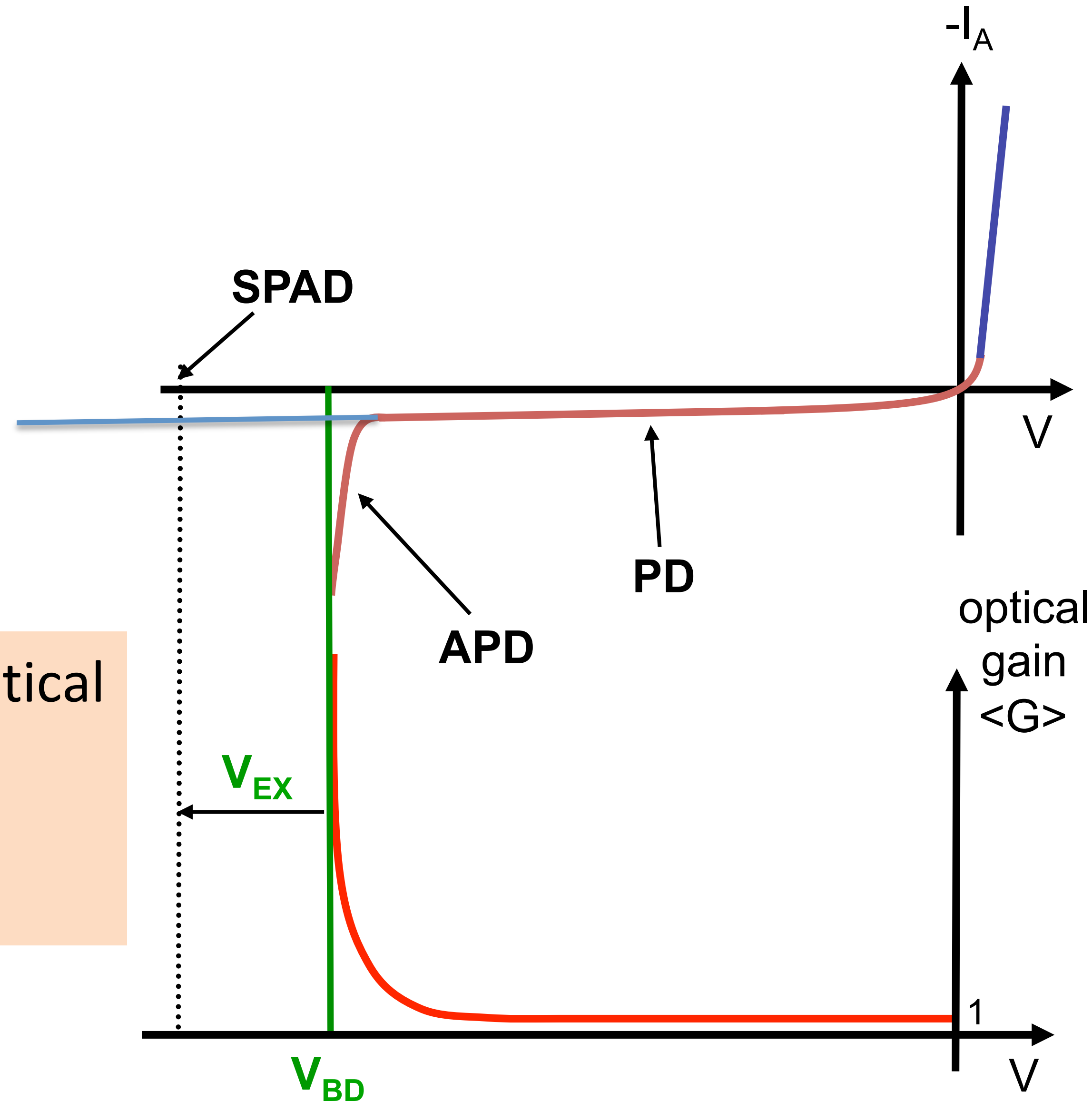
What is a SPAD?





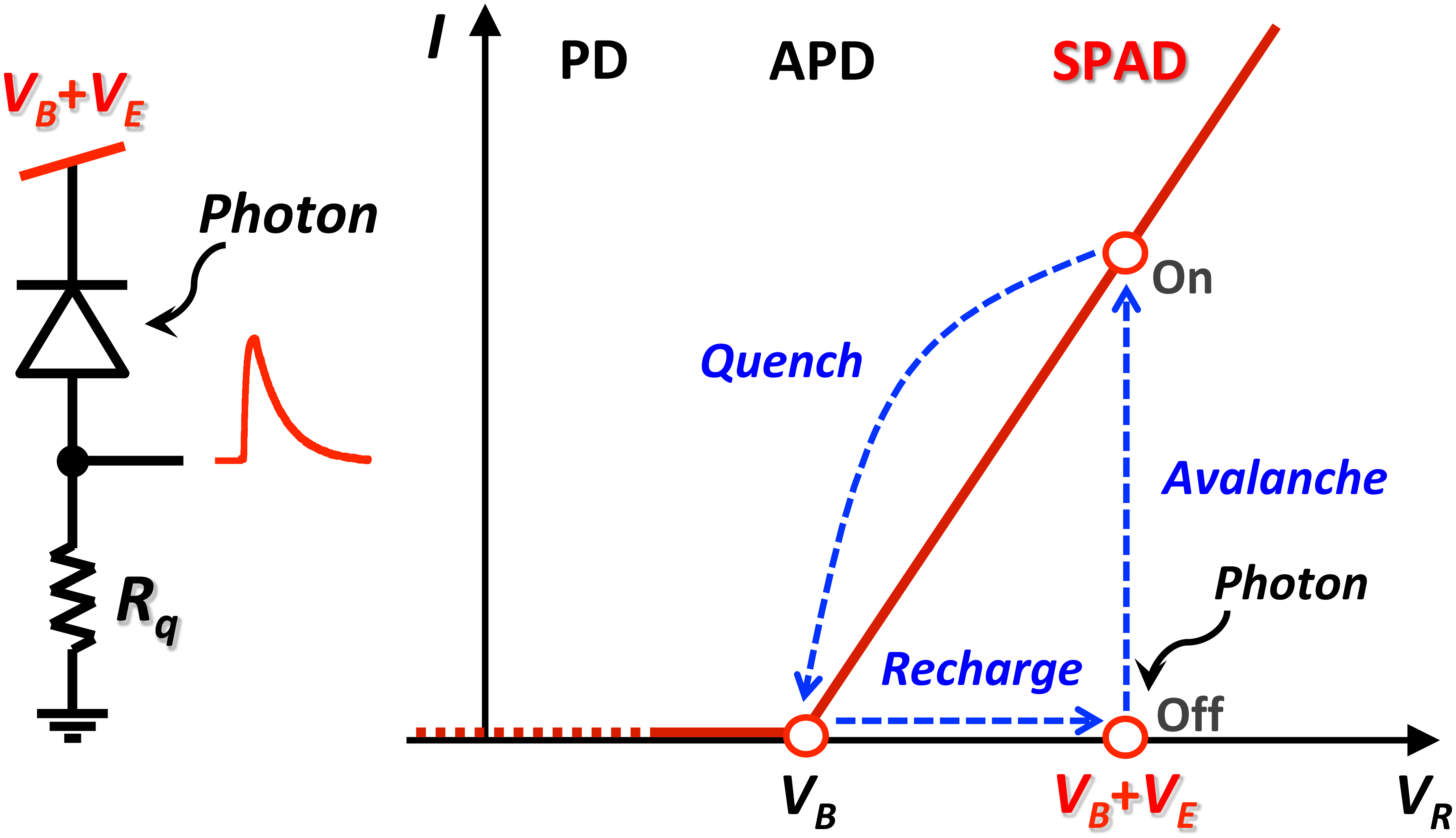
What is a SPAD?





- Virtually infinite optical gain
- Virtually zero noise
- Very fast

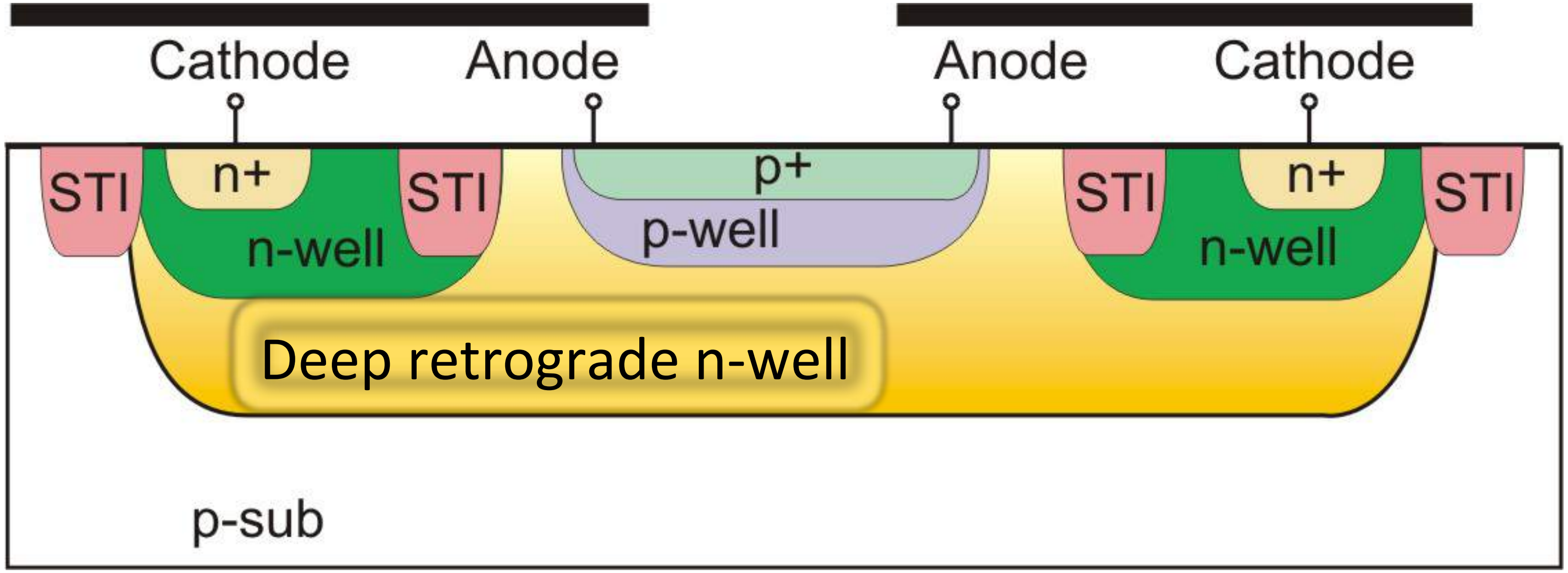
Principle of Operation



What You Can Do with SPADs

- Single-photon detection
  - Timing
  - Counting
- Multi-photon detection
  - Gating
  - Inter-arrival timing

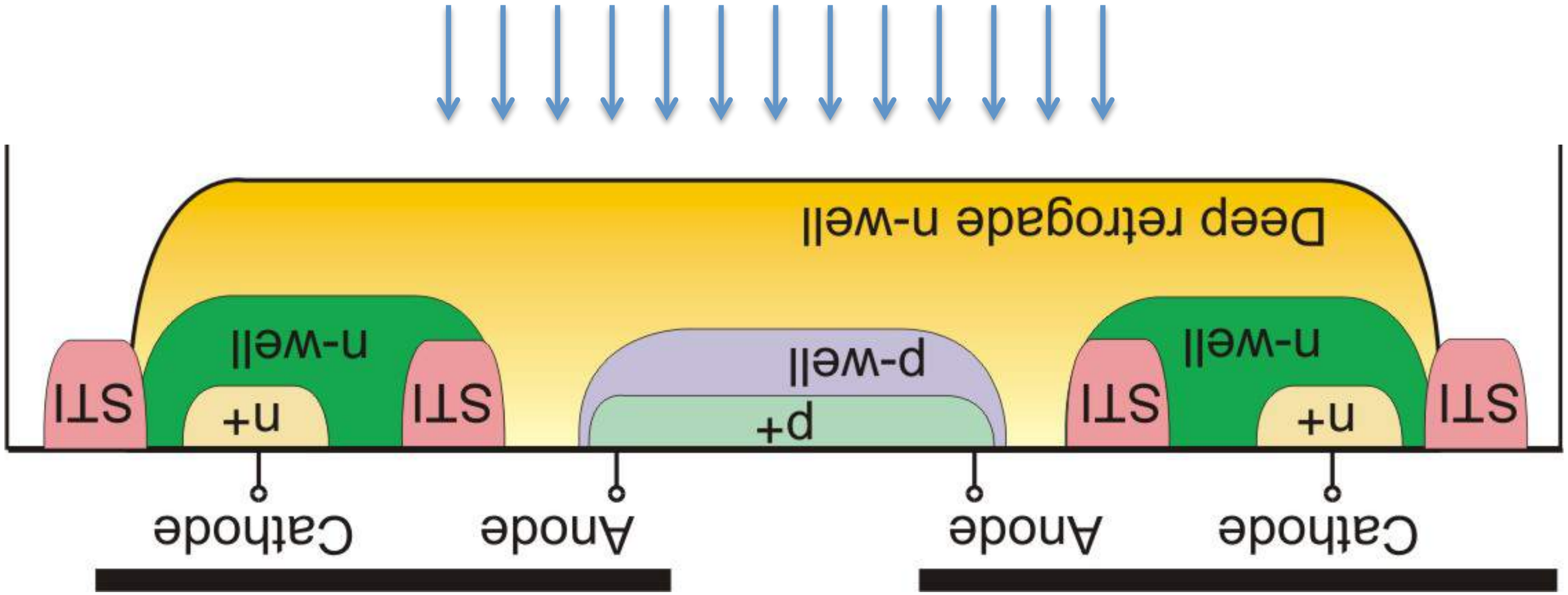
Today's Industrial SPADs (STMicroelectronics)



Henderson et al., 2009

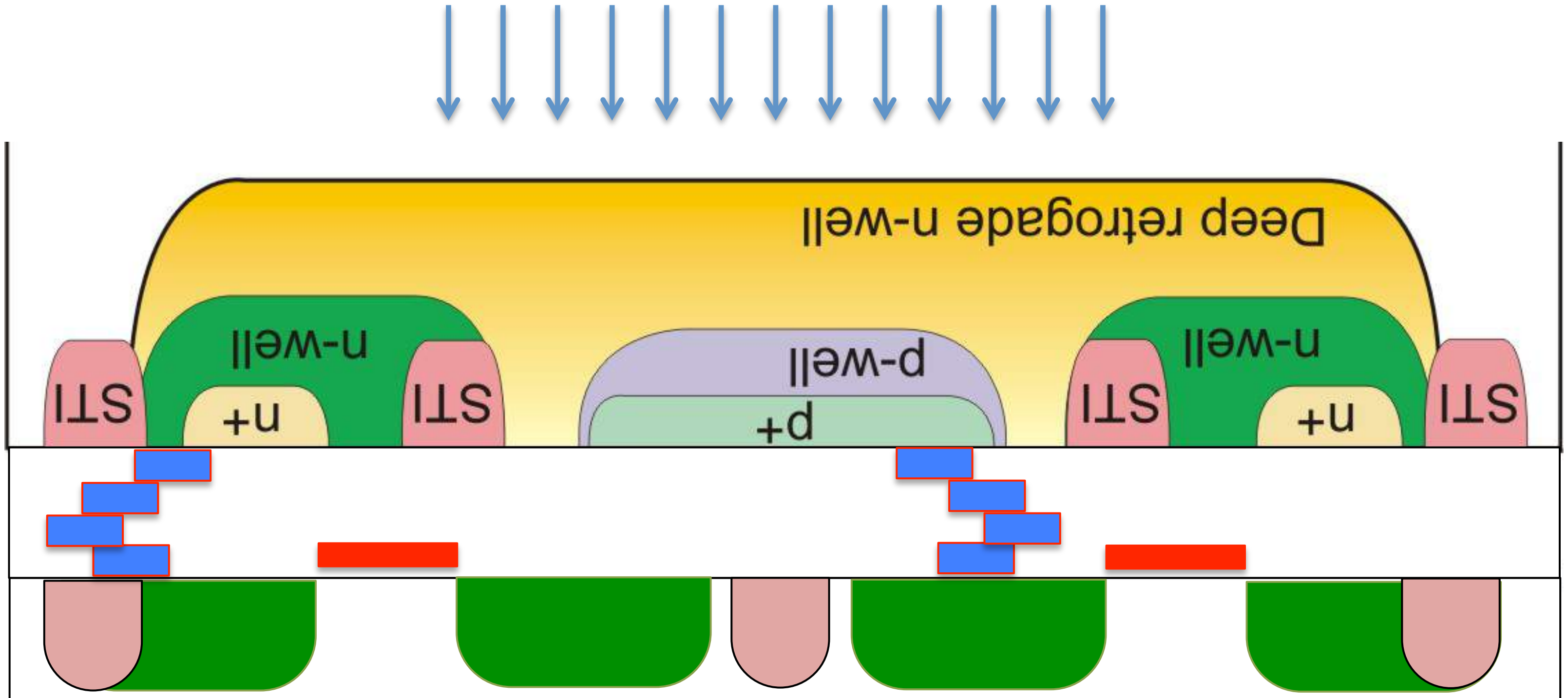
Drawing: D. Stoppa

Backside Illumination (BSI)



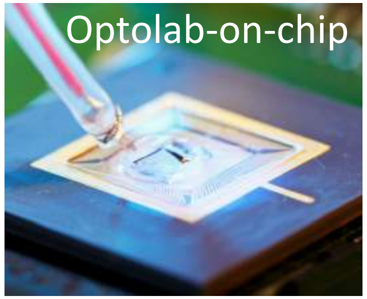
- Improve fill factor
- Free up space for processing

3D IC Integration



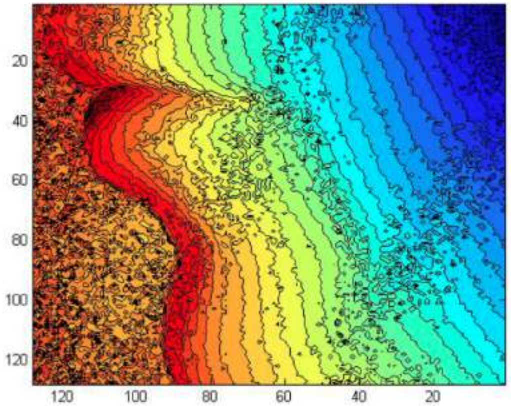
3D-stacking technology at wafer level

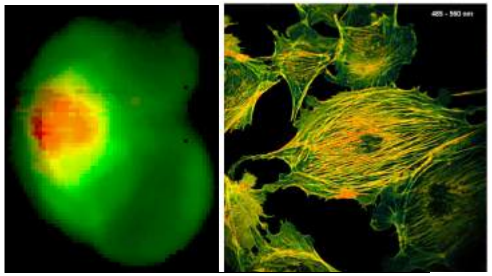
Some SPAD Applications

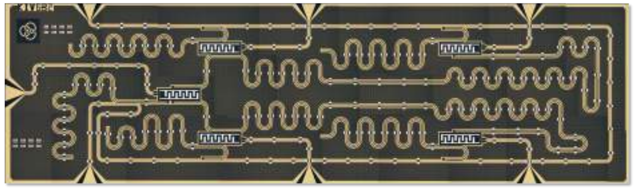

Optolab-on-chip

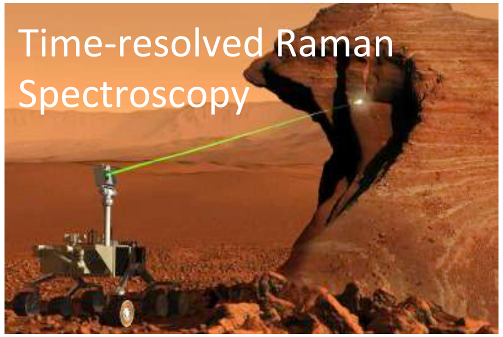

3D Vision

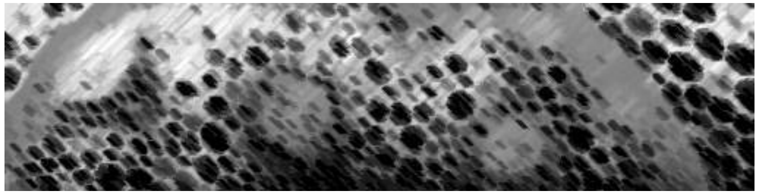
Near Infrared Imaging (NIRI)




Fluorescence Lifetime Imaging Microscopy (FLIM)


Quantum Computing
QRNG


Time-resolved Raman Spectroscopy


Super-resolution (GSDIM)

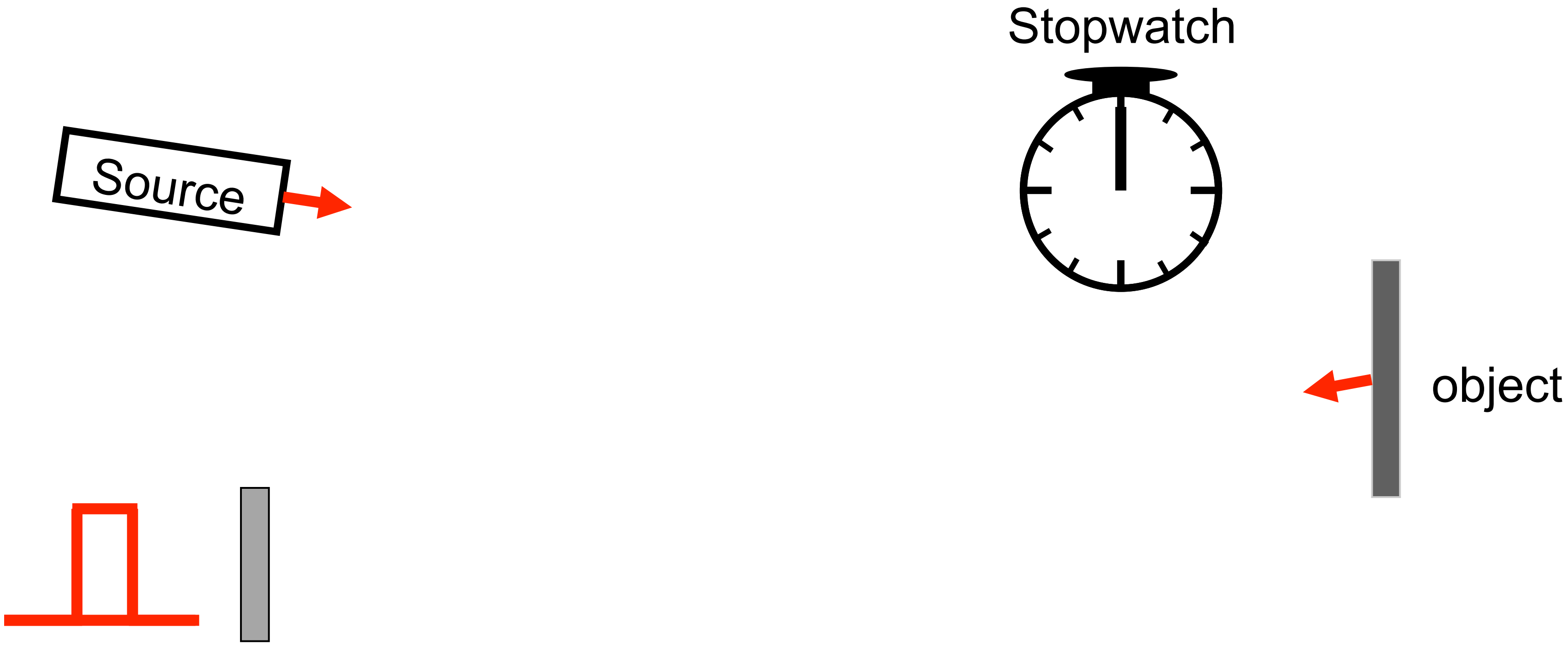
Time-of-Flight Positron Emission Tomography (TOF PET)

An Example: Time-of-Flight

3D Imaging Techniques

- Direct time-of-flight
  - Explicit measurement of the time
  - No ambiguity but precise chronometer per pixel
- Indirect time-of-flight
  - Implicit measurement through phase
  - Ambiguity but simple to implement

Direct Time-of-Flight



Source: Alexis Rochas

From a <u>short burst</u> or pulse of light, one can get distance from source to receiver

m .... ns
mm .... ps

3D Imaging Applications

Autonomous Vehicle

Night vision

Machine Vision

Next Generation 3D Vision Applications

Driving Assistance

Gesture Recognition

Service Drone and Robot

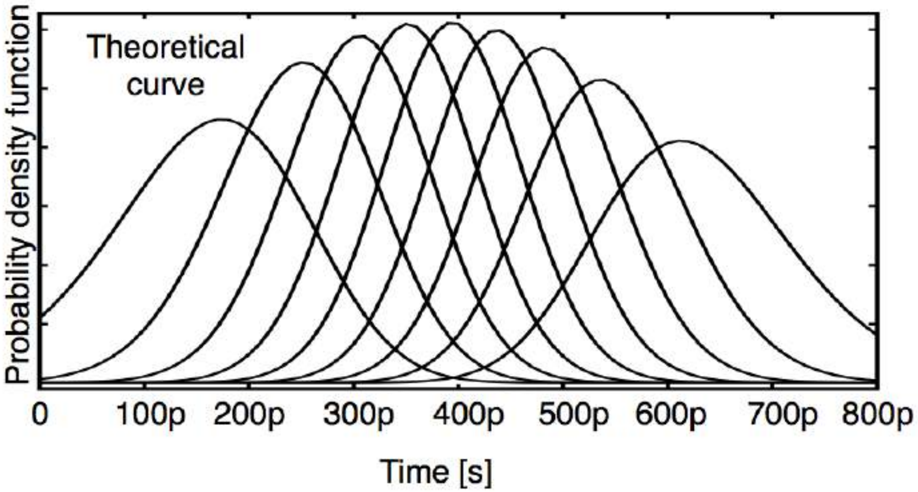
Another Example:
SPADs in Basic Science

$$f_{k:n}(t) = n\begin{pmatrix} n-1 \\ k-1 \end{pmatrix} f(t)F(t)^{k-1}(1-F(t))^{n-k}$$

$f_{k:n}(t)$: k-th order statistics
$f(t)$: probability density function
$F(t)$: cumulative density function

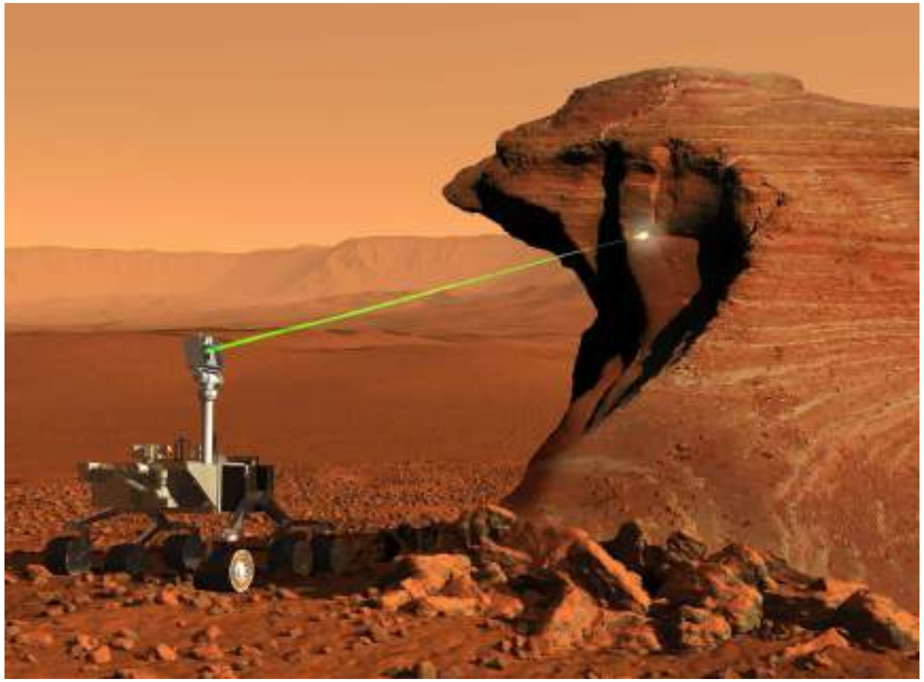
<u>Assumptions:</u>

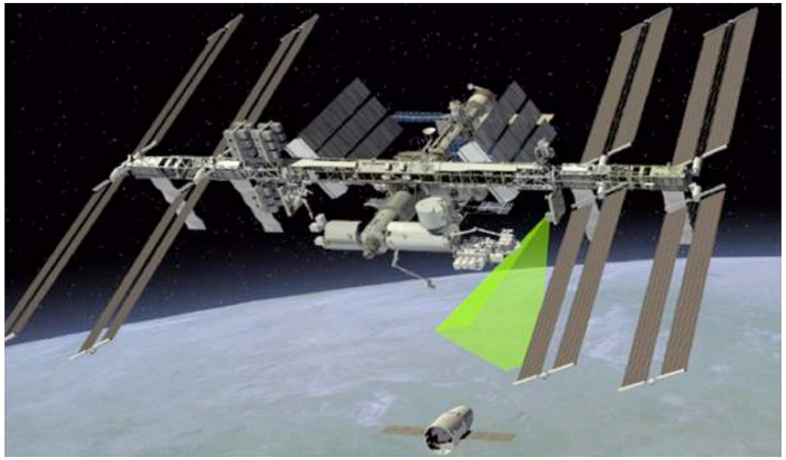
- Each photon is stat. independent
- The pulse has a Gaussian p.d.f.



S. Mandai, E. Char*bon, Optics Letters* **39**(3), 552-554 (2014)

…and SPADs in Space

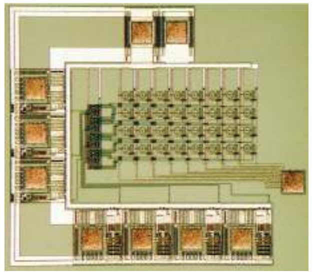




- Raman spectroscopy: non-destructive technique to observe structural and compositional information

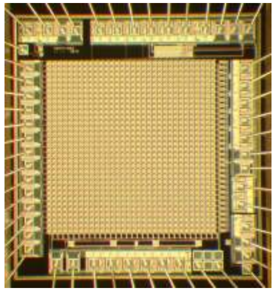
- Navigation and guidance of rovers
- Controlled landing on planetary bodies

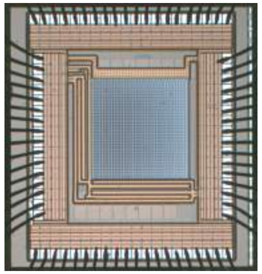
SPAD Image Sensors Targeted to Apps

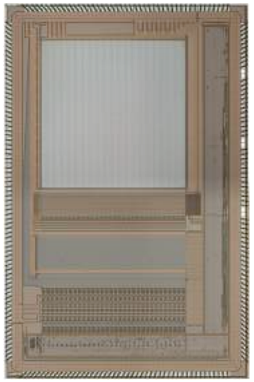

ISSCC 2004


ISSCC 2007 bis

IISW 2011


ISSCC 2005


ISSCC 2009

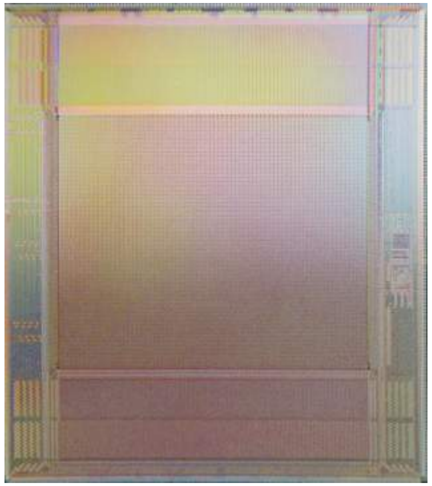

ISSCC 2008

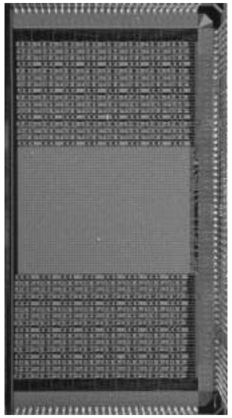

SPIE 2006

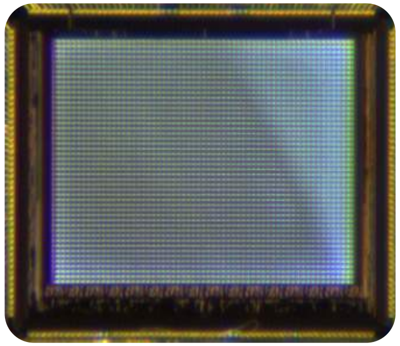
ISSCC 2013

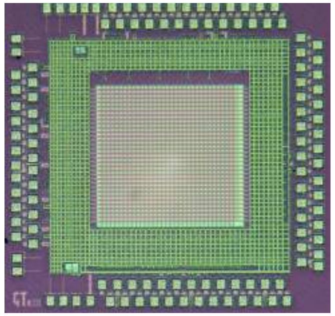

ISSCC 2007

ISSCC 2011

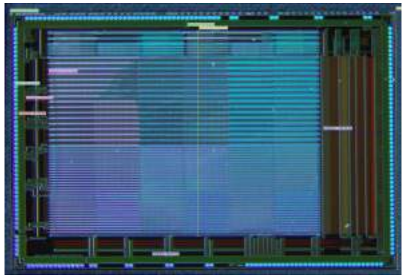



ESSCIRC 2007

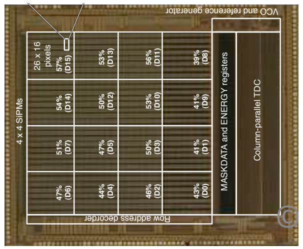

ESSCIRC 2009

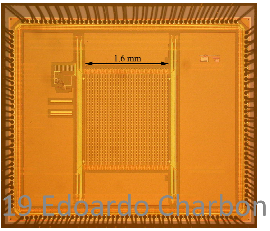

IEDM 2013

ISSCC2015

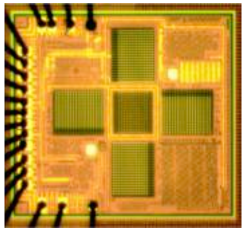

ESSCIRC 2011

NSS 2012



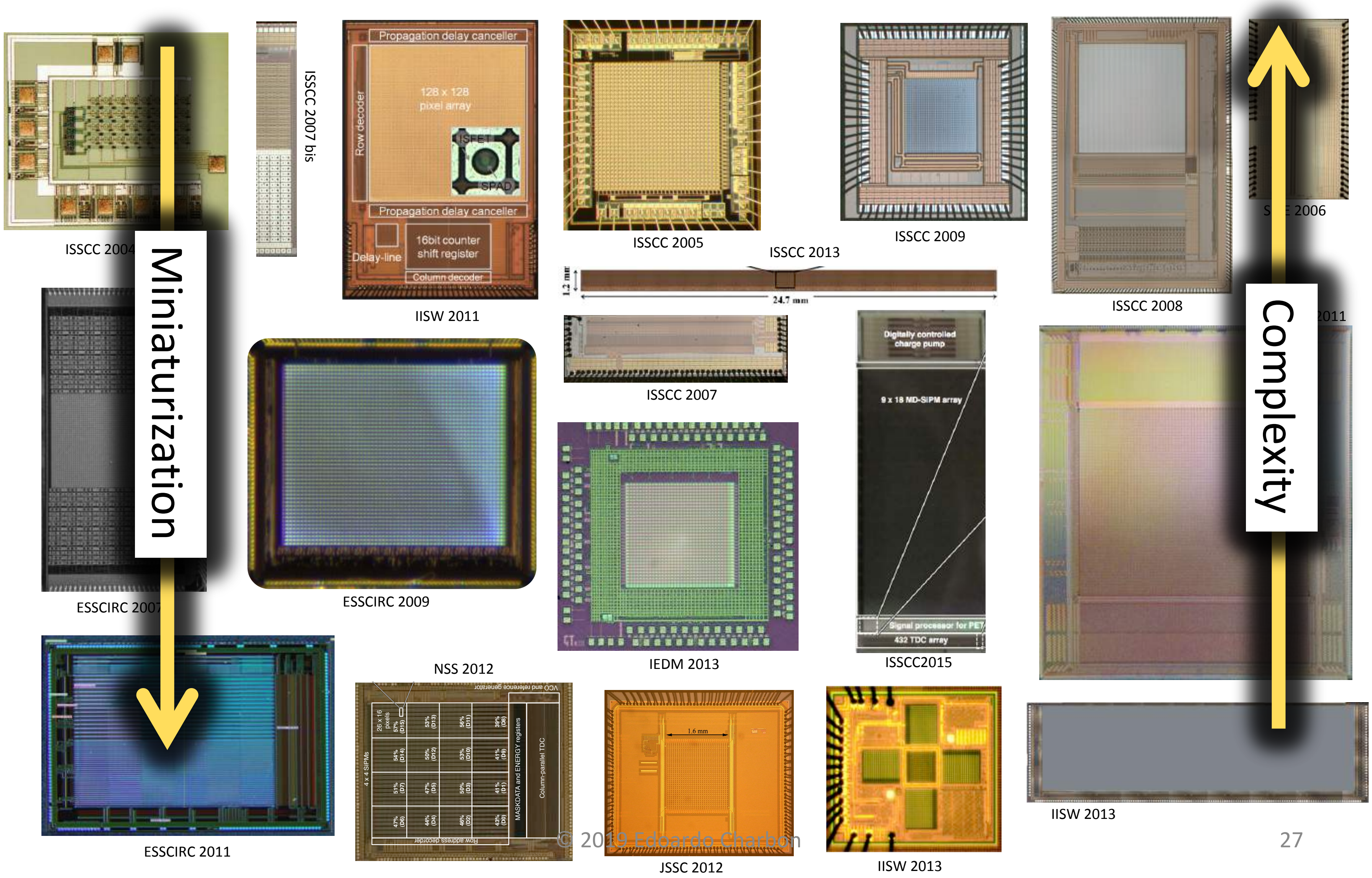


JSSC 2012


IISW 2013


IISW 2013

SPAD Image Sensors Targeted to Apps



SPAD Image Sensors

- ***Dead time***
- **Dark counts**
- **Photon detection probability** (PDP)
- **Timing resolution**
- ***Afterpulsing***

SPAD Image Sensors

- ***Dead time***
- **Dark counts**
- **Photon detection probability** (PDP)
- **Timing resolution**
- ***Afterpulsing***

Photon Detection Efficiency (PDE)
=
PDP × SENSITIVE_AREA

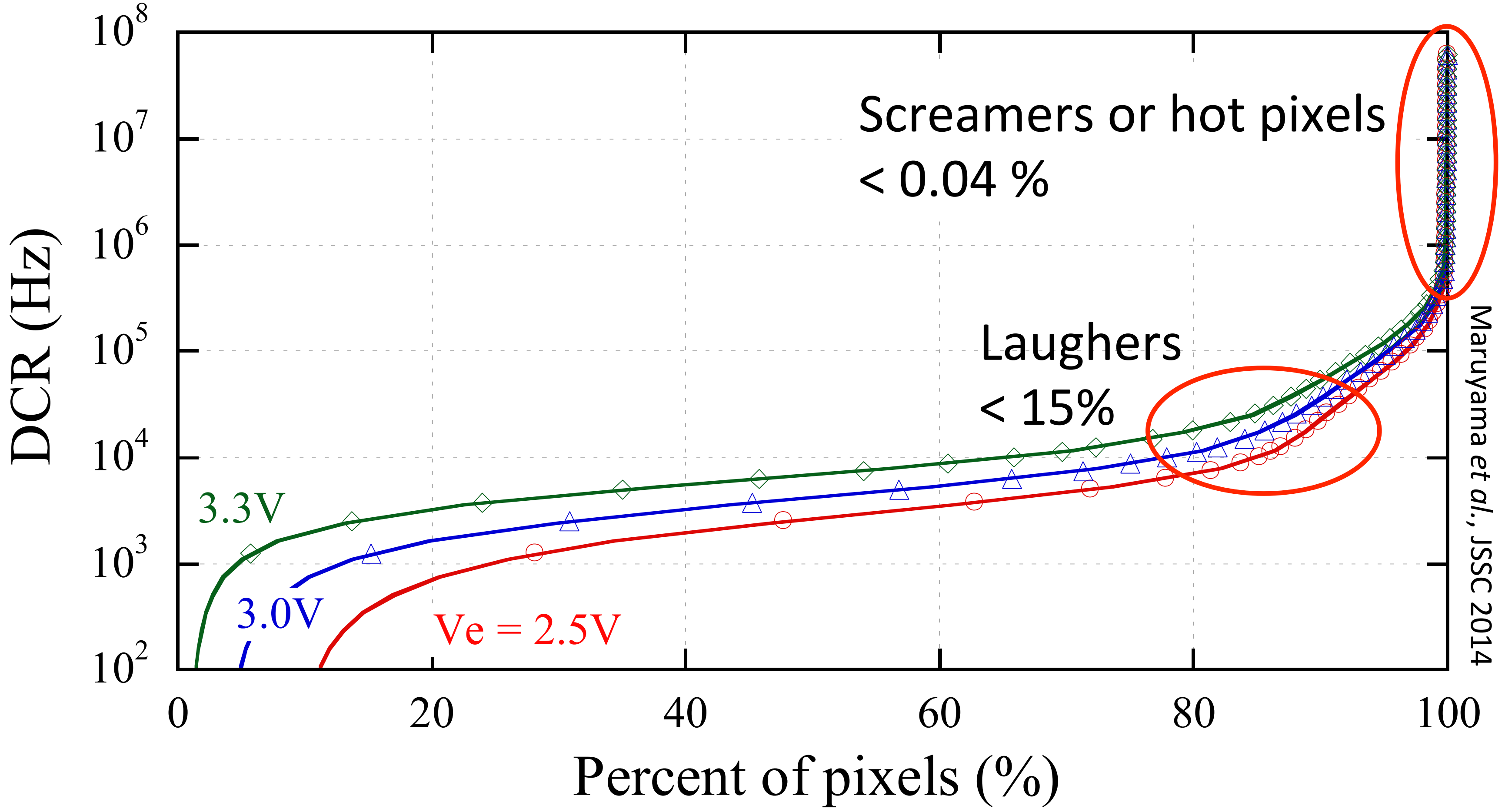
SPAD Image Sensors

- *Dead time*
- Dark counts
- Photon detection probability (PDP)
- Timing resolution
- *Afterpulsing*

… and in SPAD imagers

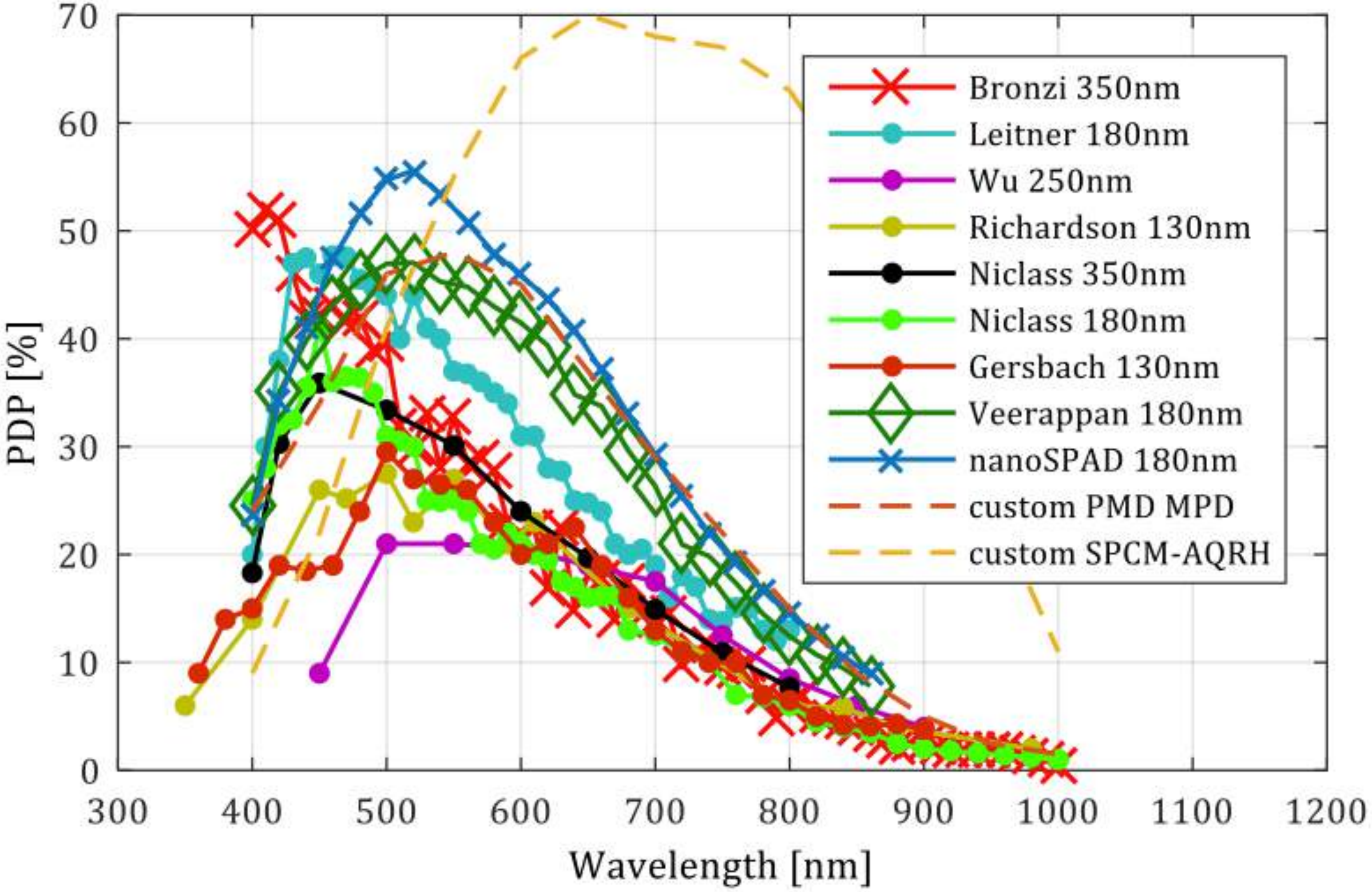
- **Crosstalk**
- **PDE Uniformity**
- **DCR Uniformity**
- **Timing Uniformity**

DCR Uniformity

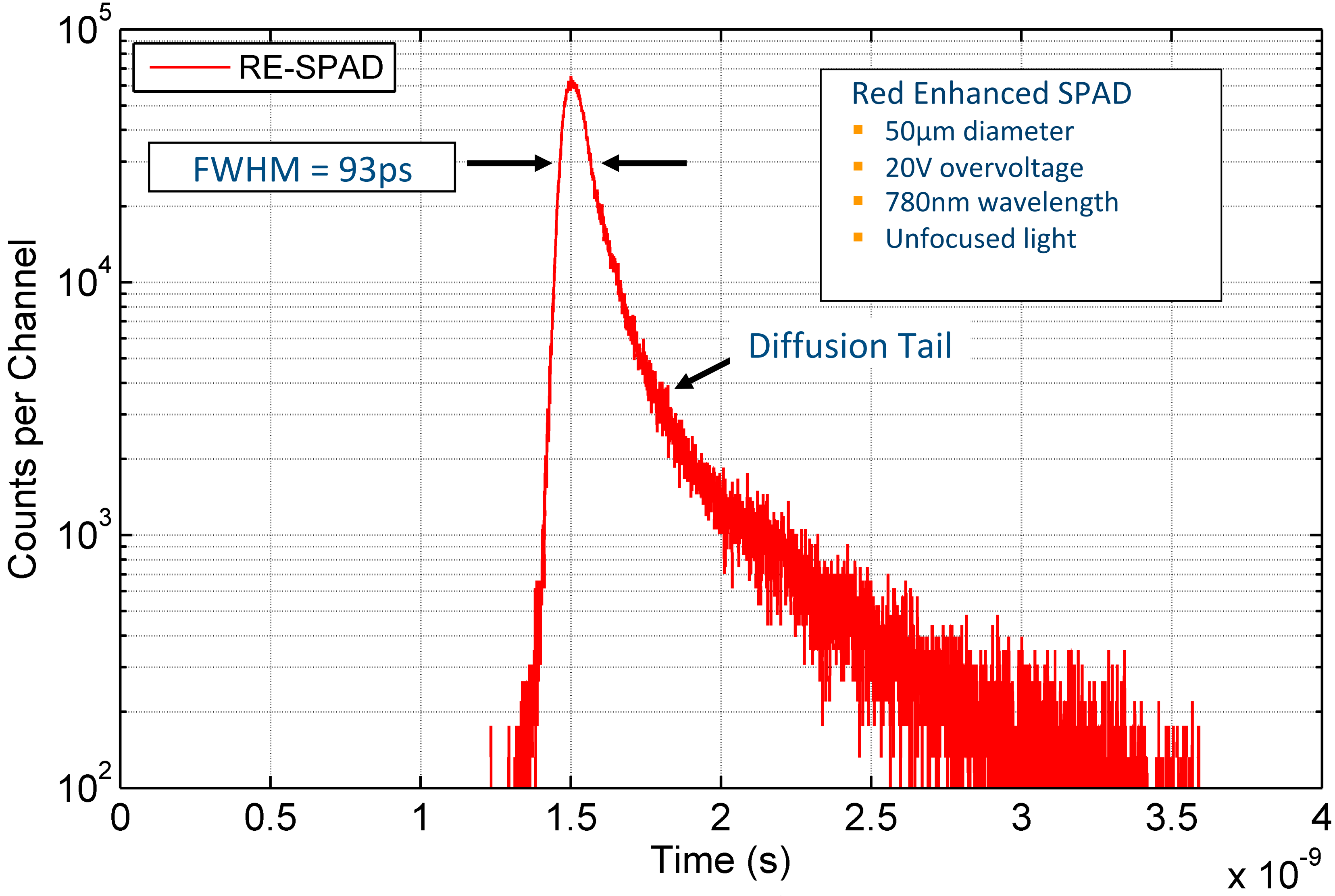


Courtesy: Yuki Maruyama

PDE State-of-the-Art (CMOS)

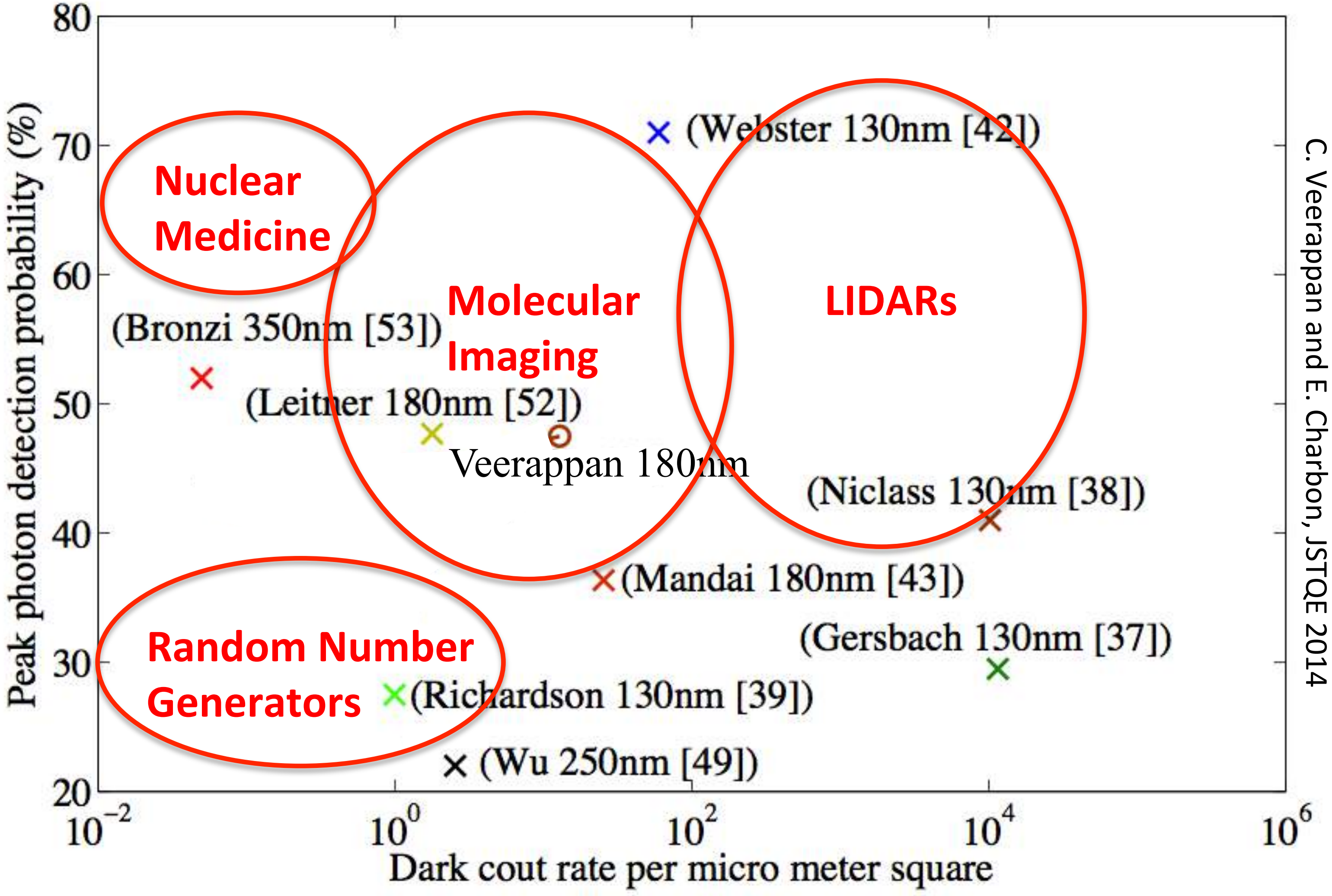


Timing Resolution



Courtesy: Sergio Cova

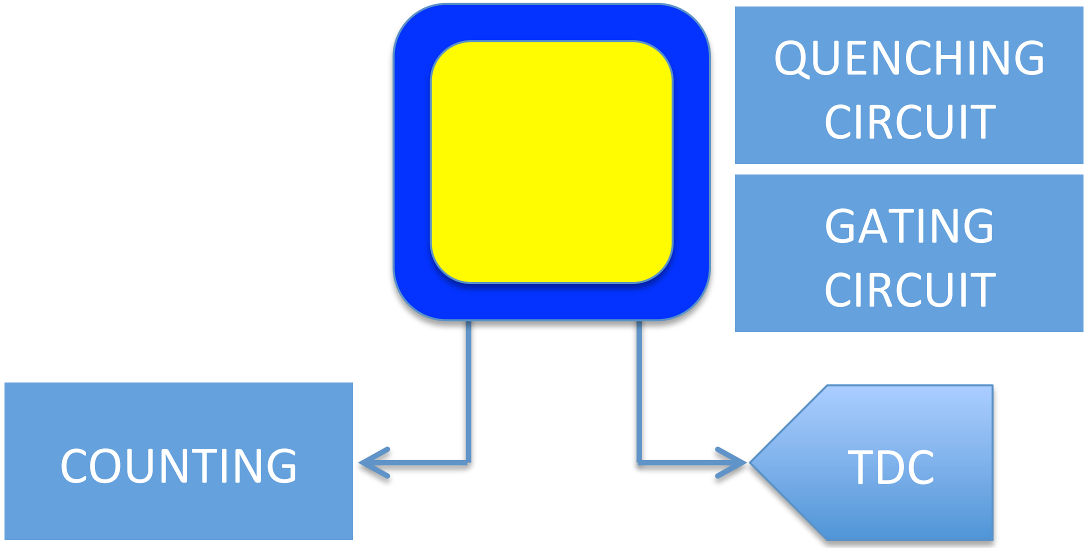
DCR vs. PDE



C. Veerappan and E. Charbon, JSTQE 2014

From a SPAD to a Camera

First, Let Us Define the Pixel



QUENCHING CIRCUIT

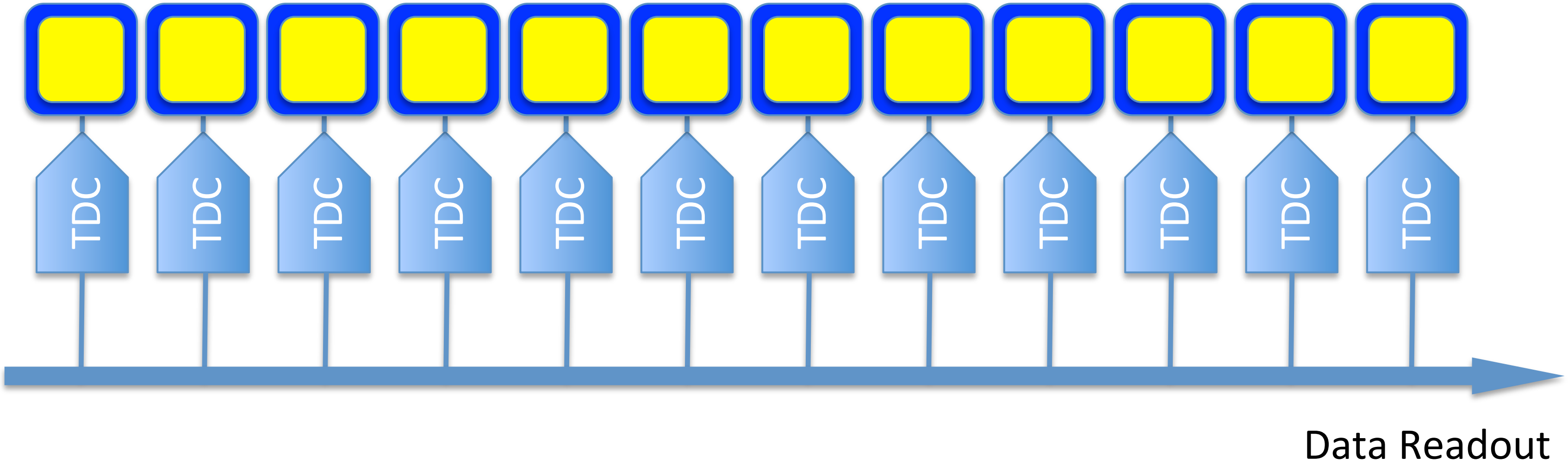
GATING CIRCUIT

COUNTING

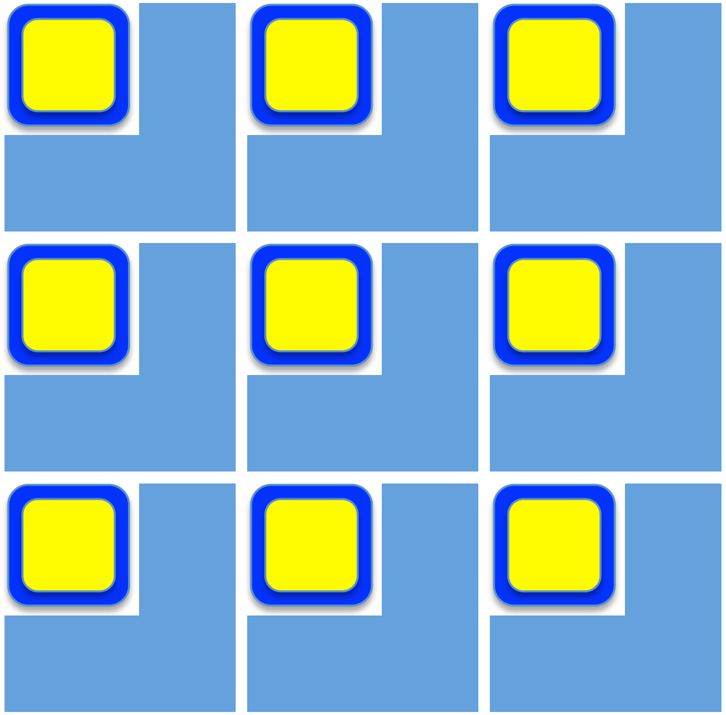
TDC

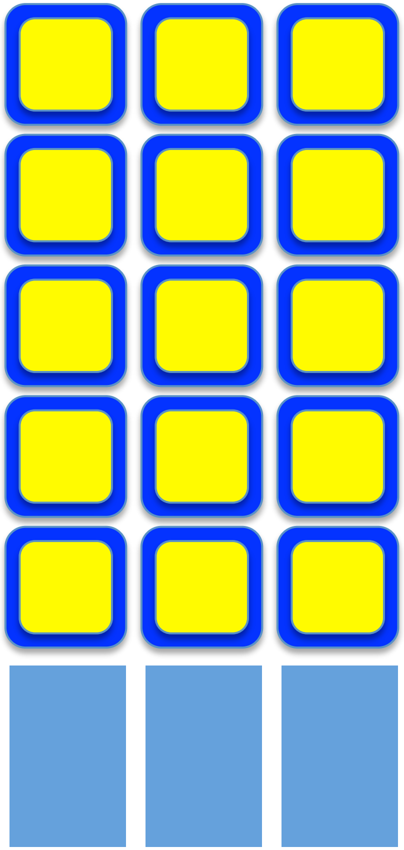
1D Arrays

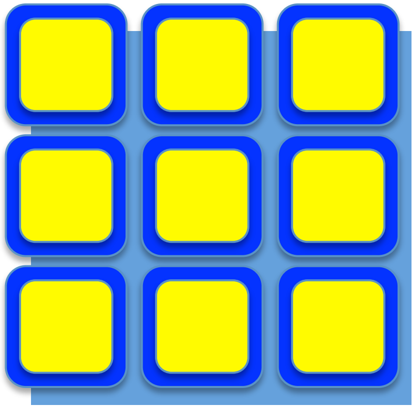
- No sharing of resources
- High fill factor



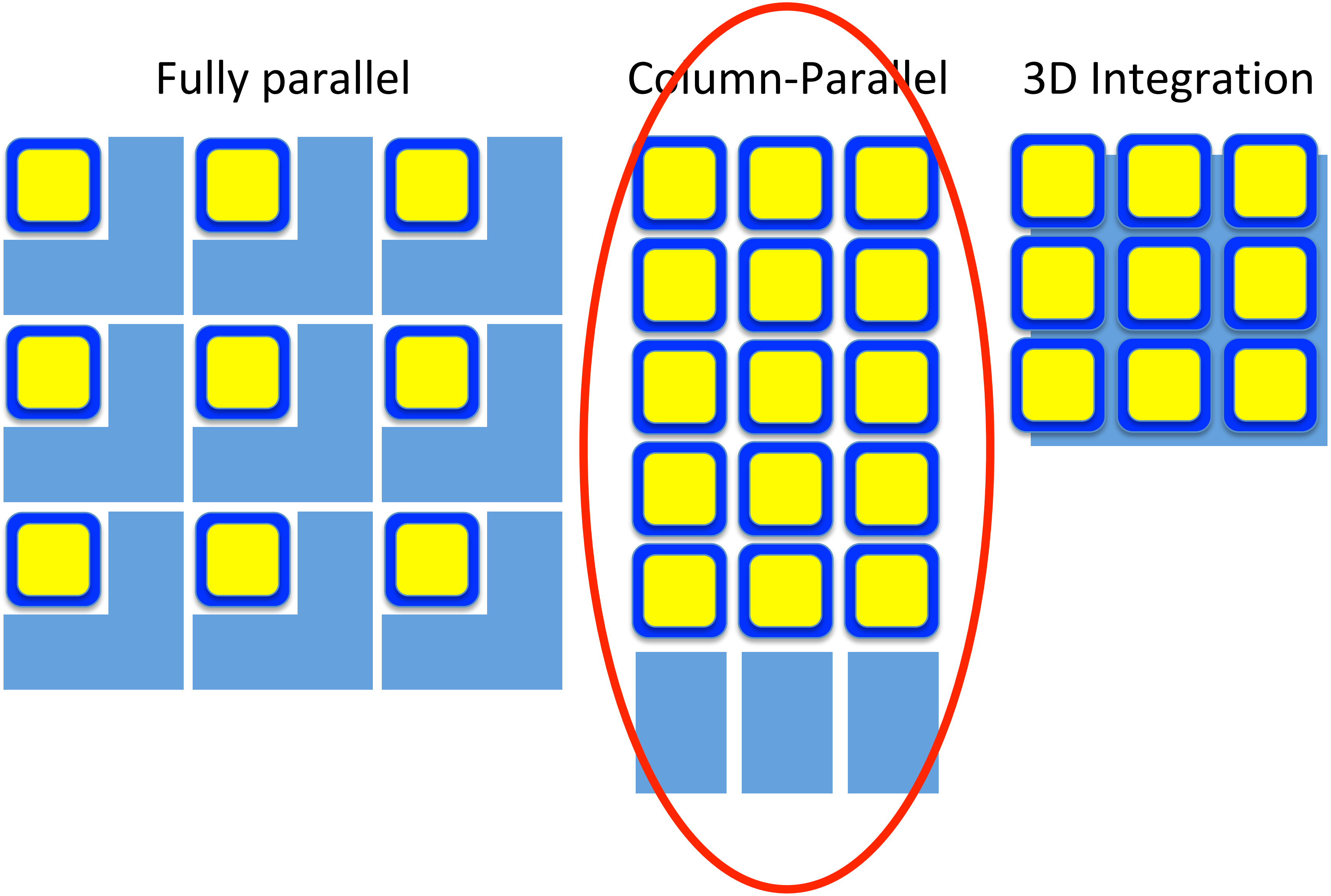
2D Arrays


Fully parallel

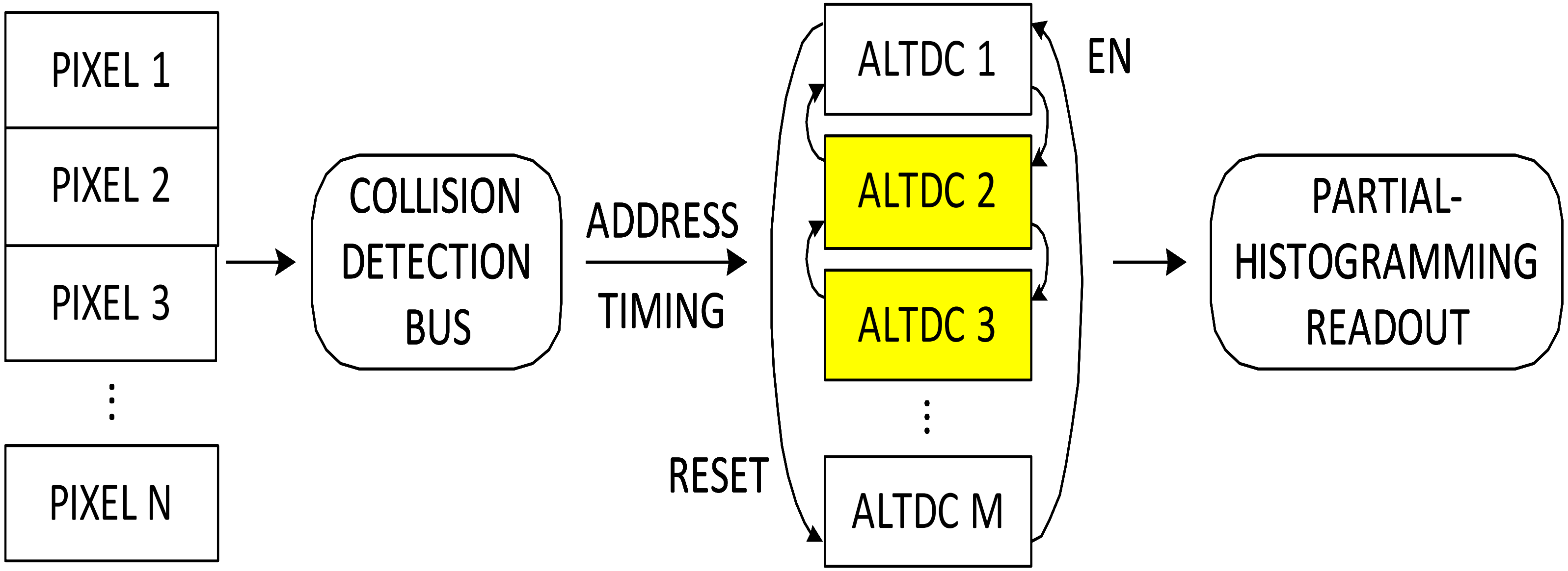

Column-Parallel


3D Integration

2D Arrays

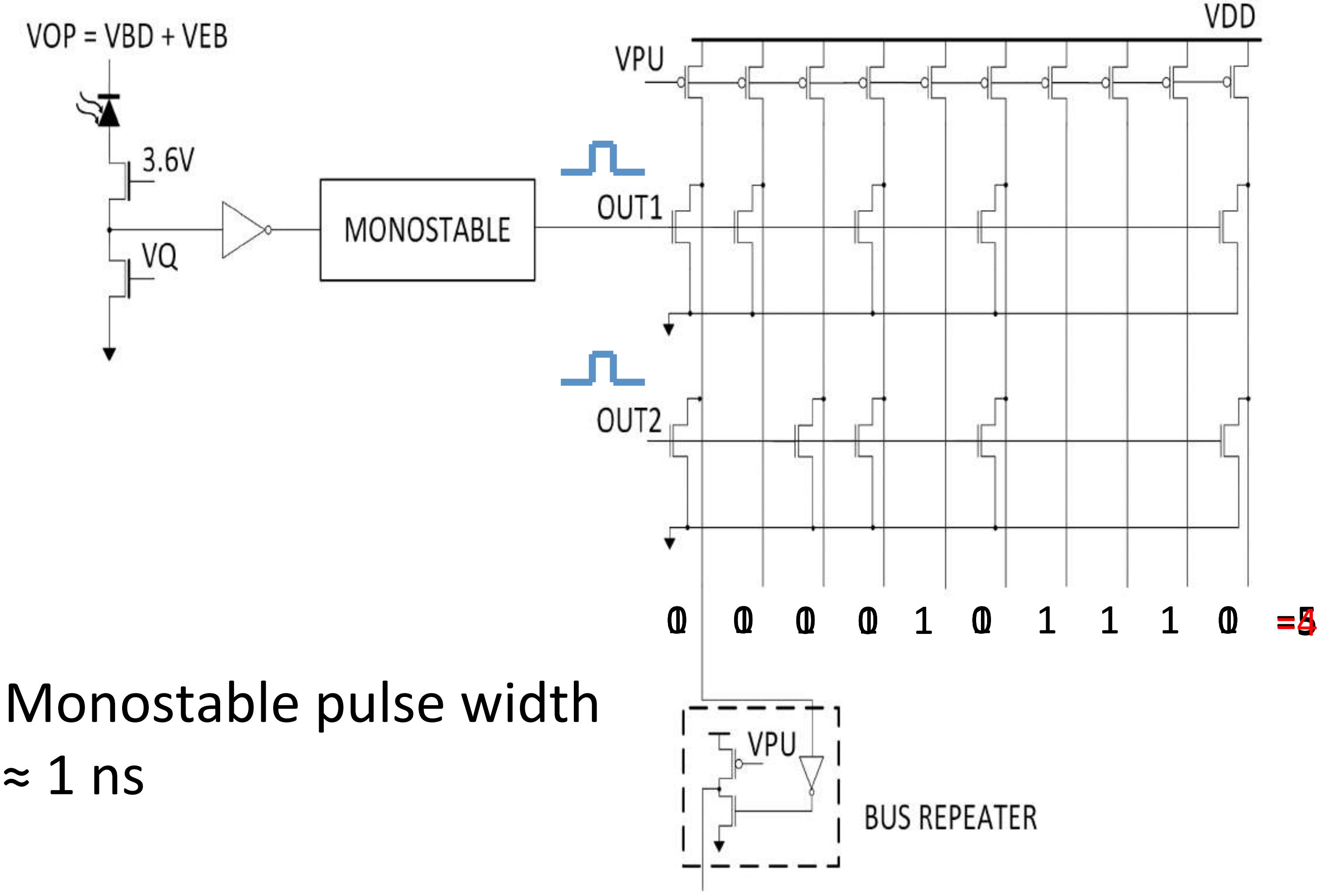


The Ocelot Approach



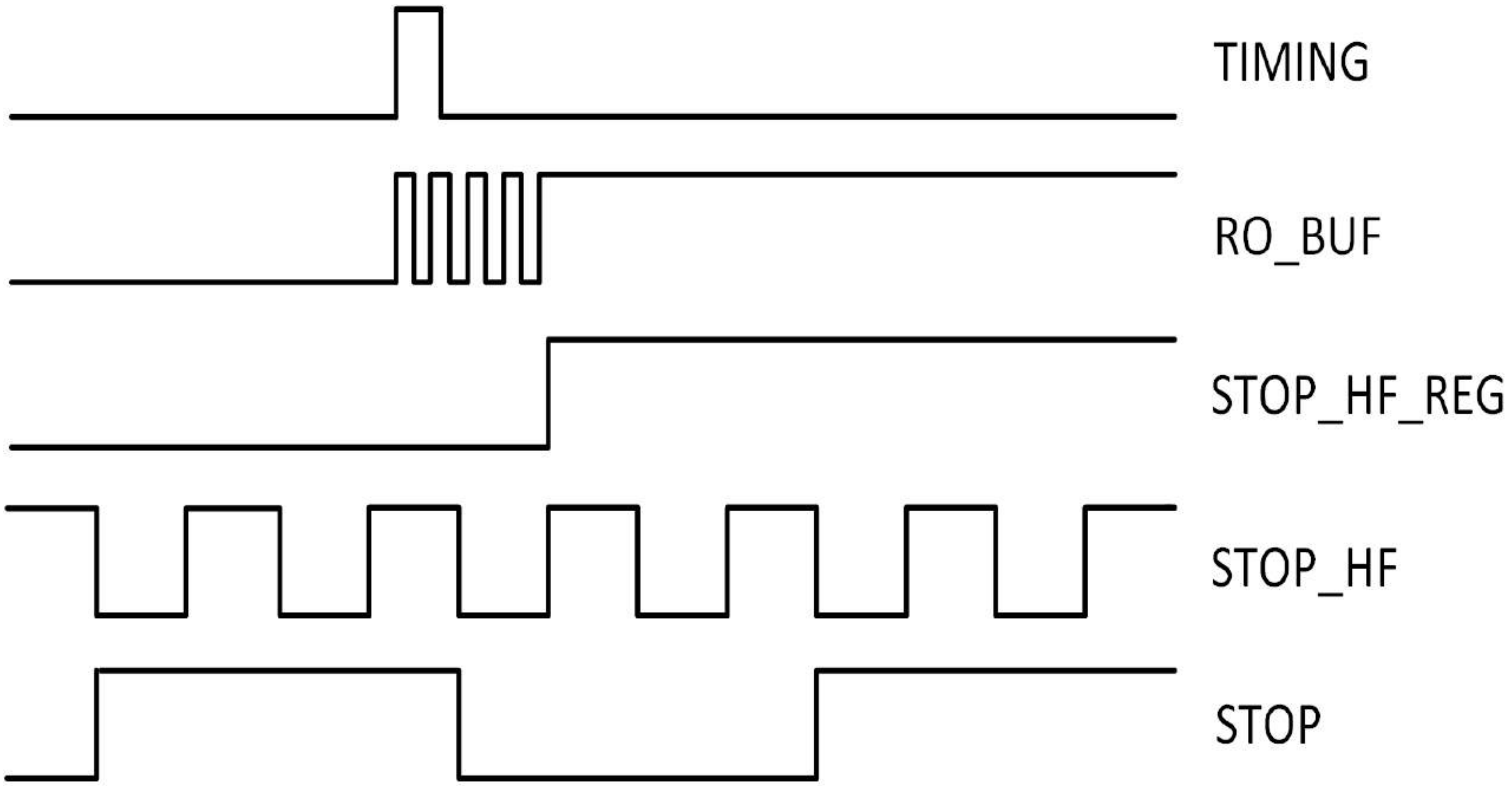
S. Lindner, C. Zhang *et al.*, *Symposium of VLSI*, 2018
C. Zhang, S. Lindner *et al.*, *JSSC*, 2019

Collision Detection Bus

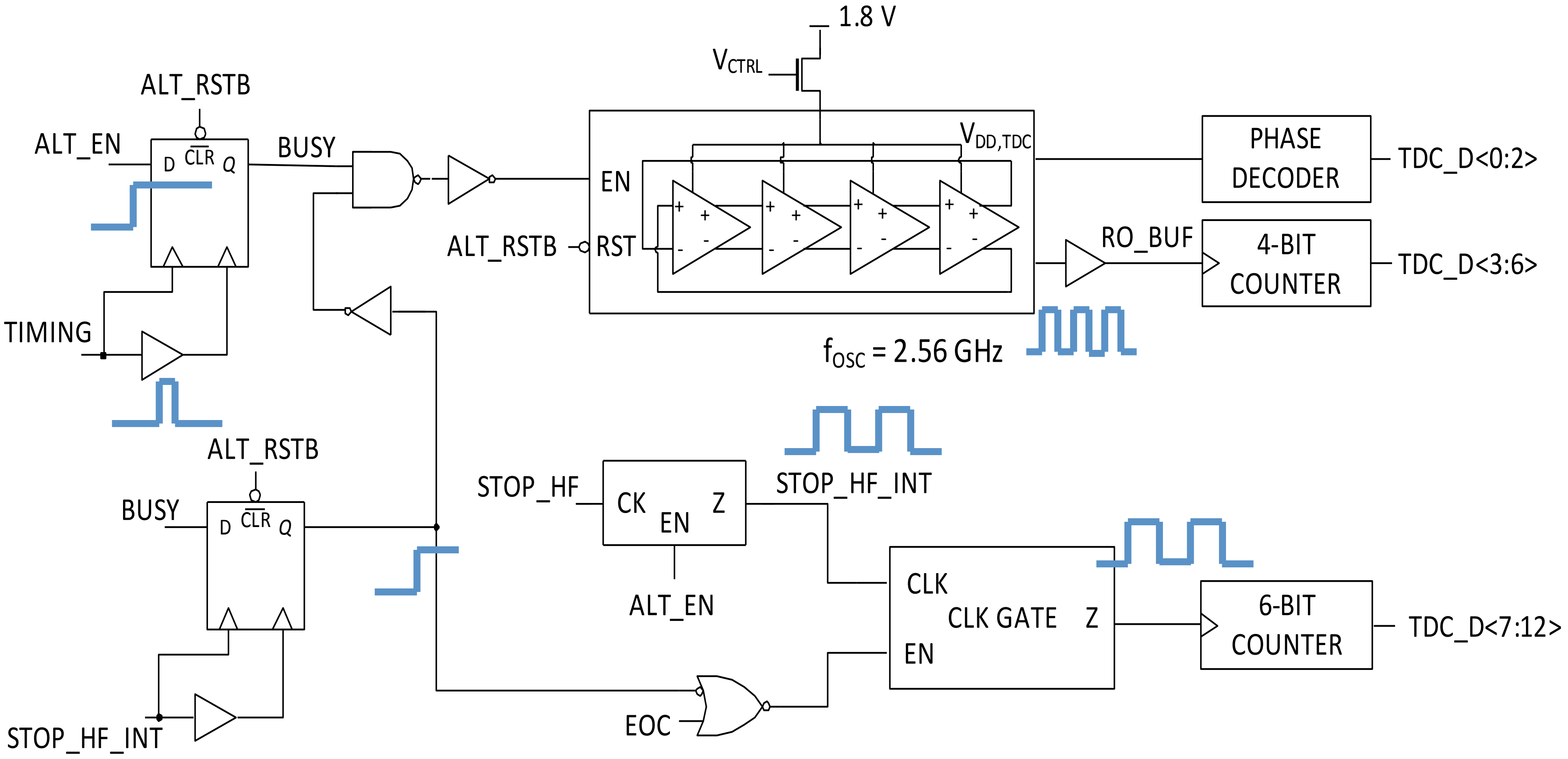


- Monostable pulse width ≈ 1 ns

Dual-clock Time-to-digital Converter

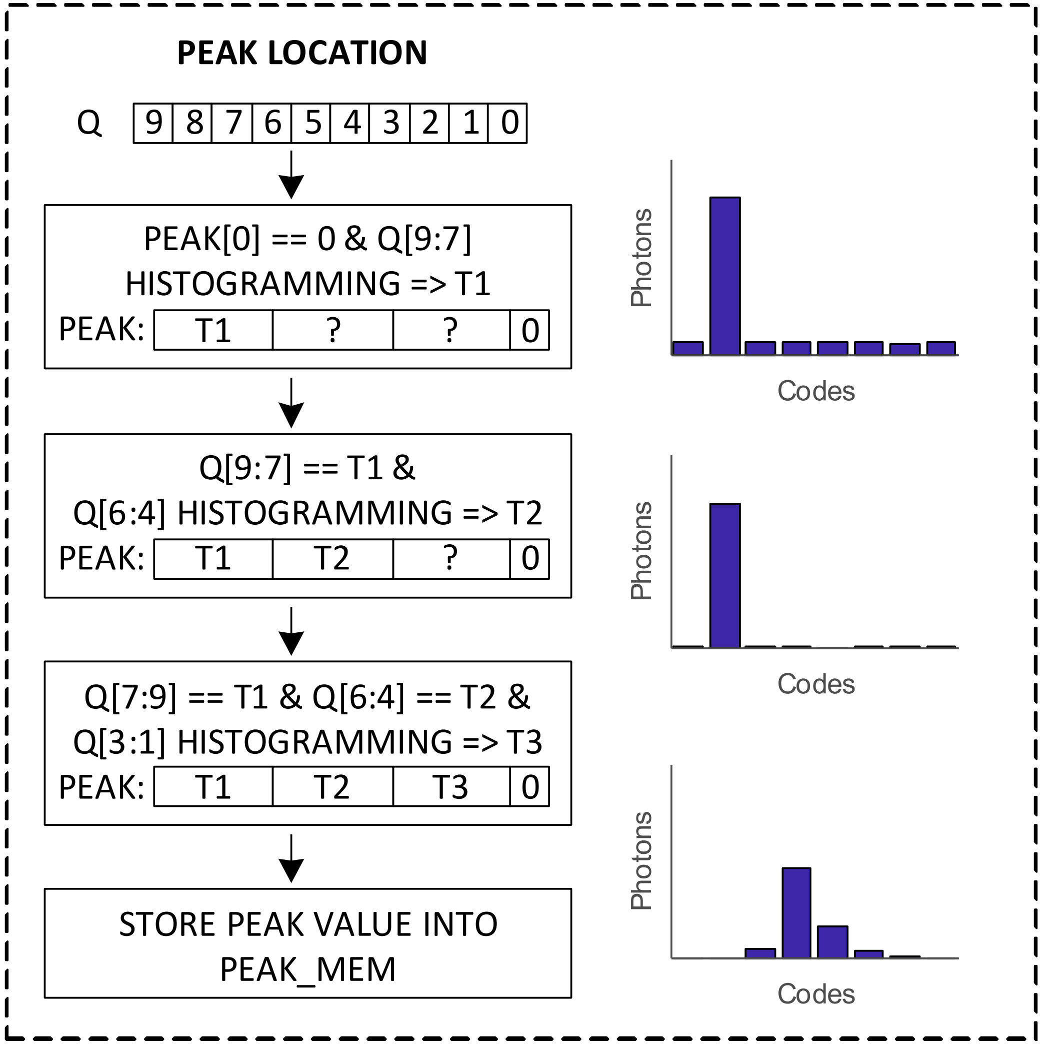


Dual-clock Time-to-digital Converter



- STOP_HF = 320 MHz
- LSB = 48.8 ps (nominal)

Partial-histogramming Readout



PEAK LOCATION

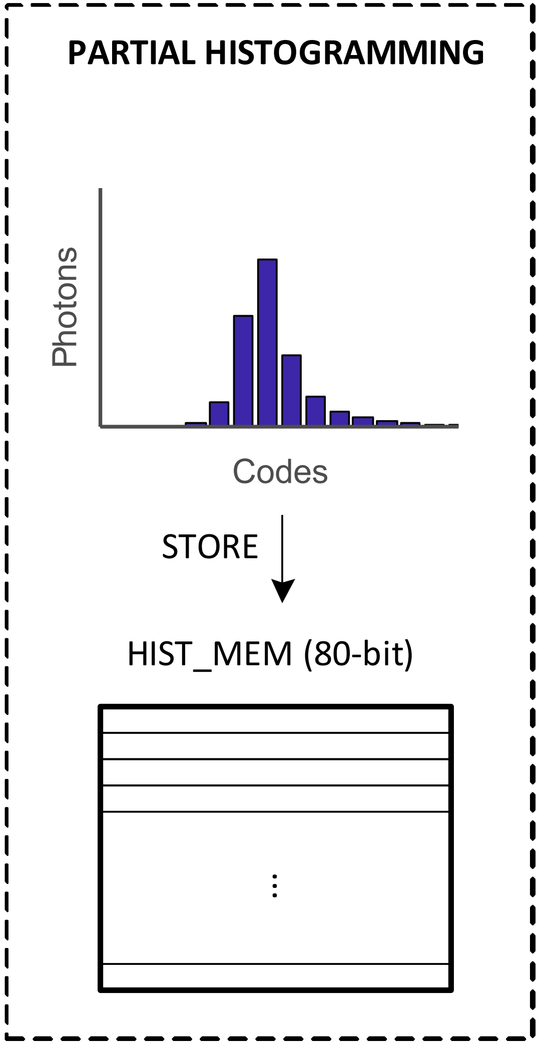
Q	9	8	7	6	5	4	3	2	1	0

PEAK[0] == 0 & Q[9:7]
HISTOGRAMMING => T1
PEAK: T1 | ? | ? | 0

Q[9:7] == T1 &
Q[6:4] HISTOGRAMMING => T2
PEAK: T1 | T2 | ? | 0

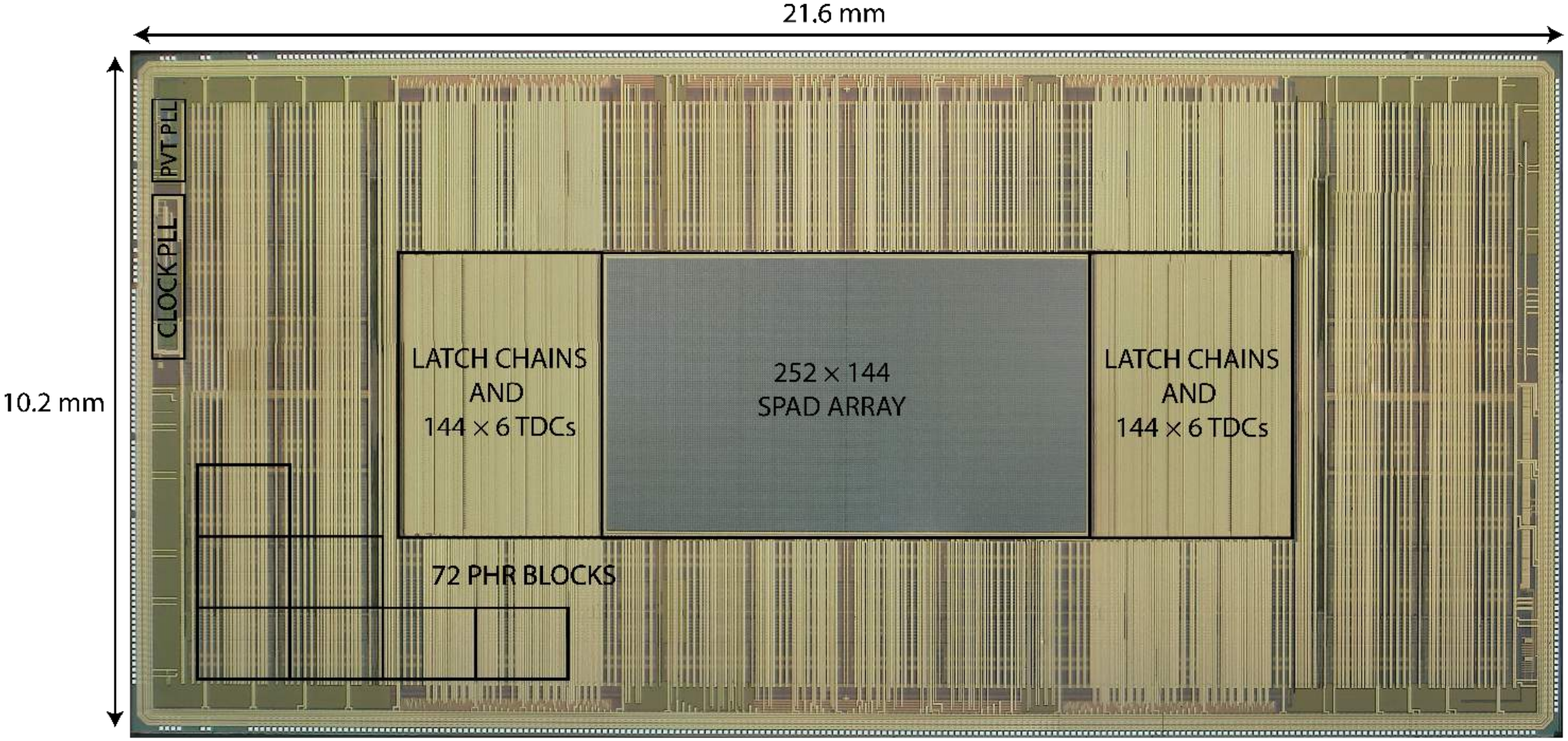
Q[7:9] == T1 & Q[6:4] == T2 &
Q[3:1] HISTOGRAMMING => T3
PEAK: T1 | T2 | T3 | 0

STORE PEAK VALUE INTO
PEAK_MEM



PARTIAL HISTOGRAMMING

Ocelot

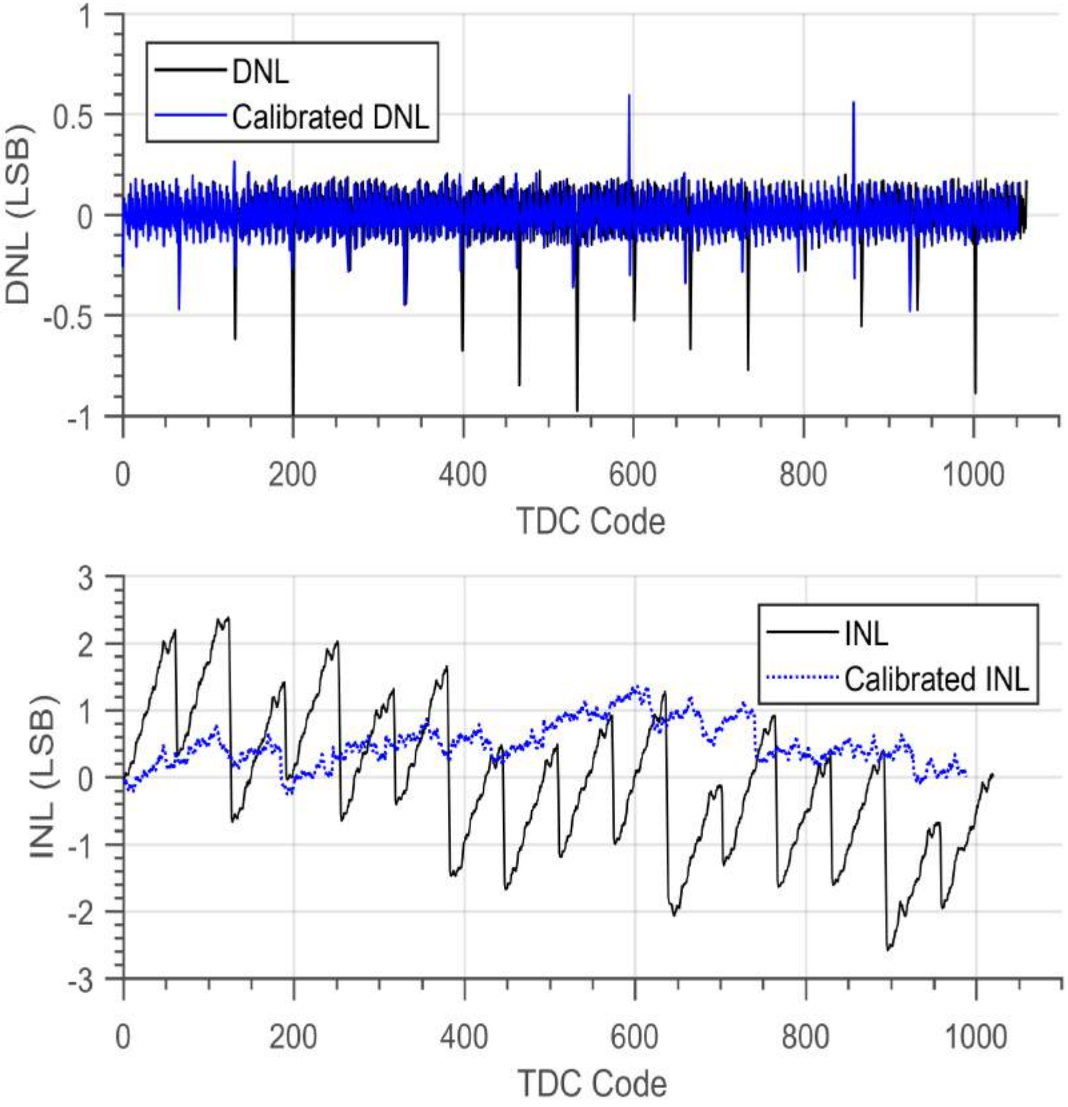


S. Lindner, C. Zhang *et al.*, *Symposium of VLSI*, 2018
C. Zhang, S. Lindner *et al.*, *JSSC*, 2019

- 180nm CMOS
- 28% Fill factor (28.5µm pitch)
- 11.2 Gbit/s output data bandwidth

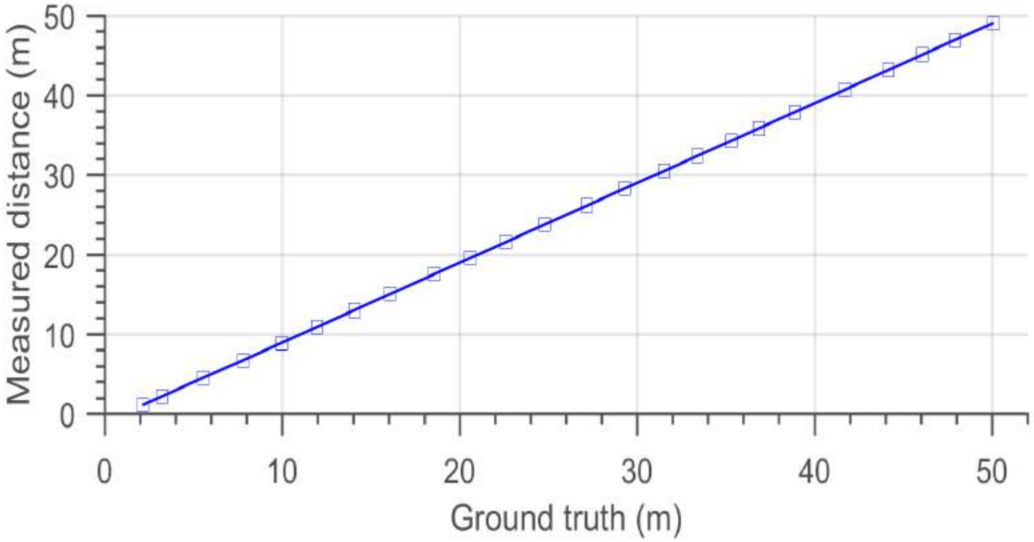
Results - TDC Nonlinearity

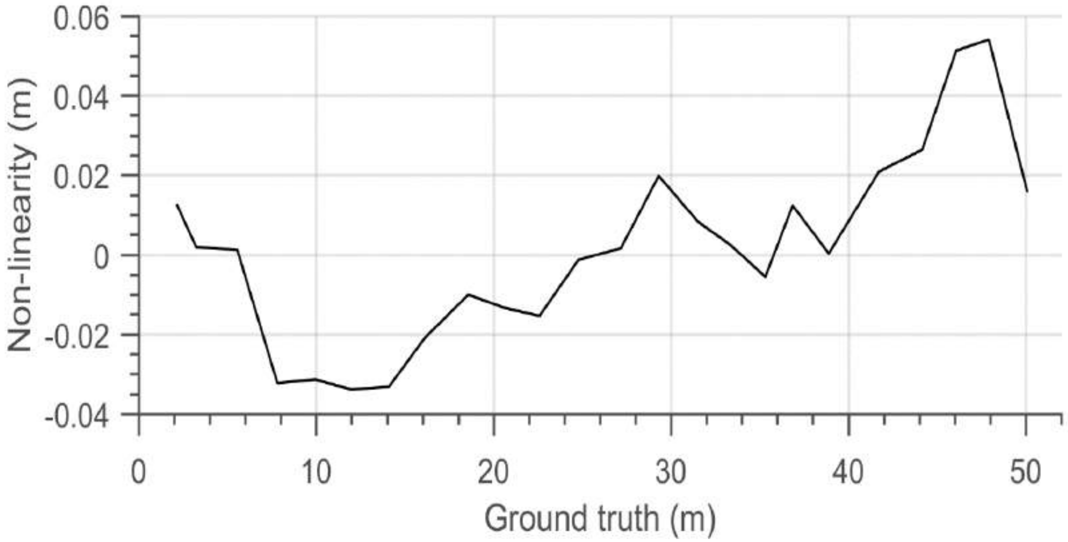
- DNL = +0.22/-1 LSB
- INL = +2.39/-2.6 LSB
- After calibration for clock transition:
- DNL = +0.6/-0.48 LSB
- INL = +0.89/-1.67 LSB



Single-point Measurement

- 2 mW laser
- 637 nm
- Non-linearity = 8.8 cm
- Detector verified for higher wavelengths

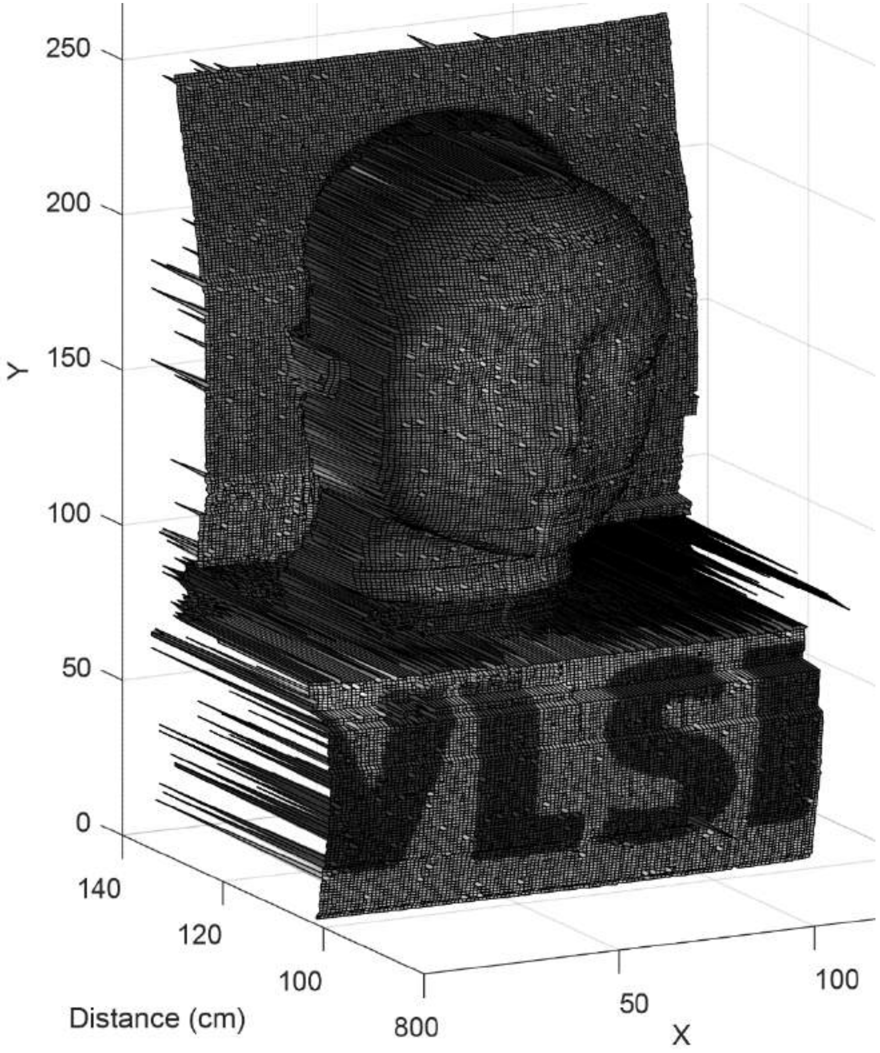




Flash LiDAR

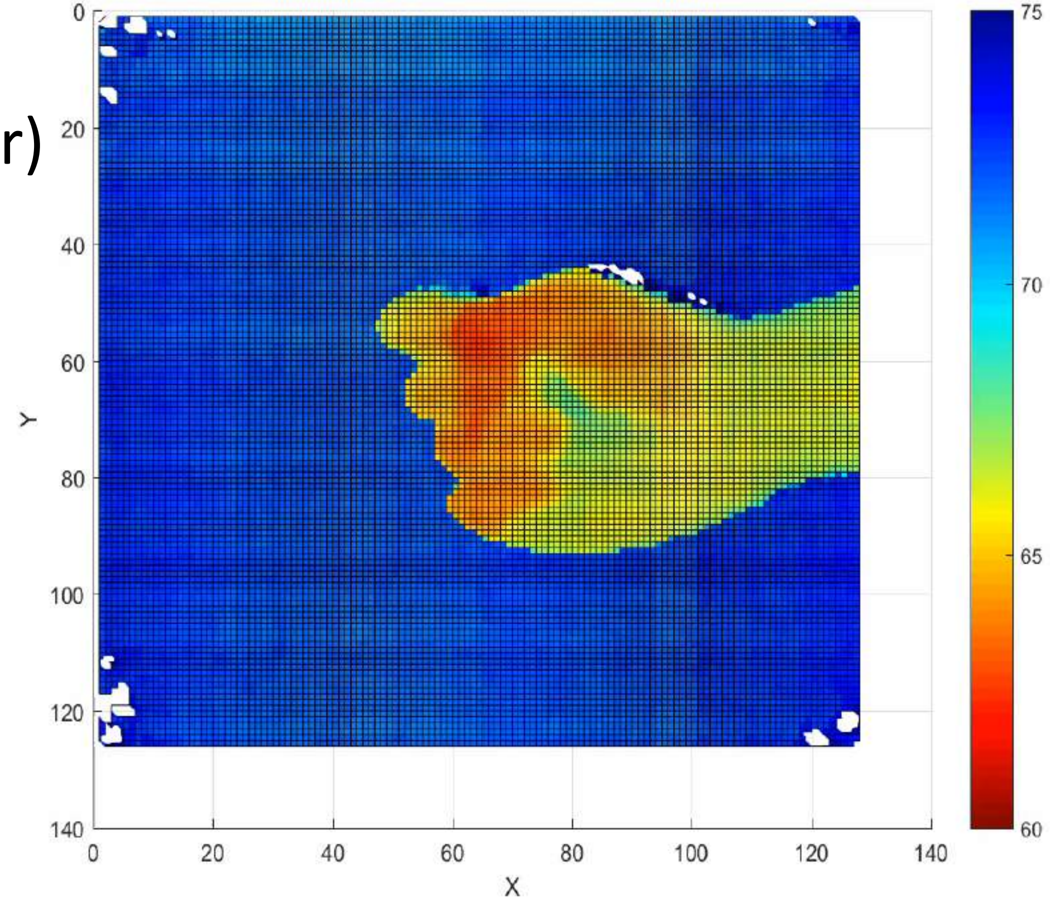
S. Lindner, C. Zhang et al., Symposium of VLSI, 2018

- 1m distance
- 8 illumination exposures
- 14.9-to-1 data compressior



Flash Video Demo

- 2 mW laser
- 637 nm
- 126 × 128 (half sensor)
- 30 fps

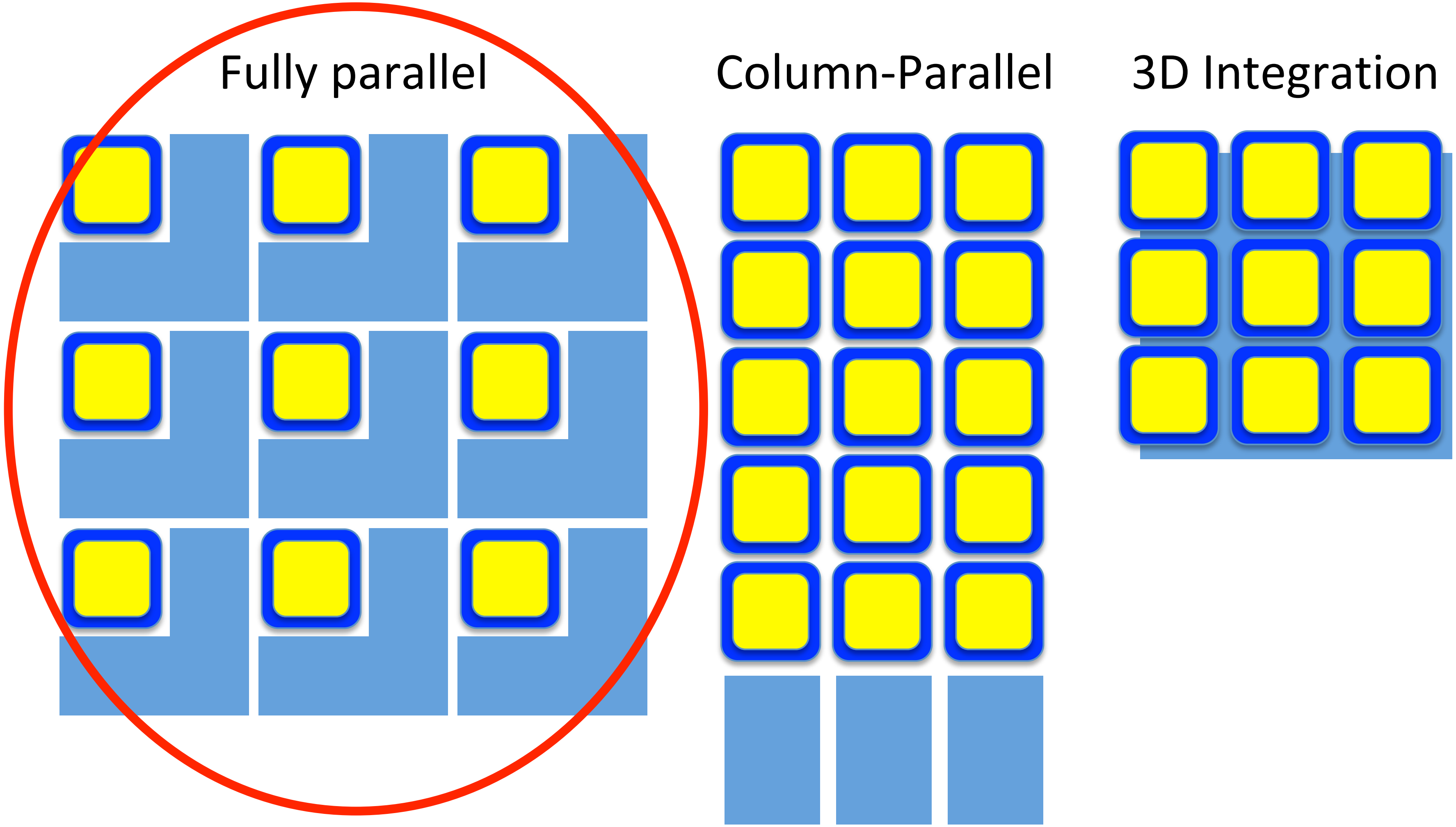


Ocelot Comparison

Parameter	Unit	**This work**	JSSC'2013	VLSI'2017	JSSC'2017
Technology	nm	180 nm	180 nm	130nm CIS	150 nm
Sensor resolution		252 × 144	32 × 1(1)	512 × 1(1)	64 × 64(1)
Sensor characteristics					
Pixel pitch	µm	28.5	25	23.78	60
Fill factor	%	28	70	49.31	26.5
DCR @ VEB	cps/µm^2	0.62 @ 5V	6 @ 3.3	N/A	57 @ 3
Integrated histogramming		Per-pixel	None	Per-pixel	None
No. of TDCs		1728	32	512	4096
TDC area	µm^2	4200	31000(2)	5400(2)	N/A
Measured distance performance					
Distance range	m	2 - 50	128	N/A	367 - 5862(4)
Accuracy (Non-linearity)	m	0.08	0.37(3)	N/A	1.5-35(4)

(1) Macro pixel resolution. (2) Estimated from paper. (3) Measured at 100m. (4) Emulated results.

2D Arrays



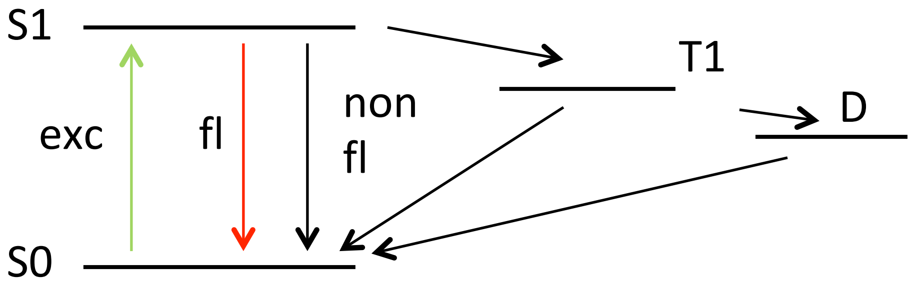
Fully parallel

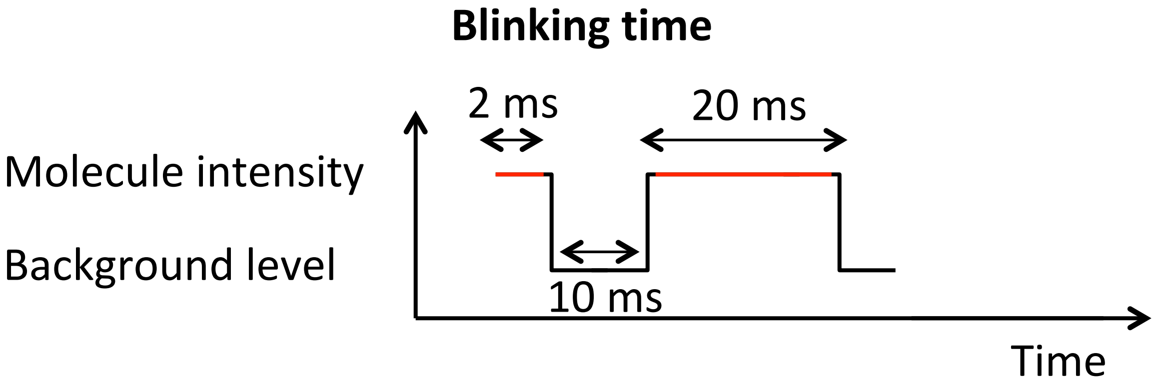
Column-Parallel

3D Integration

Localization Super-resolution

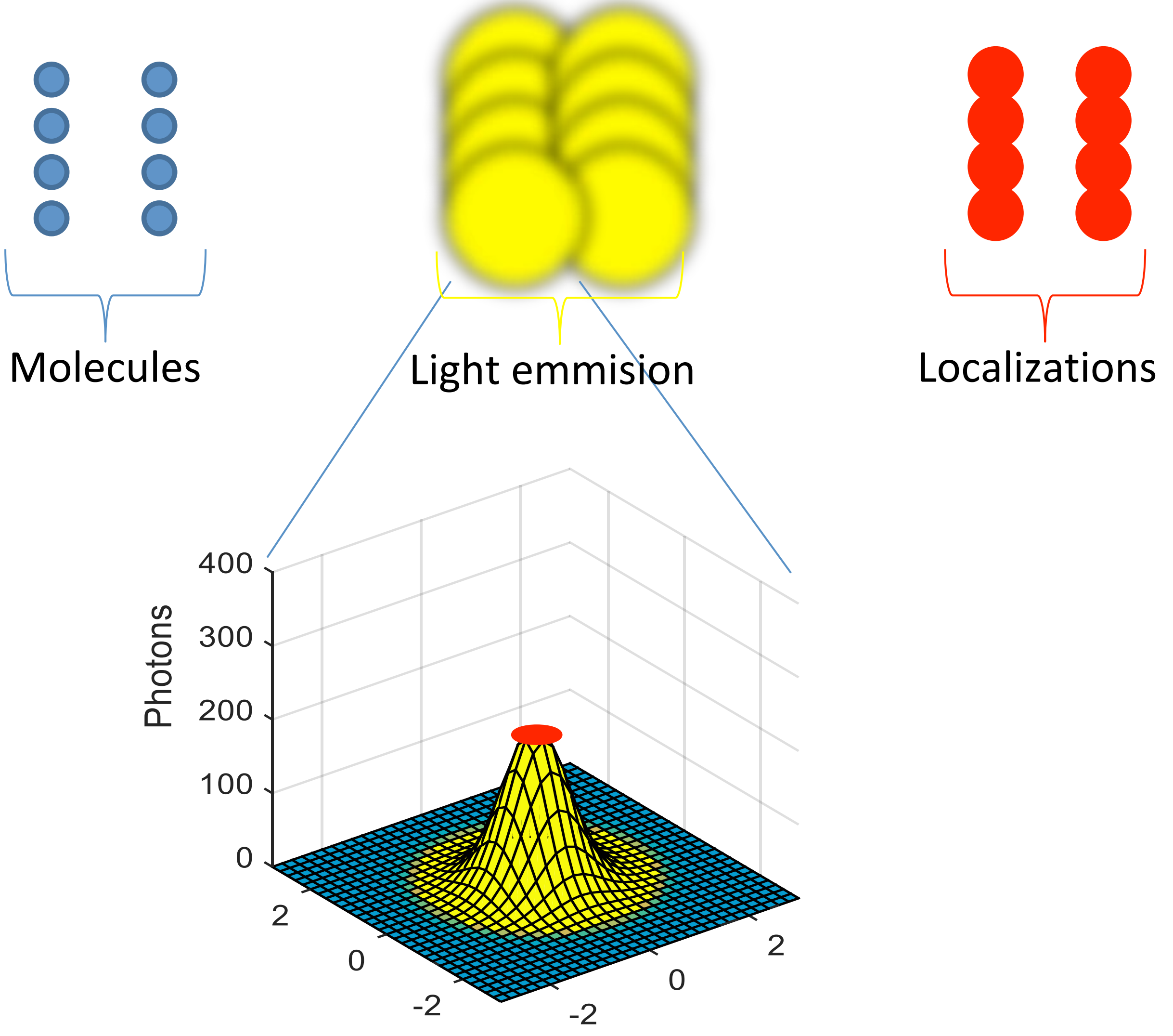
- PALM
- STORM
- dSTORM/GSDIM*





*) GSDIM = Ground-state depletion and single-molecule return

Localization Super-resolution

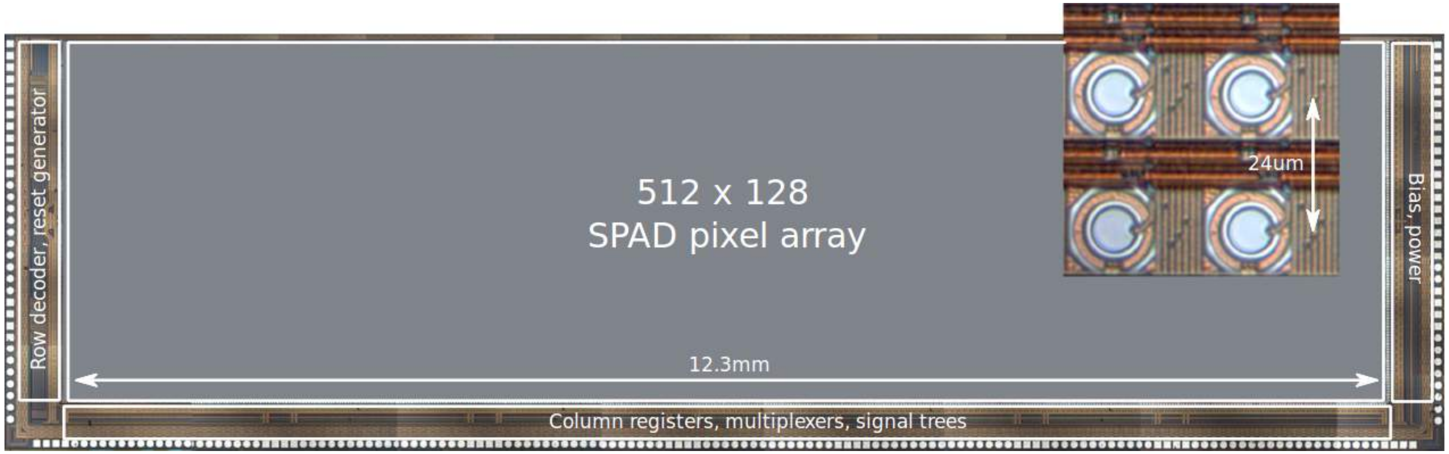


Molecules

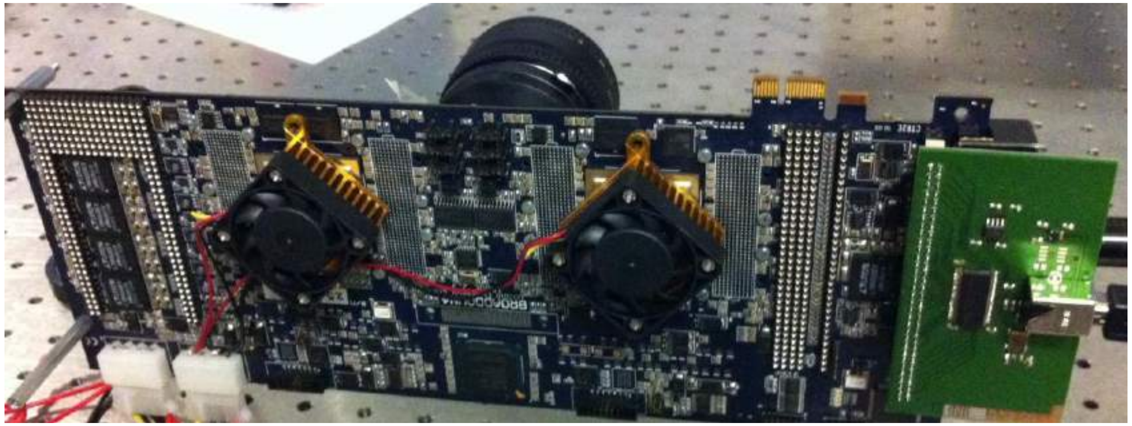
Light emmision

Localizations

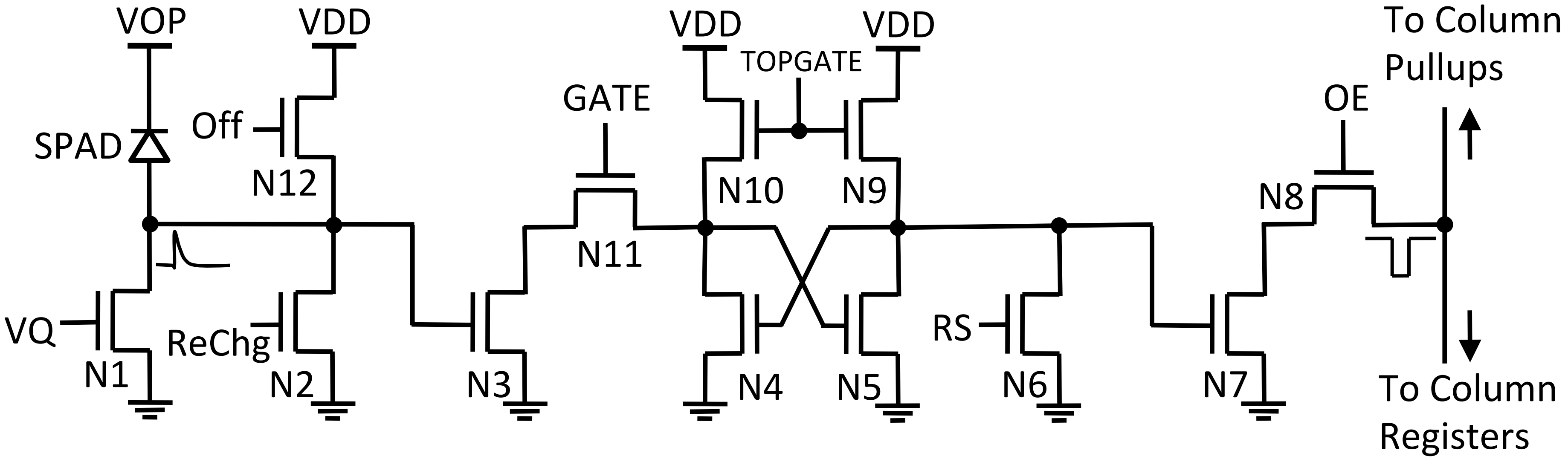
SwissSPAD



S. Burri *et al.*, *Optics Express*, 2014

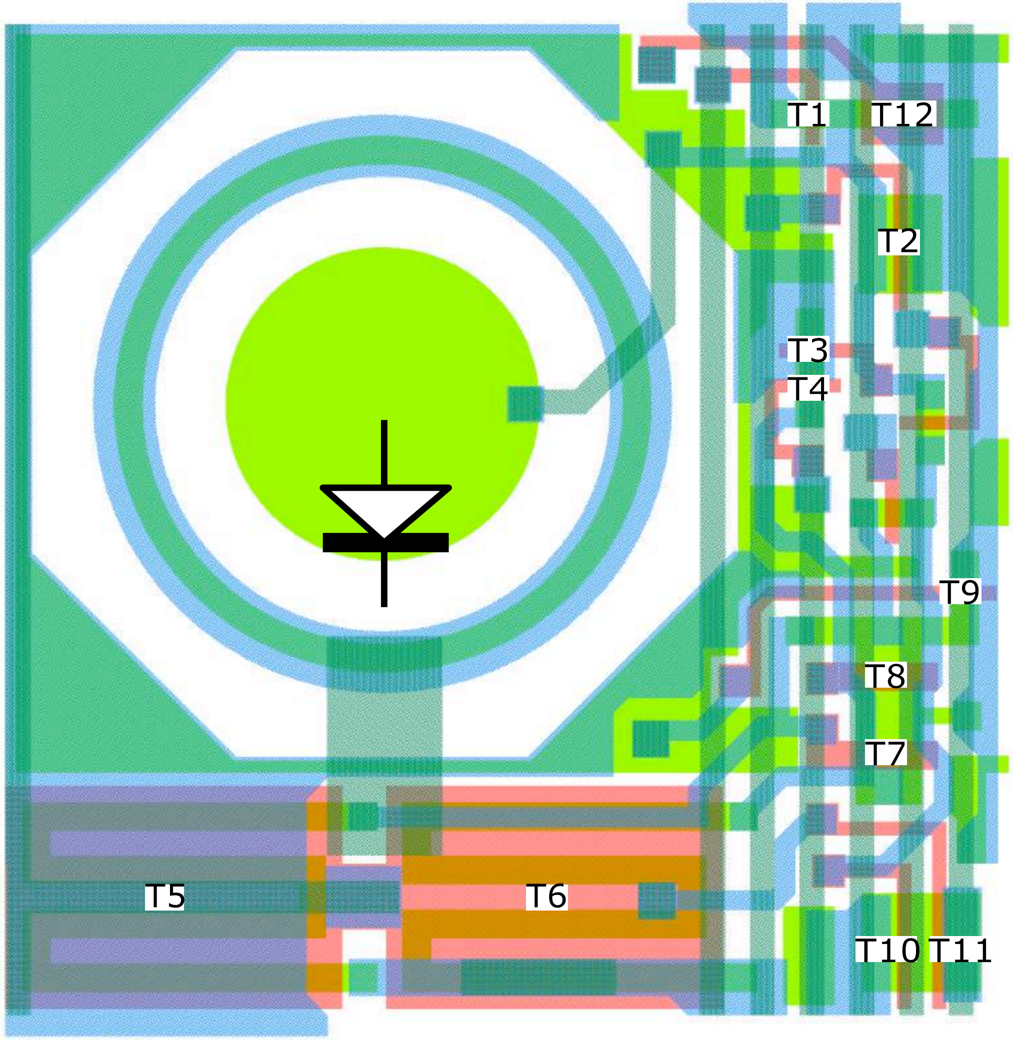


Pixel Architecture

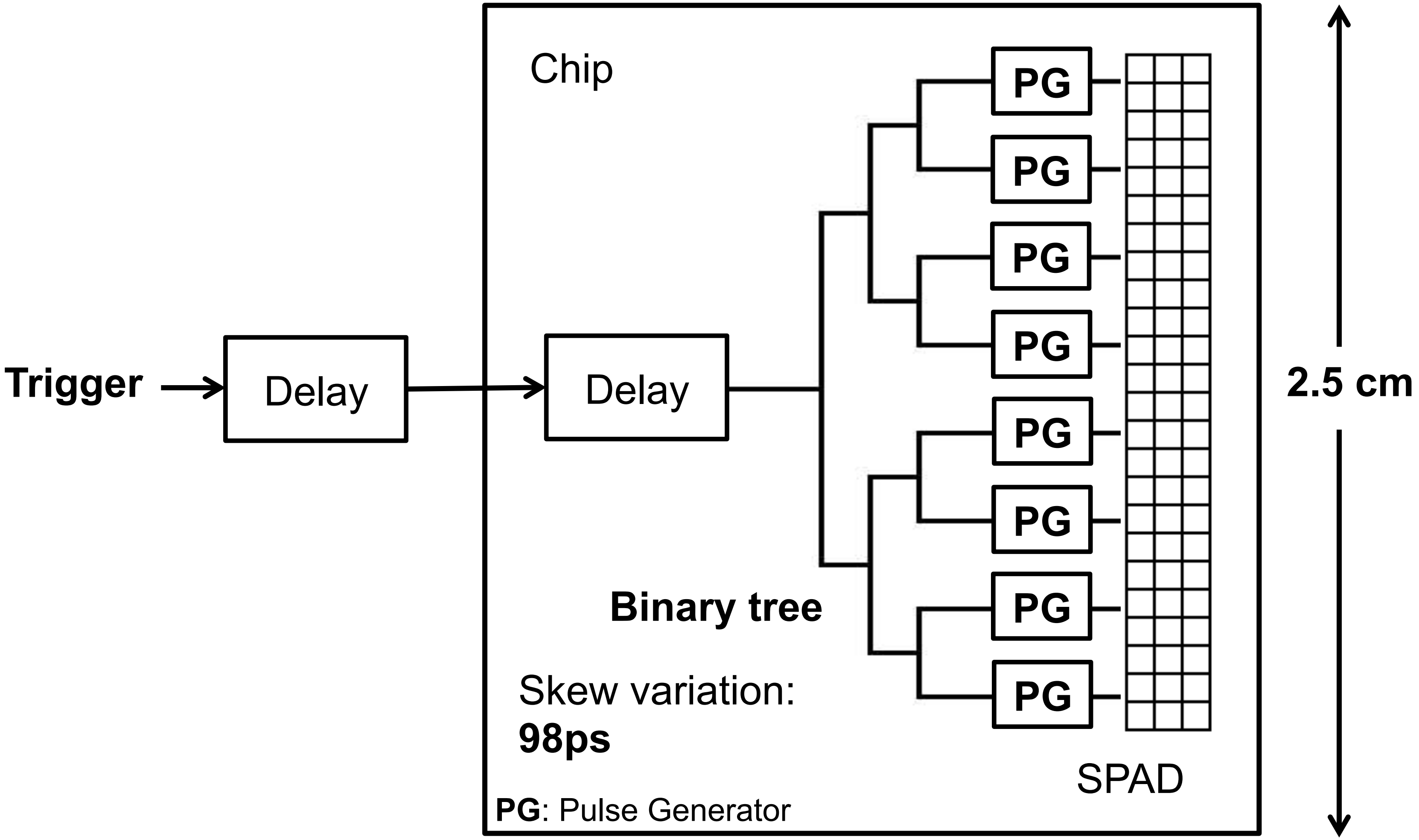


S. Burri *et al.*, *Optics Express,* 2014

Pixel Layout



Gating Synchronization: B-Trees

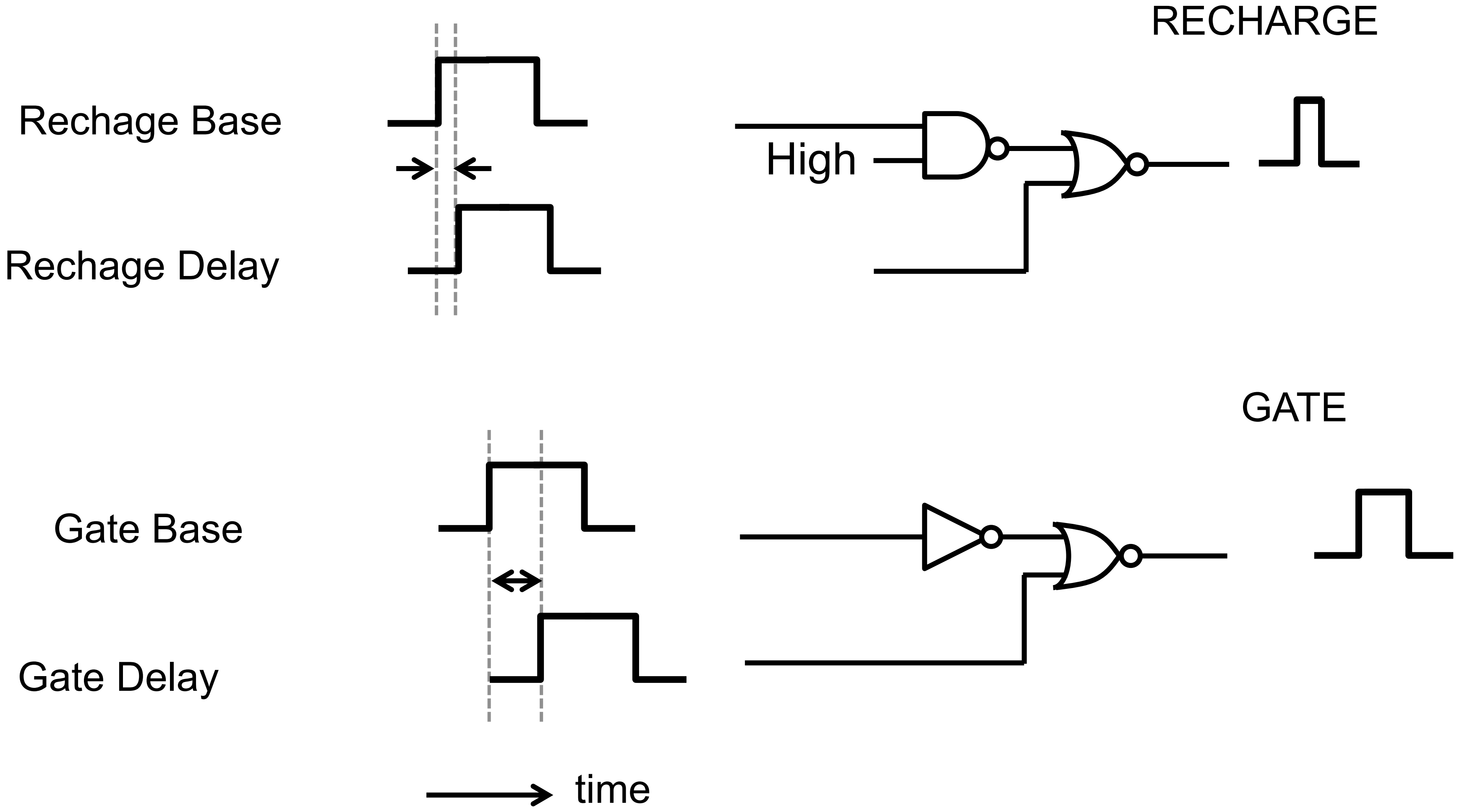


Skew variation:
98ps

PG: Pulse Generator

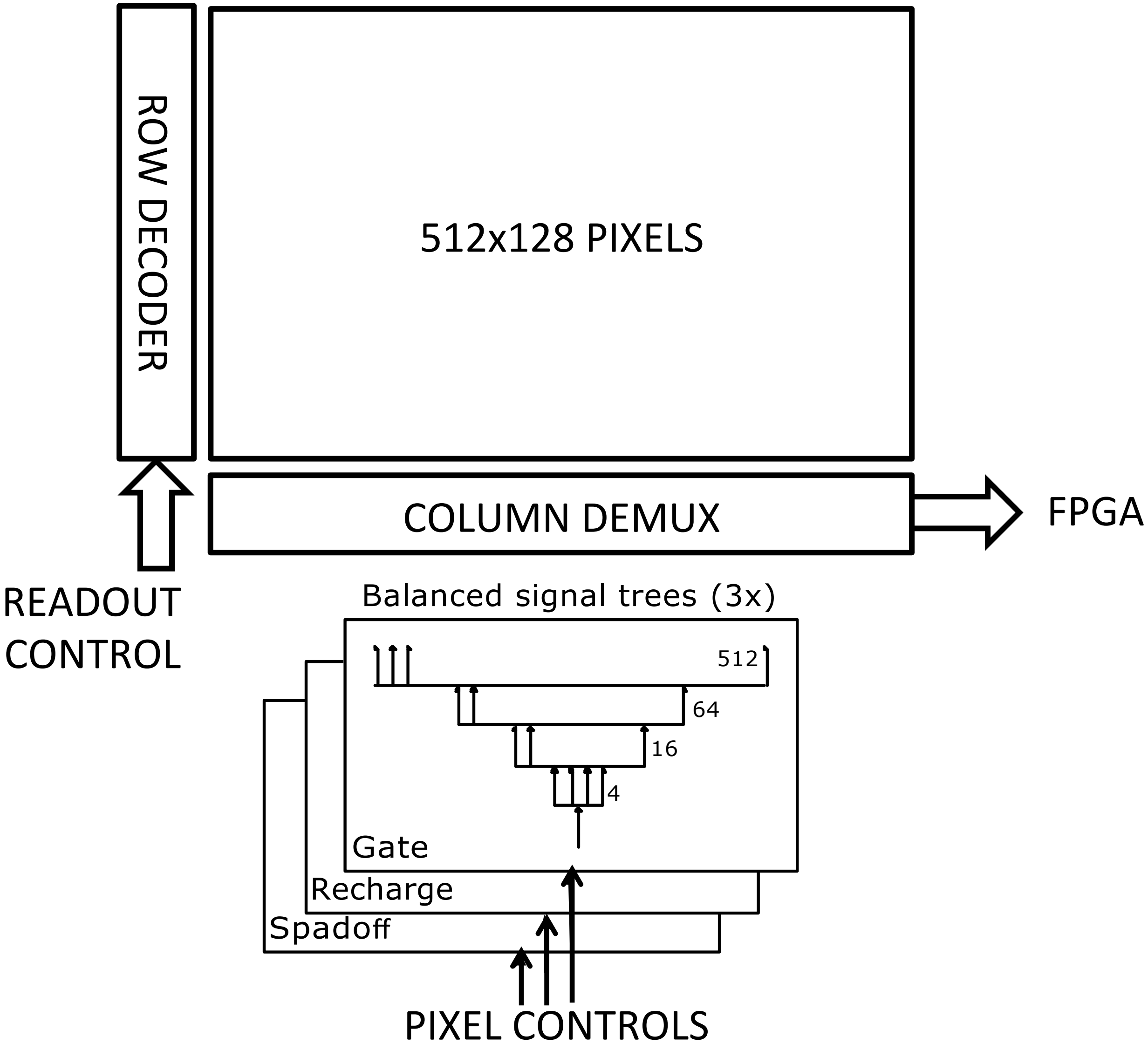
Courtesy: Yuki Maruyama

Gate Pulse Generation



Courtesy: Yuki Maruyama

Overall Readout Architecture



ROW DECODER

512x128 PIXELS

COLUMN DEMUX

FPGA

READOUT
CONTROL

Balanced signal trees (3x)

Gate

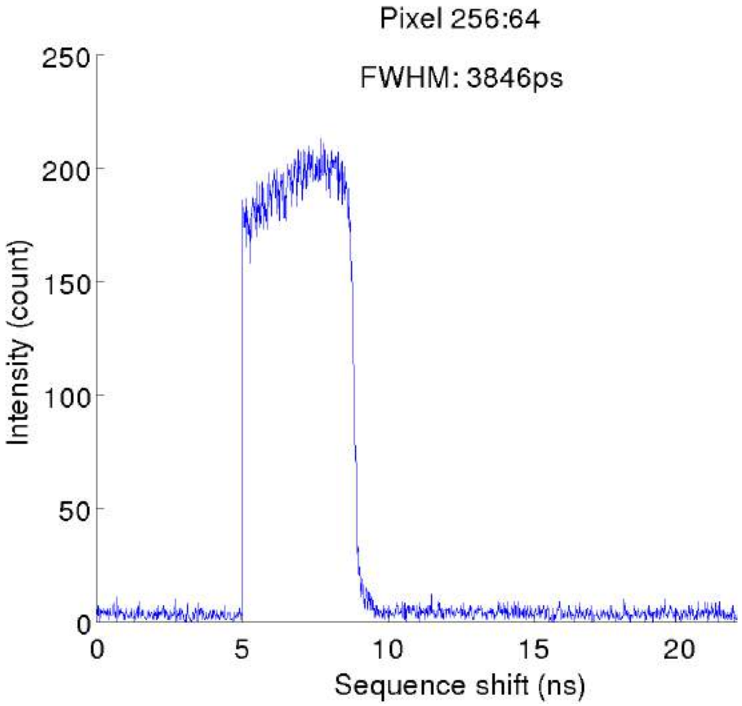
Recharge

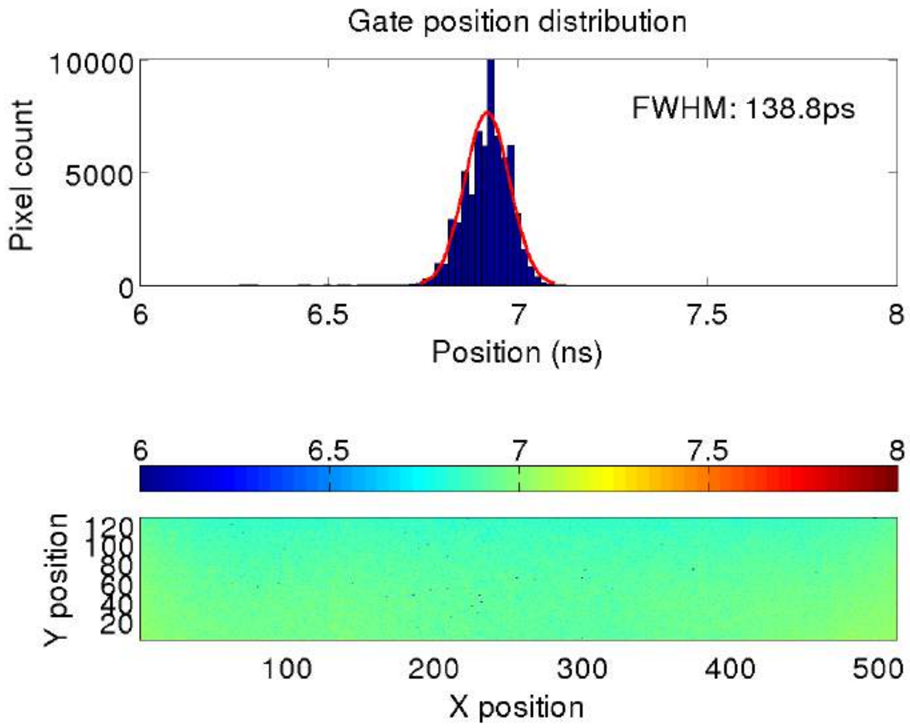
Spadoff

PIXEL CONTROLS

Gate Accuracy and Uniformity

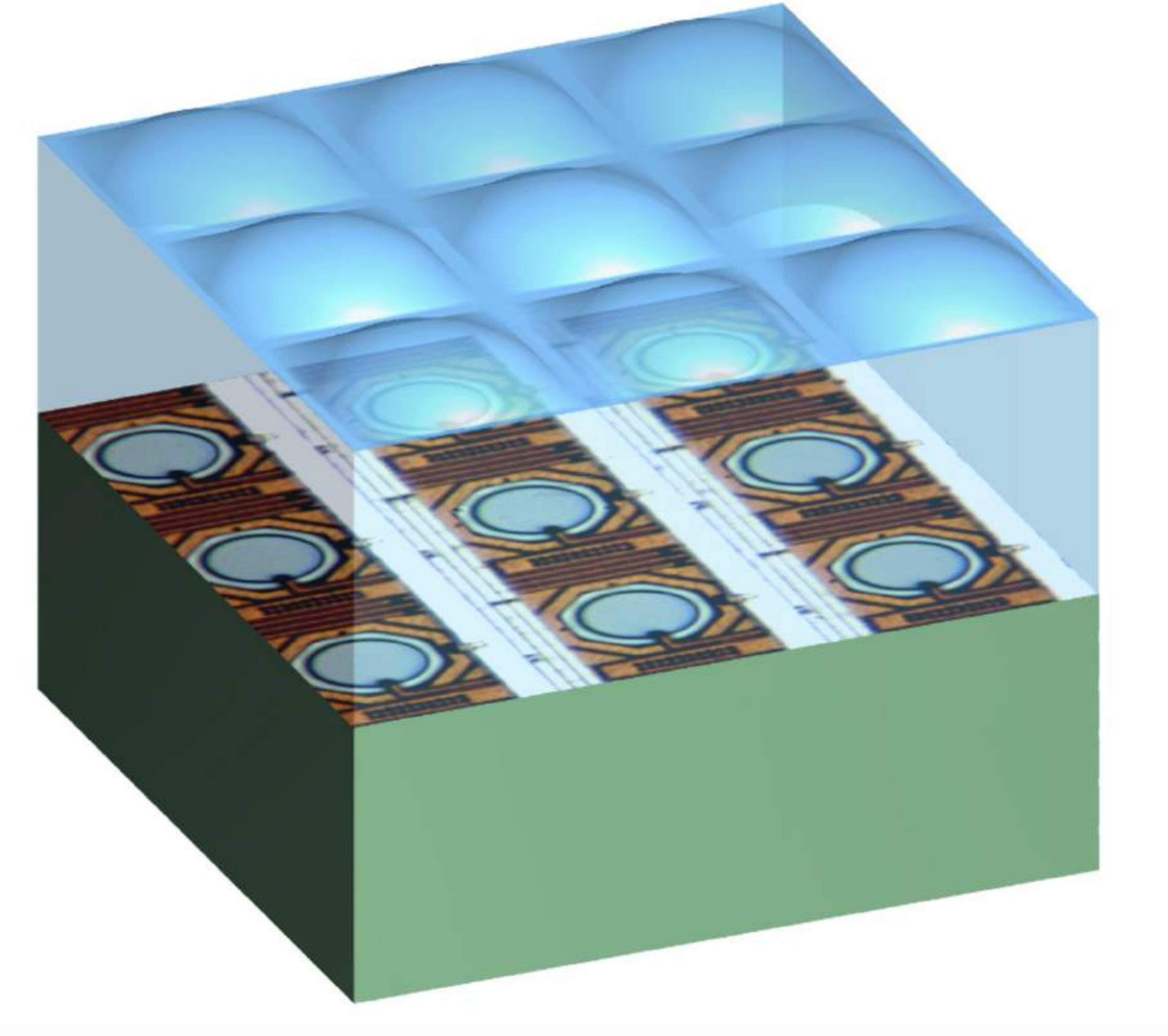
- 4ns gating (138ps FWHM)
- 156kfps frame rate



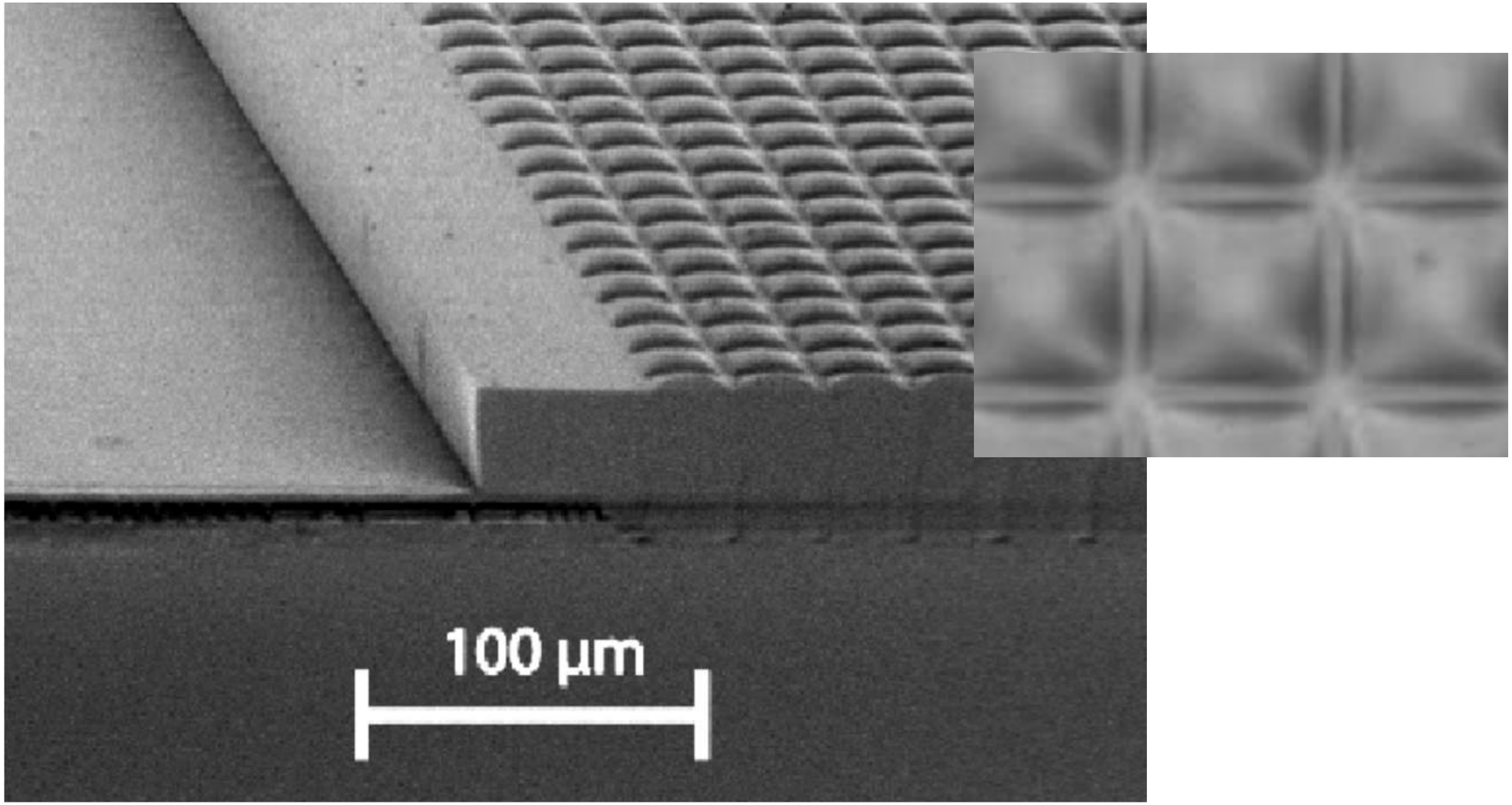


S. Burri *et al.*, *Optics Express*, 2014

Fill Factor Recovery: Microlenses

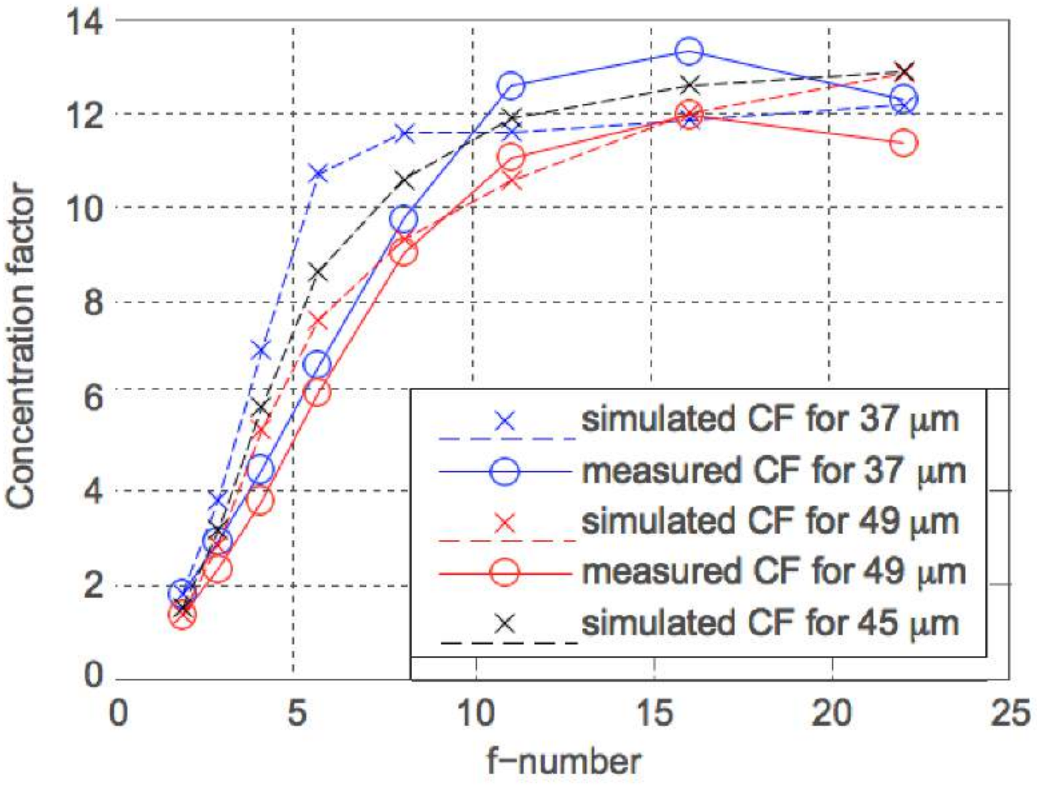


Fill Factor Recovery: Microlenses



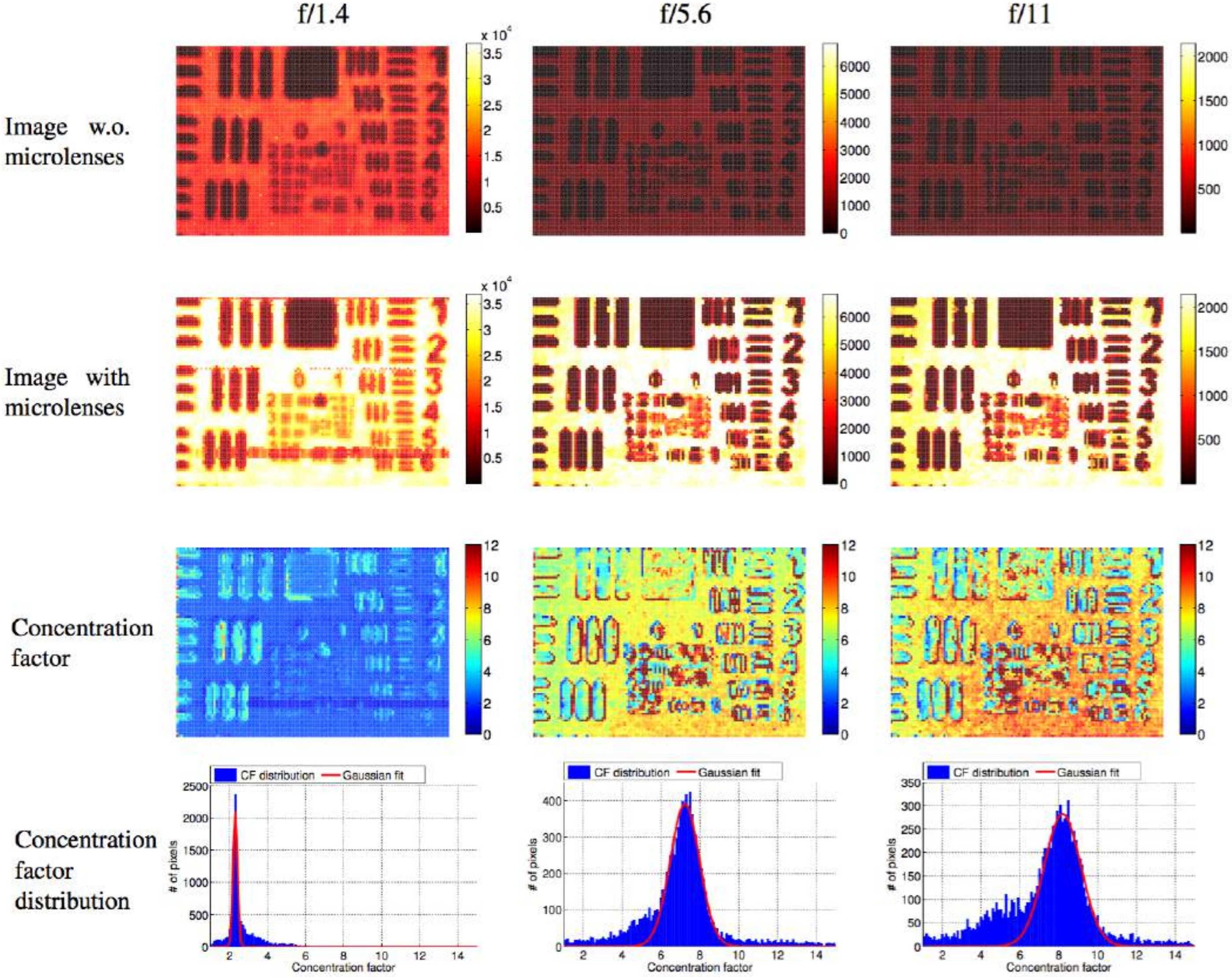
J. Mata Pavia *et al.*, *Optics Express,* 2014

Fill Factor Recovery: Microlenses



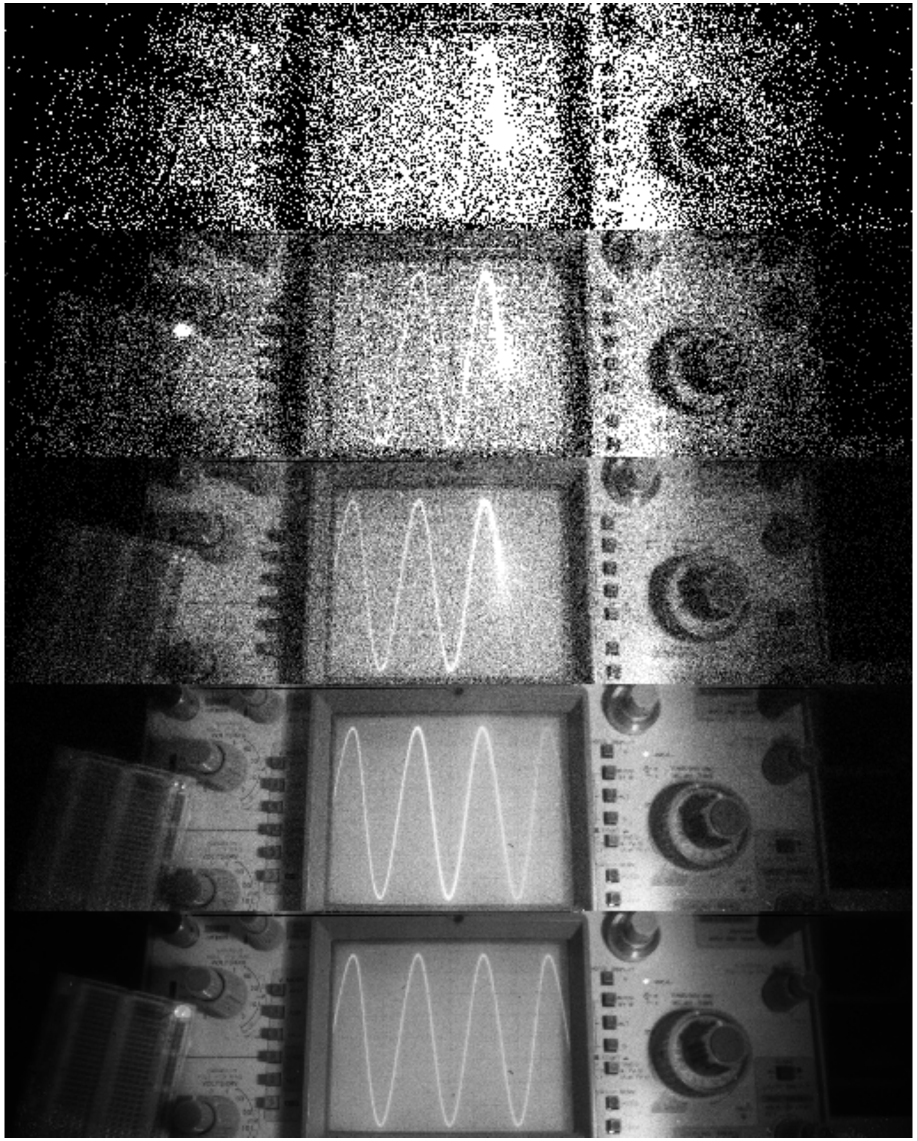
J. Mata Pavia *et al*., *Optics Express*, 2014

Fill Factor Recovery: Microlenses



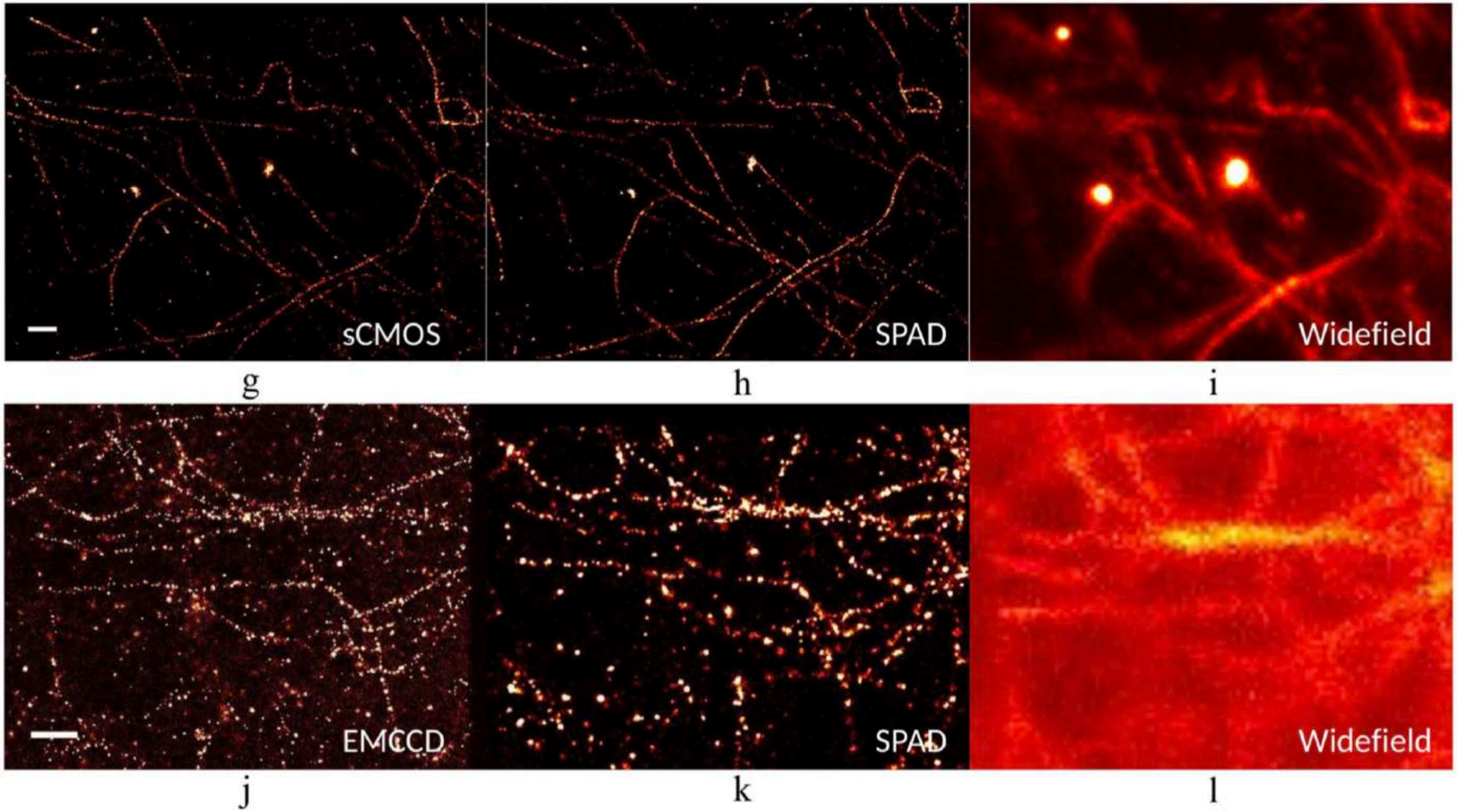
J. Mata Pavia *et al.*, *Optics Express*, 2014

SwissSPAD: Pixel Resolution vs. Speed



S. Burri *et al.*, *Optics Express*, 2014

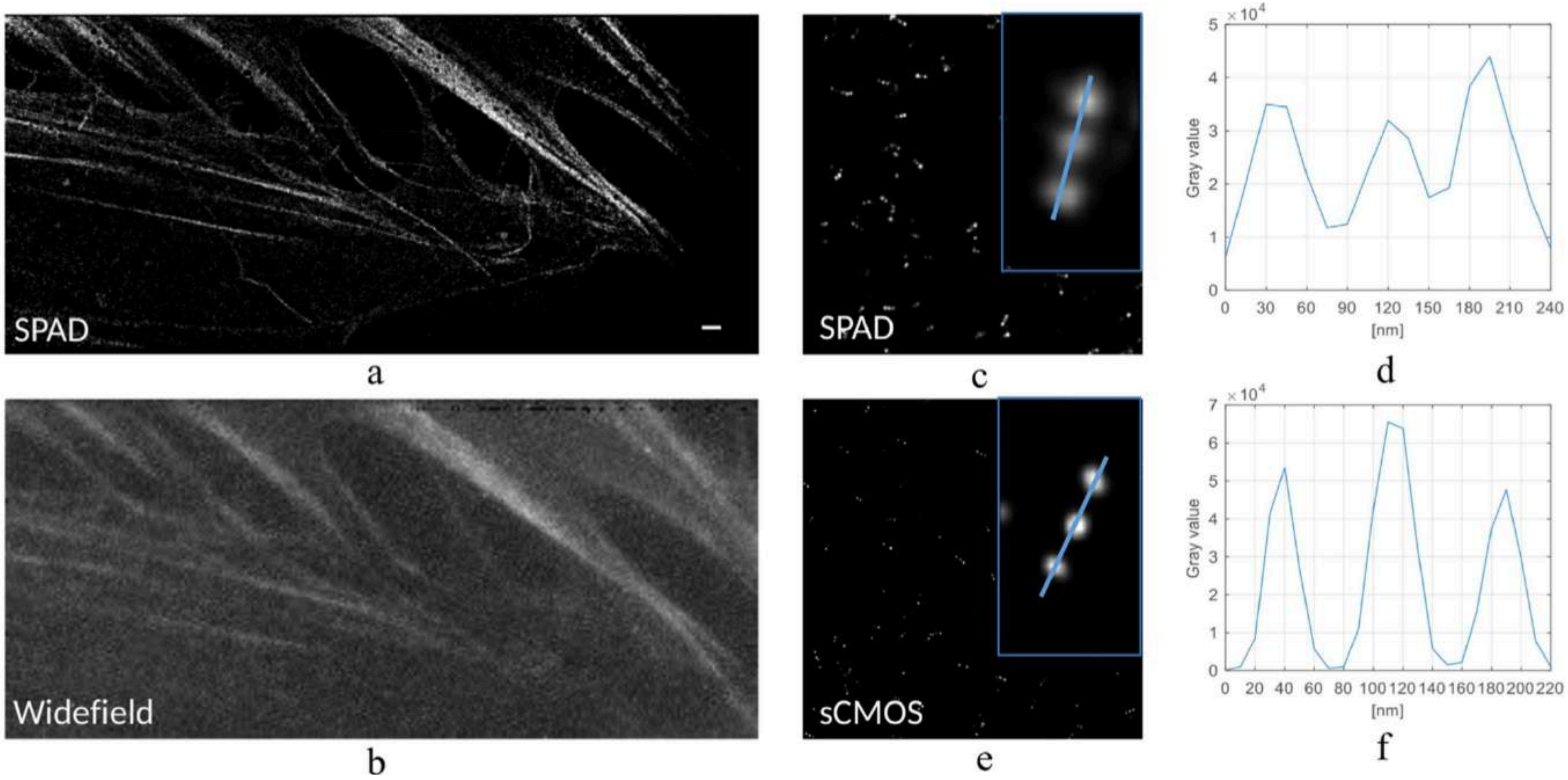
GSDIM Images



U2OS cells stained with Alexa 647, Vectashield buffer

I.M. Antolovic, S. Burri, R. Hoebe, Y. Maruyama, C. Bruschini, E. Charbon, *Nature Scientific Reports*, 2017

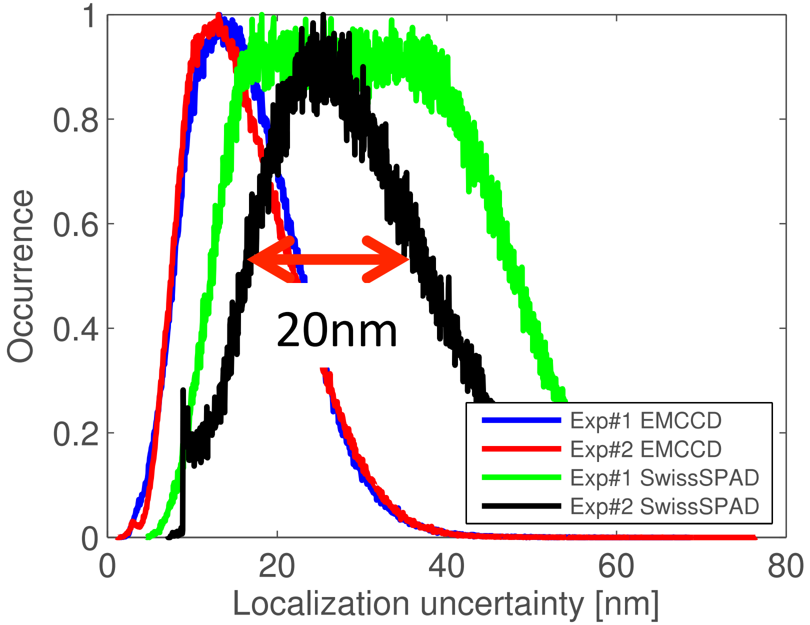
GSDIM Images

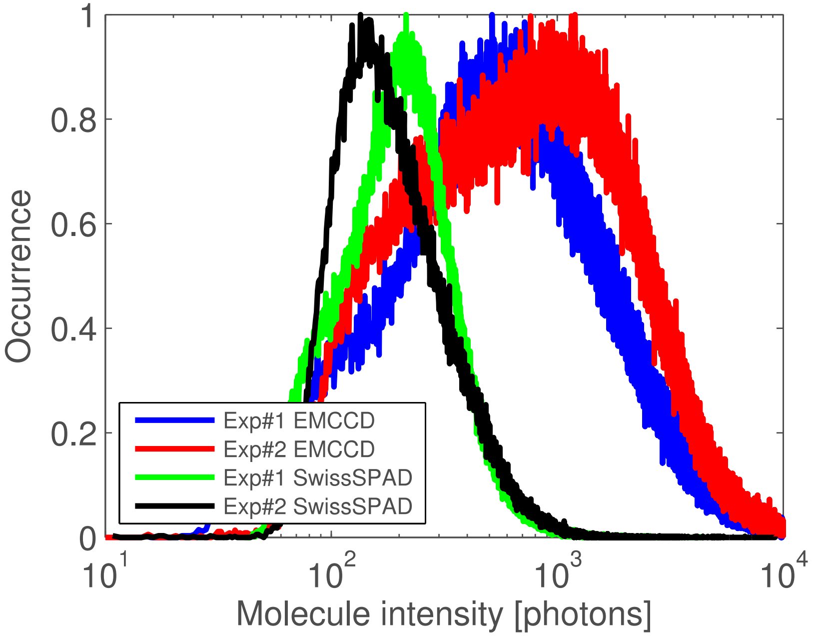


U2OS cells stained with Alexa 647, Vectashield buffer

I.M. Antolovic, S. Burri, R. Hoebe, Y. Maruyama, C. Bruschini, E. Charbon, *Nature Scientific Reports*, 2017

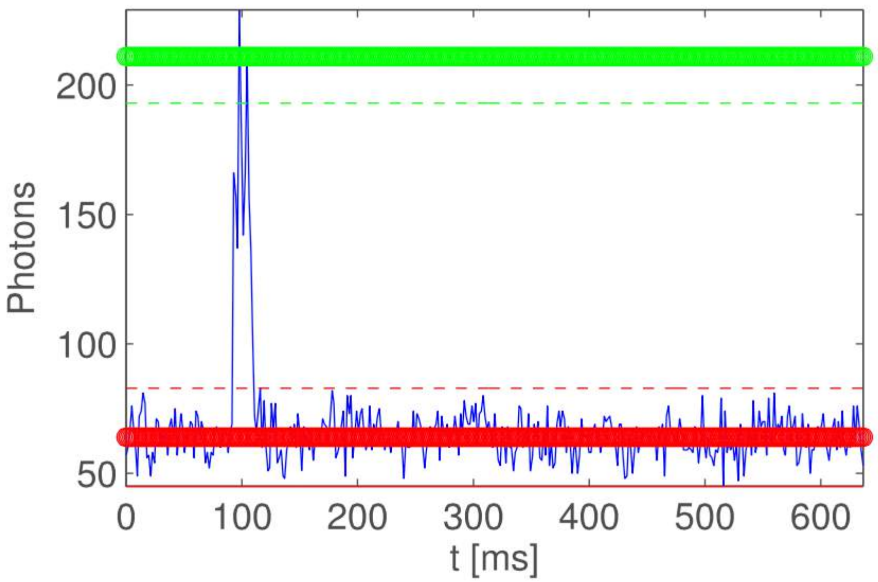
Localization Accuracy



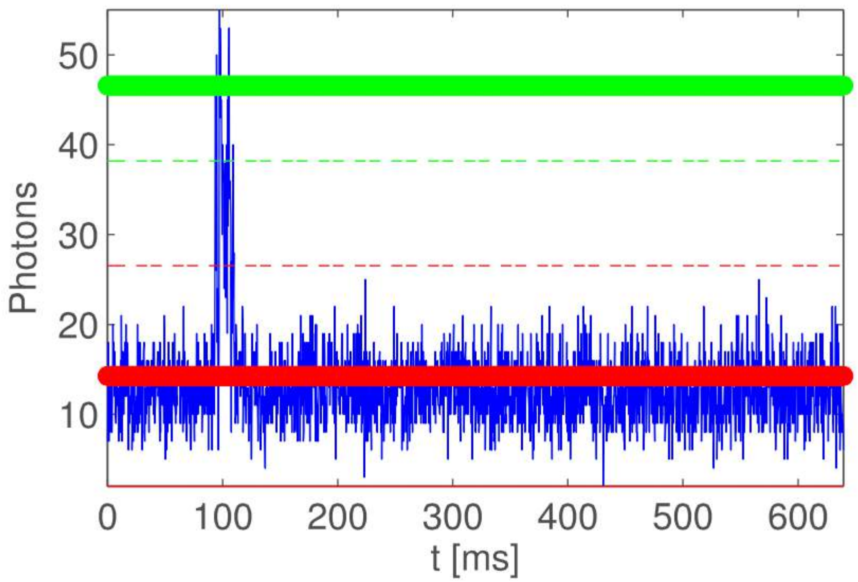


Blinking Statistics

- Blinking of molecules important signature
- Better resolution due to multiplication of CSDIM localizations



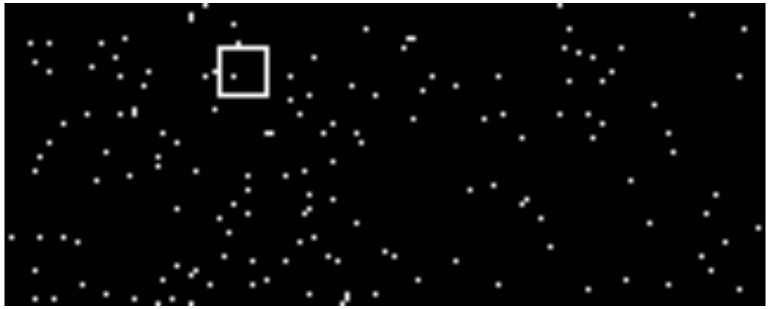
1.6ms resolution



0.3ms resolution

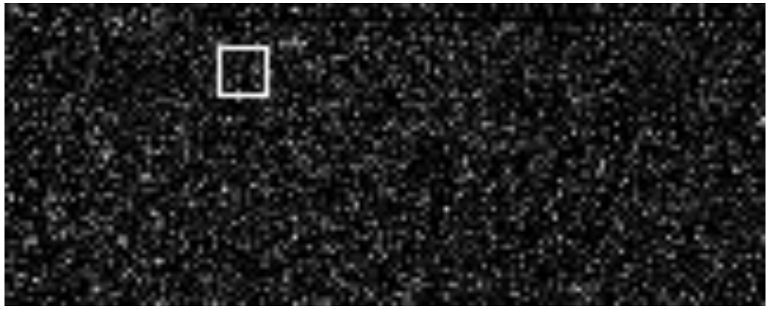
I.M. Antolovic, S. Burri, R. Hoebe, Y. Maruyama, C. Bruschini, E. Charbon, *MDPI Sensors*, **16**, 1005, 2016

Blinking Effects

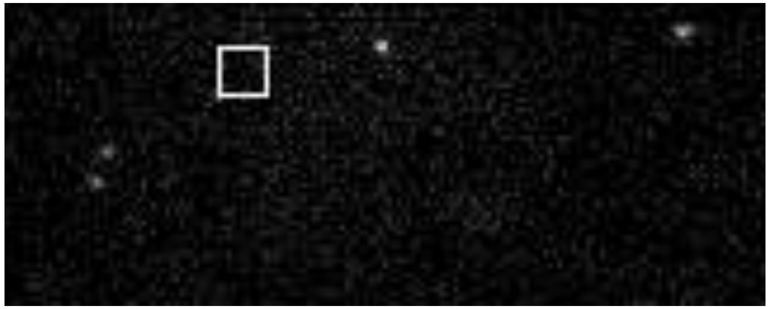


6.4 μs frame time

1.6 ms frame time

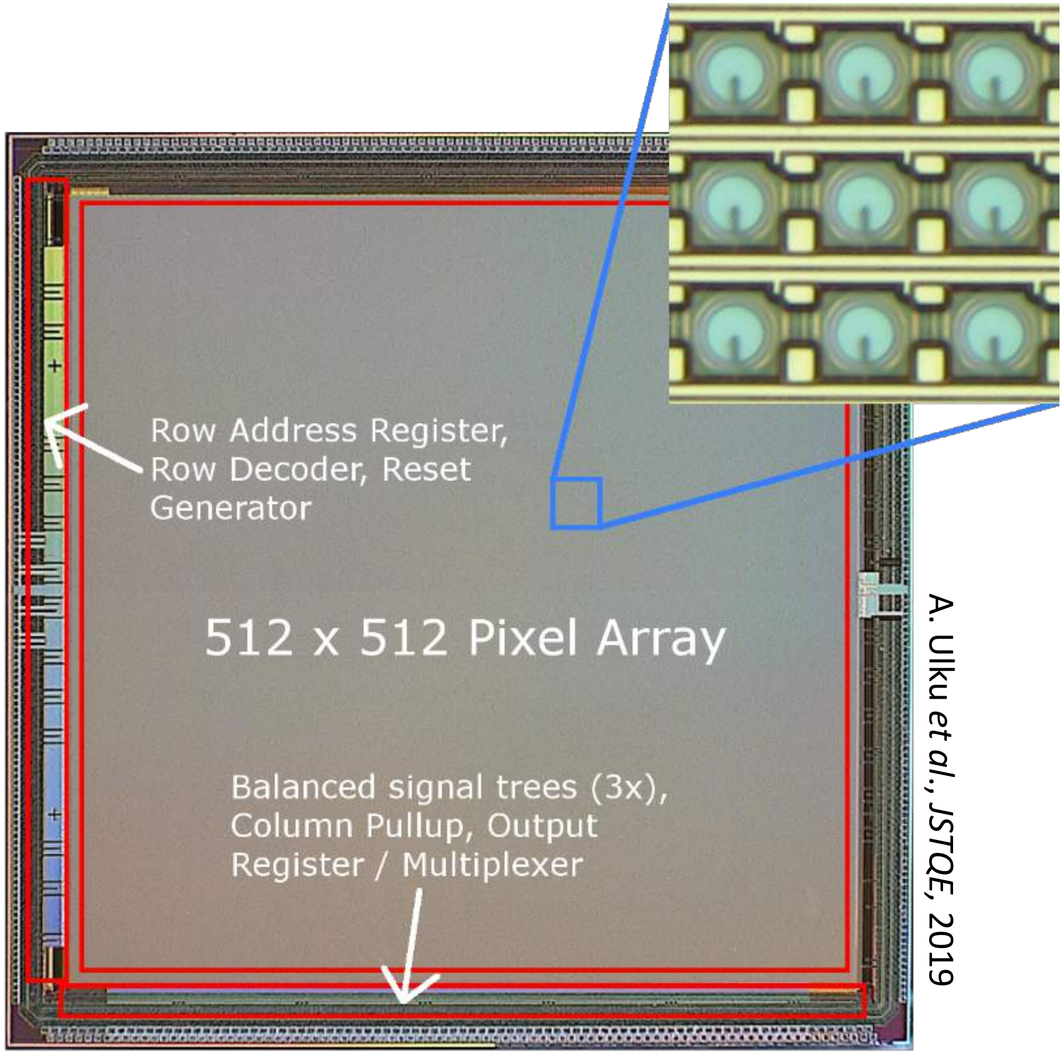


0.3 ms frame time



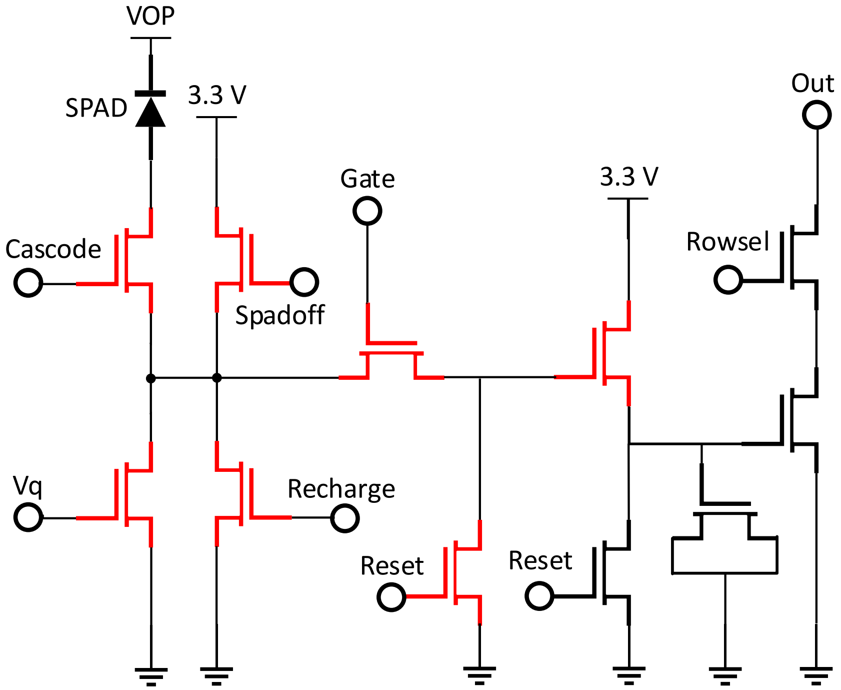
10 ms frame time

SwissSPAD-2



A. Ulku *et al., JSTQE*, 2019

SwissSPAD-2 Pixel

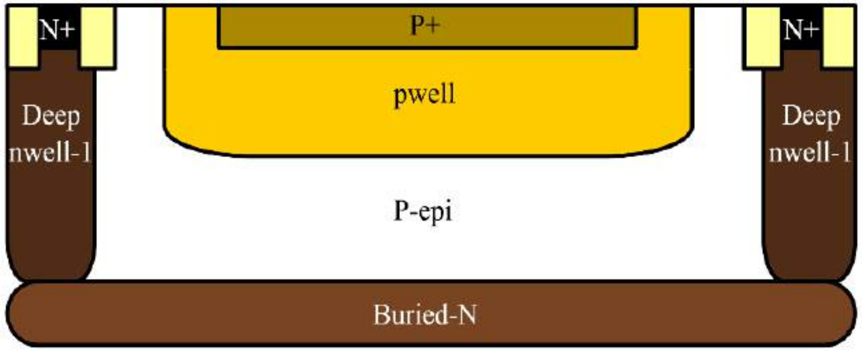


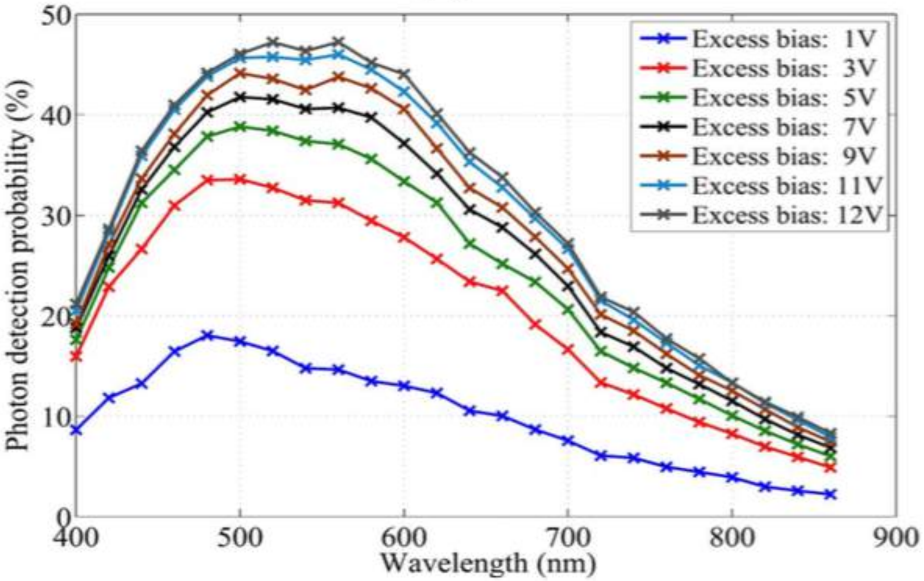
Pixel Features:

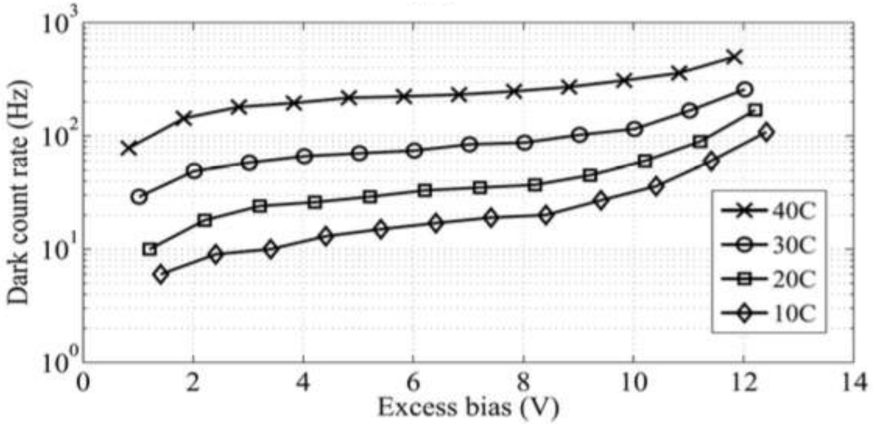
- **Passive quenching**
- **Cascode transistor:**
  - **Excess bias up to 6.6**
  - **Higher PDP**
- **Active recharge**
- **Time gating**
- **Memory reset**
- **1-bit DRAM**
- **Row selection**

SwissSPAD-2 Pixel

- 512x512 SPAD pixels
- 2x fill factor
- 5x less DCR
- 2x more PDP
- Better uniformity, crosstalk
- Equal readout speed, gating

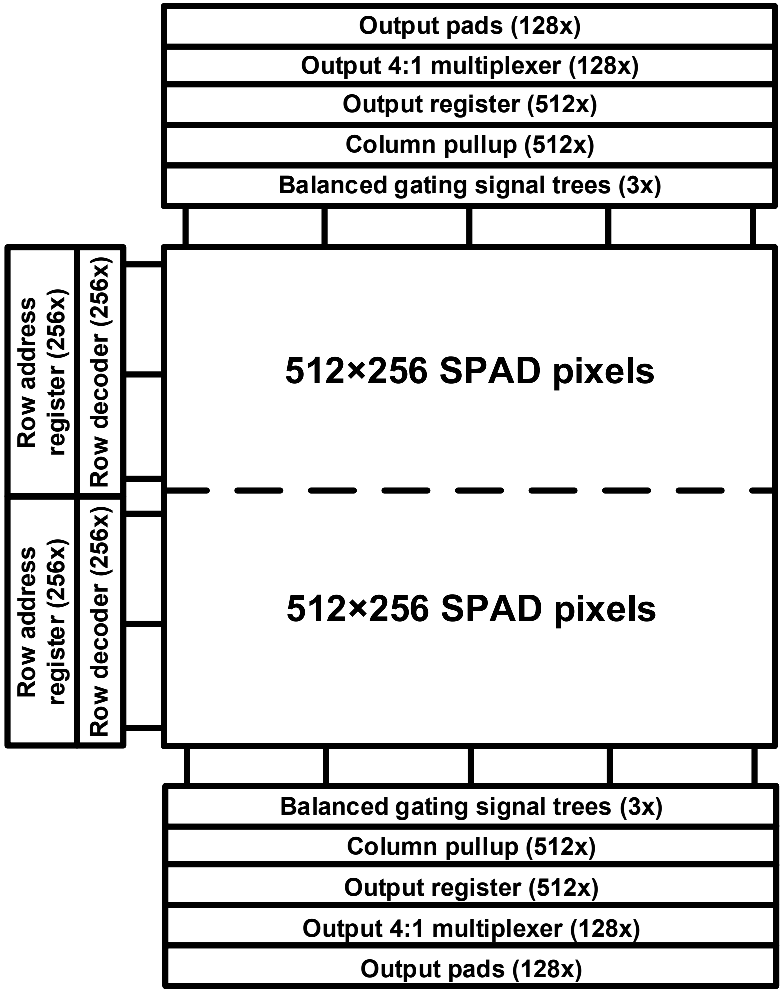






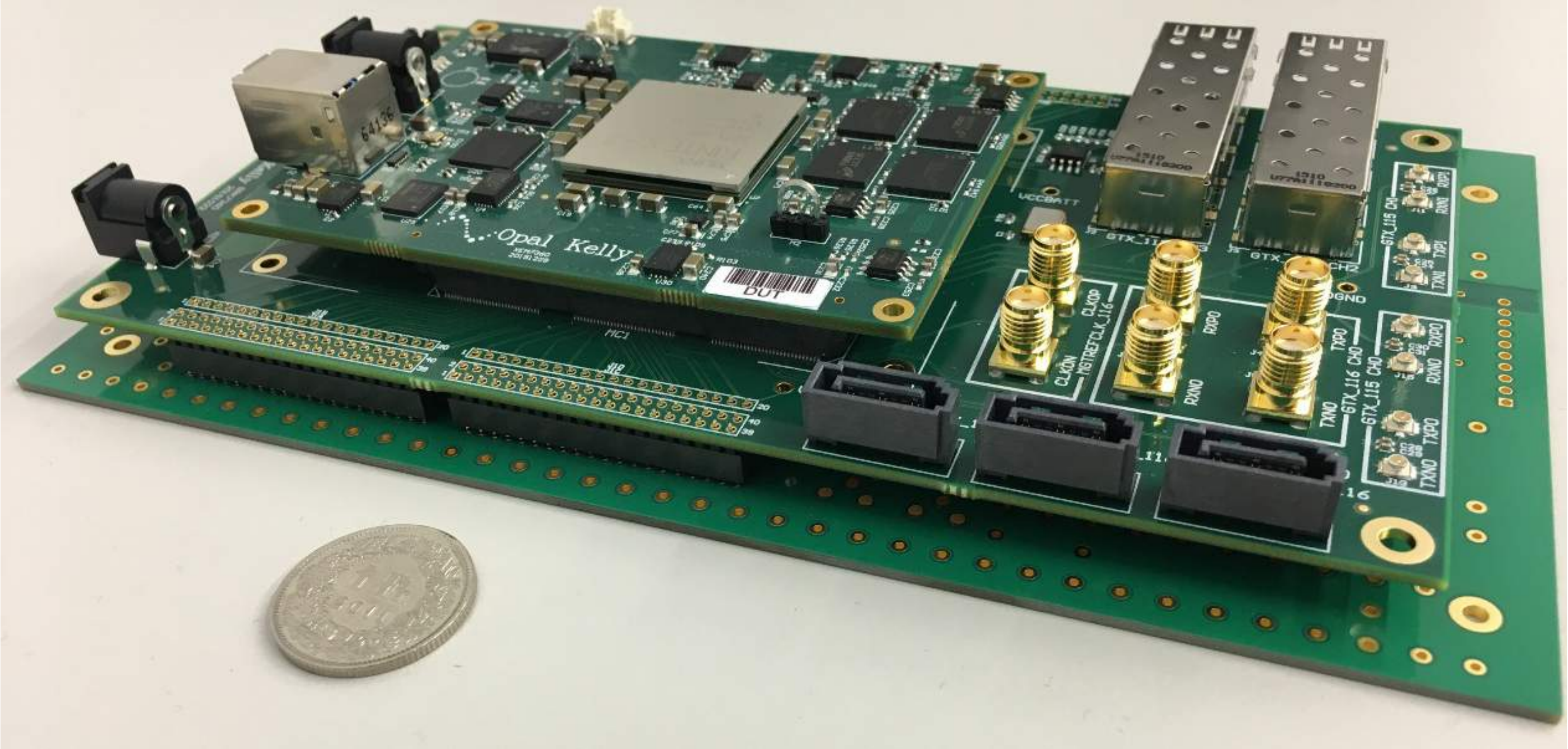
A. Ulku *et al.*, *JSTQE,* 2019

SwissSPAD-2 Architecture



Number of Pixels	**512×512**
Process	**0.18 μm CMOS**
Chip Size	**9.5×9.6 mm**
Pixel Pitch	**16.38 μm**
Fill Factor	**10.5%**
Max. Frame Rate (1-bit)	**97.7 kfps**
Max. PDP	**55% (V_{ex} = 11 V, λ = 520 nm)**
Dark Count Rate	**0.18 Hz/μm^2 (V_{ex} = 3 V)** **1.67 Hz/μm^2 (V_{ex} = 11 V)**
Gate Jitter	**110 ps**

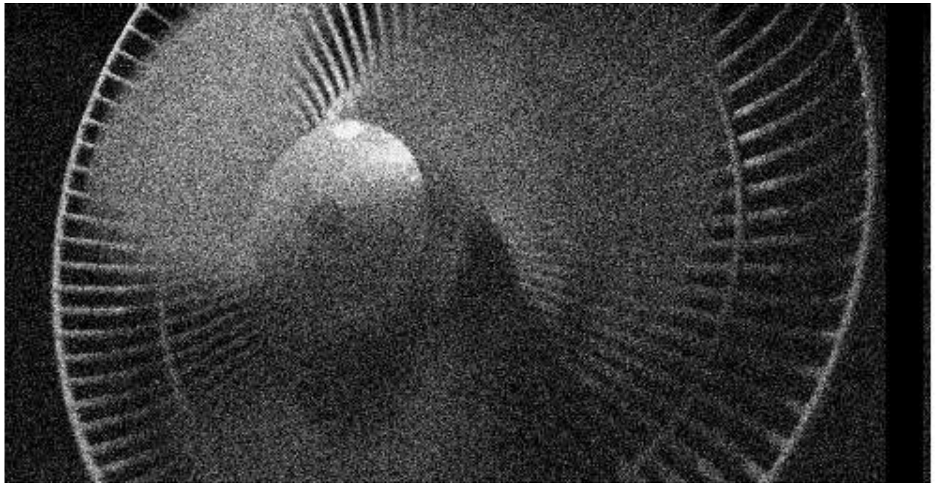
SwissSPAD-2 System



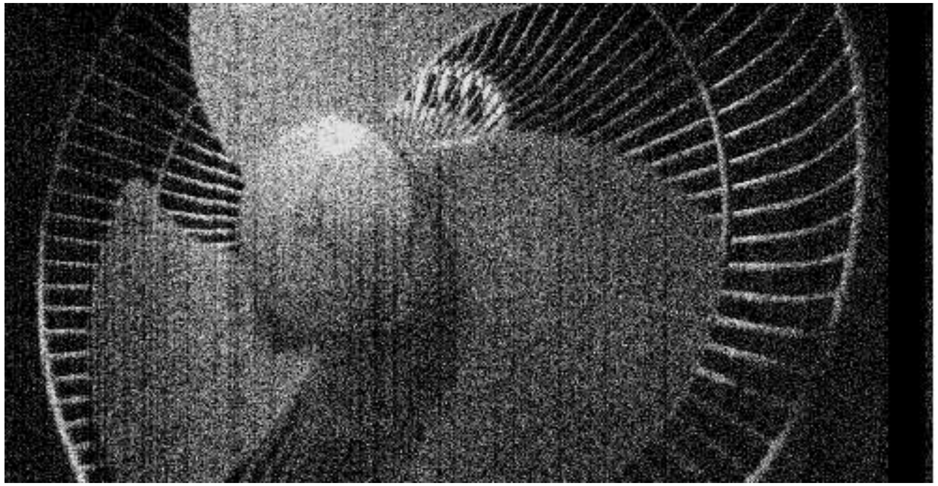
A. Ulku *et al.*, *IISW,* 2017

SwissSPAD-2 Gating Trials

10kfps, 3 bits

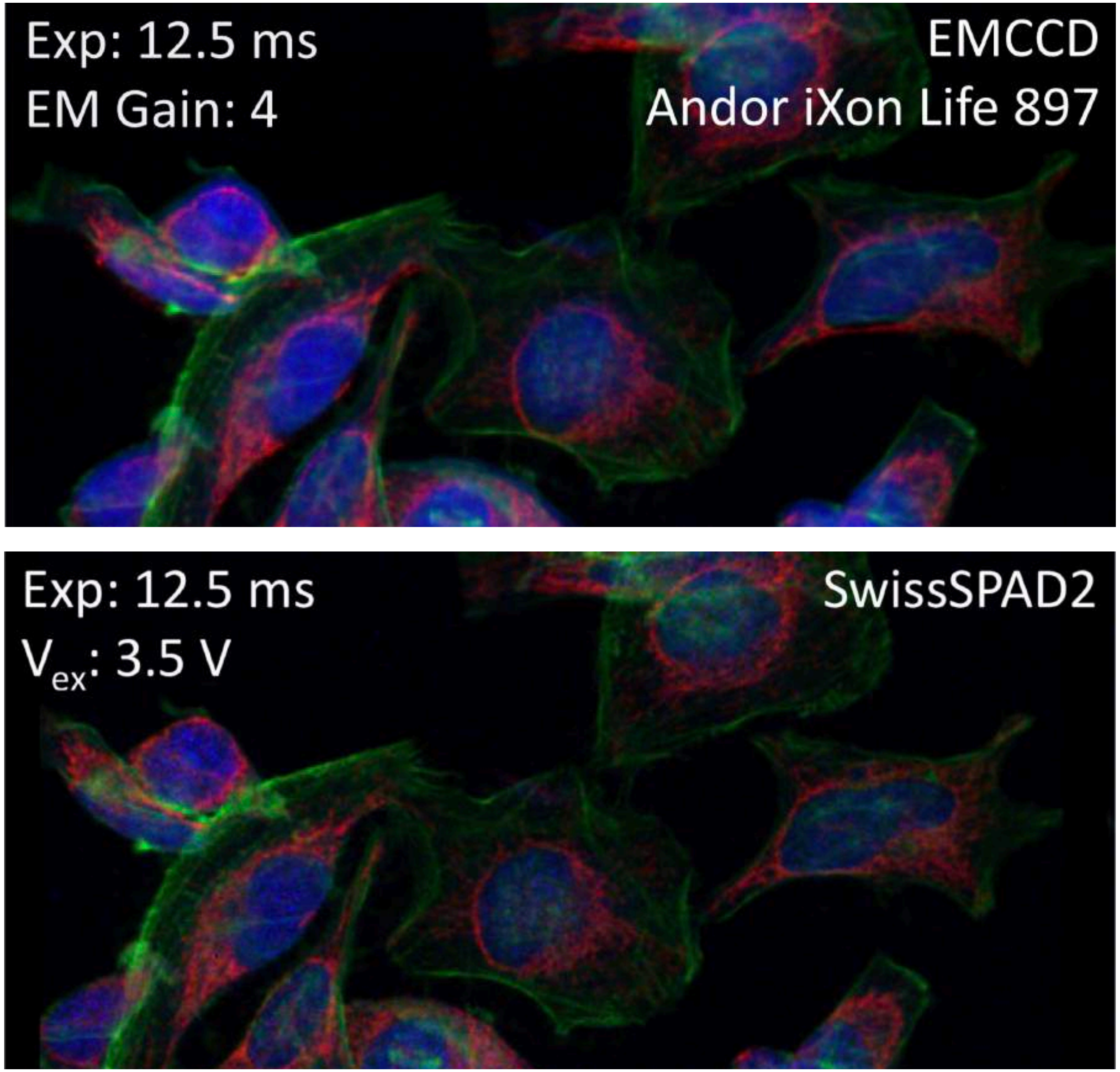


100kfps, 1 bit



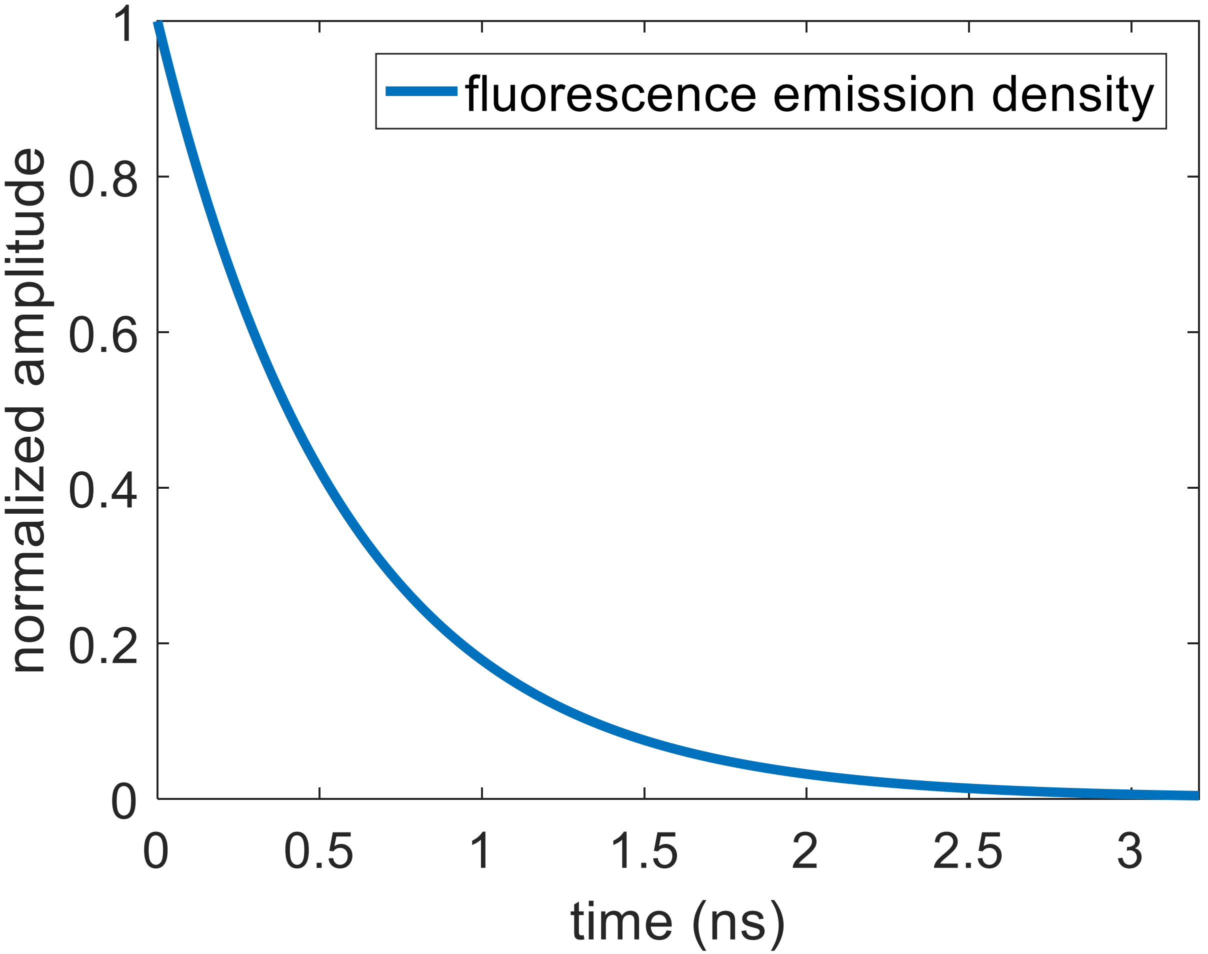
A. Ulku *et al.*, talk at *IISW* 2017

Comparison with EMCCD

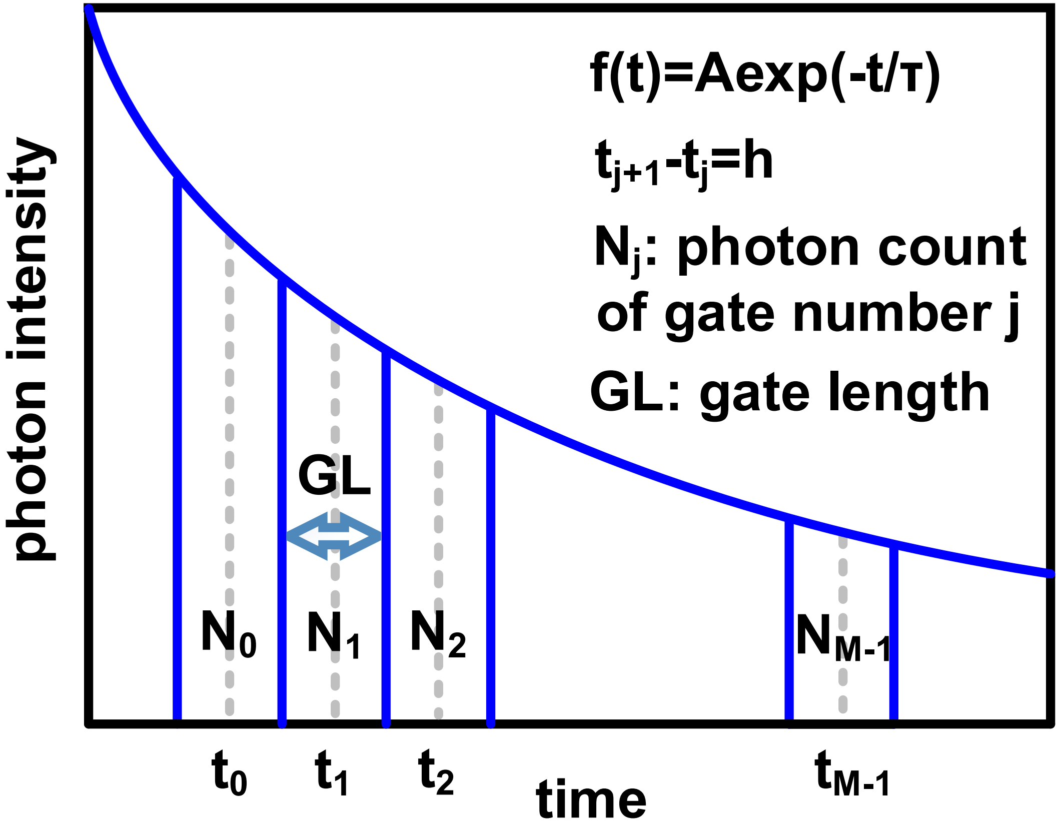


A. Ulku *et al.*, *JSTQE*, 2019
HeLa cells labeled with DAPI Alexa 488 and Alexa 555

Fluorescence Lifetime Imaging Microscopy (FLIM)



FLIM via Gating



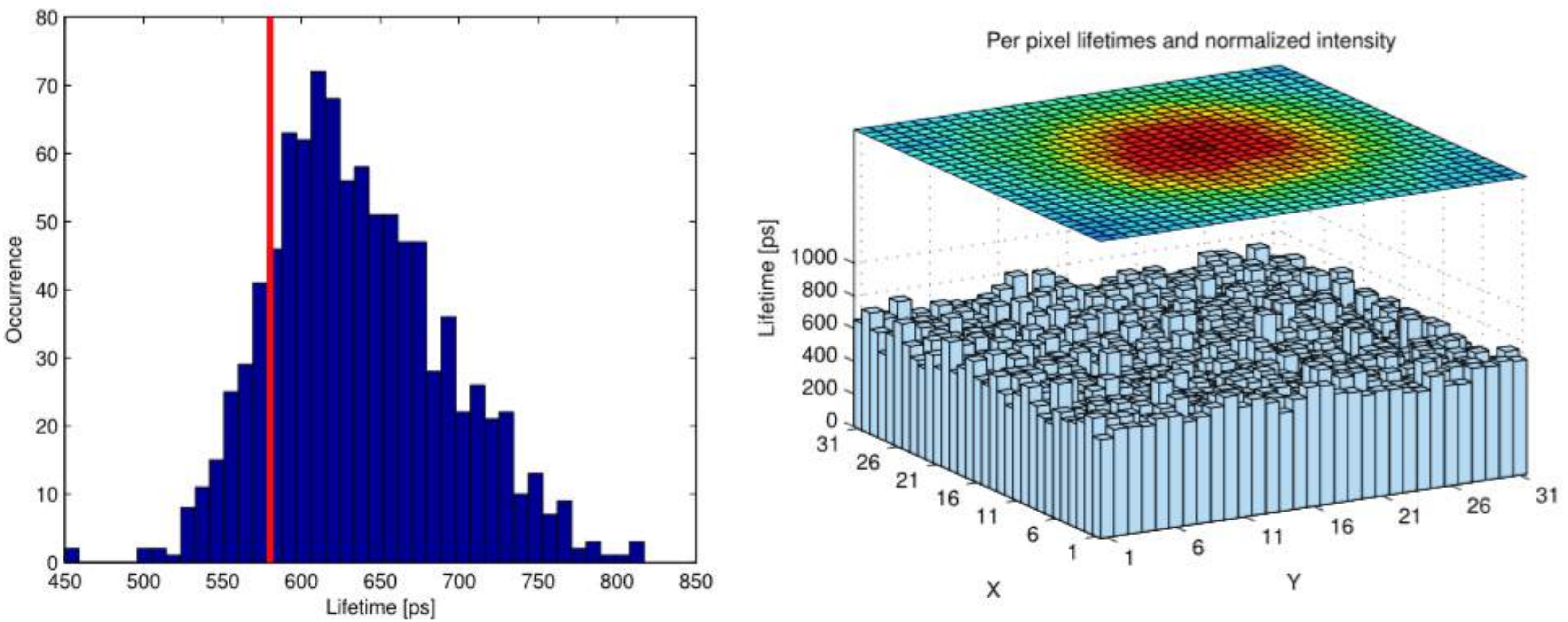
$f(t)=A\exp(-t/\tau)$

$t_{j+1}-t_j=h$

N_j: photon count of gate number j

GL: gate length

FLIM Histograms

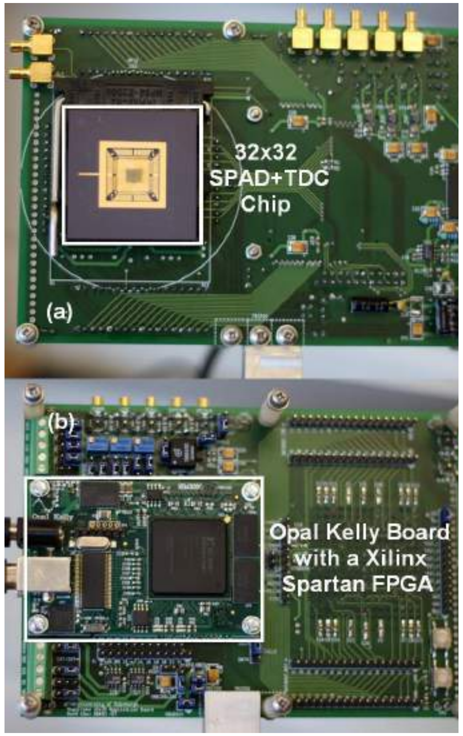


(a) (b)

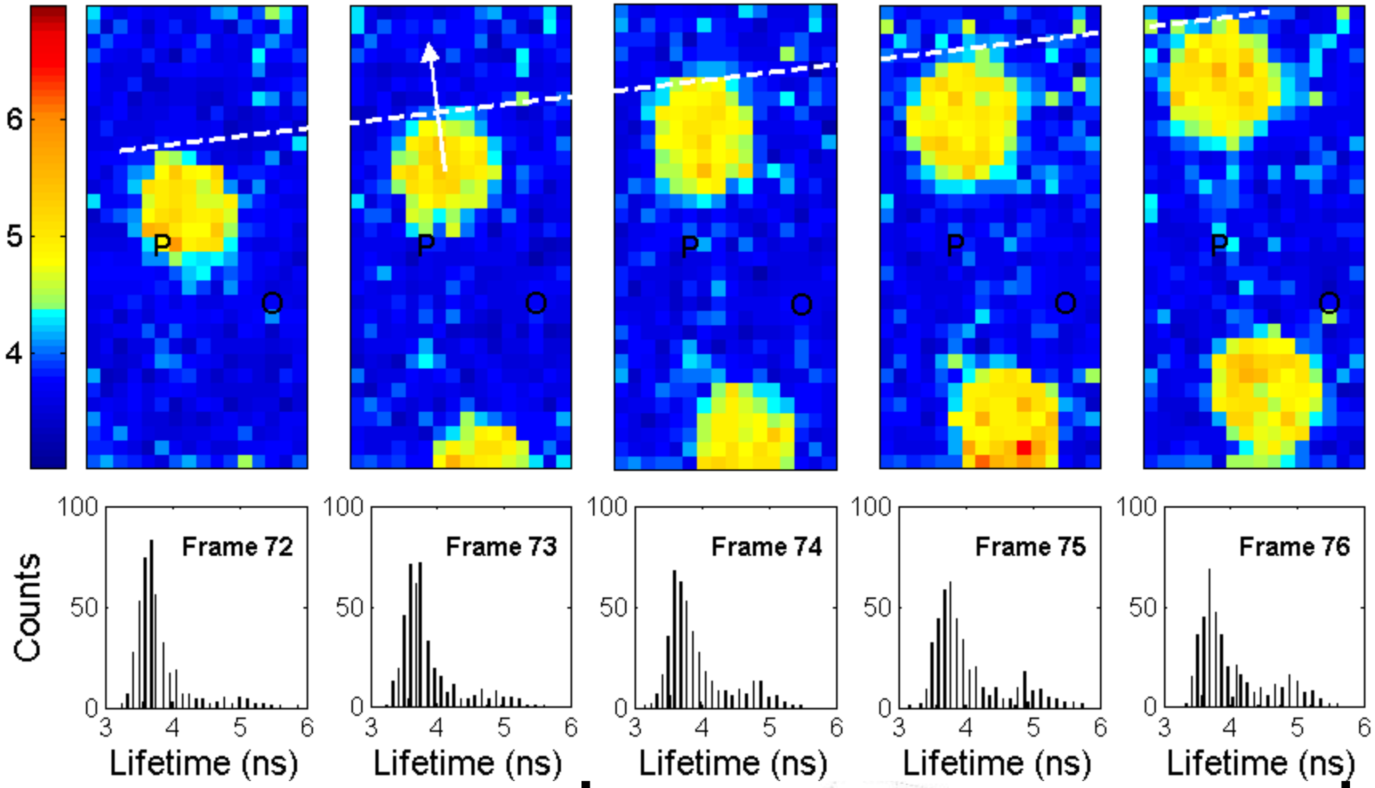
Figure 19. (**a**) FLIM results show extracted lifetimes distribution of 31 × 31 pixels compared to reference lifetime of 40 μM ICG in milk (red). (**b**) shows the comparison of intensity and lifetime per pixel.

I.M. Antolovic, S. Burri, R. Hoebe, Y. Maruyama, C. Bruschini, E. Charbon, *MDPI Sensors*, **16**, 1005, 2016

Video-rate FLIM (> 100fps)



Li et al., 2011, 2012
Arlt et al., 2013

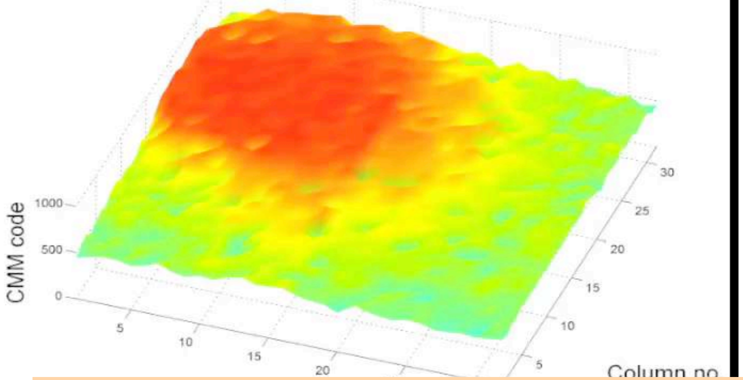


Fast FLIM:

$$\tau = \frac{\sum_{i=1}^{N_C} t_i}{N_C}, N_C = \sum_{j=1}^{M} N_j$$

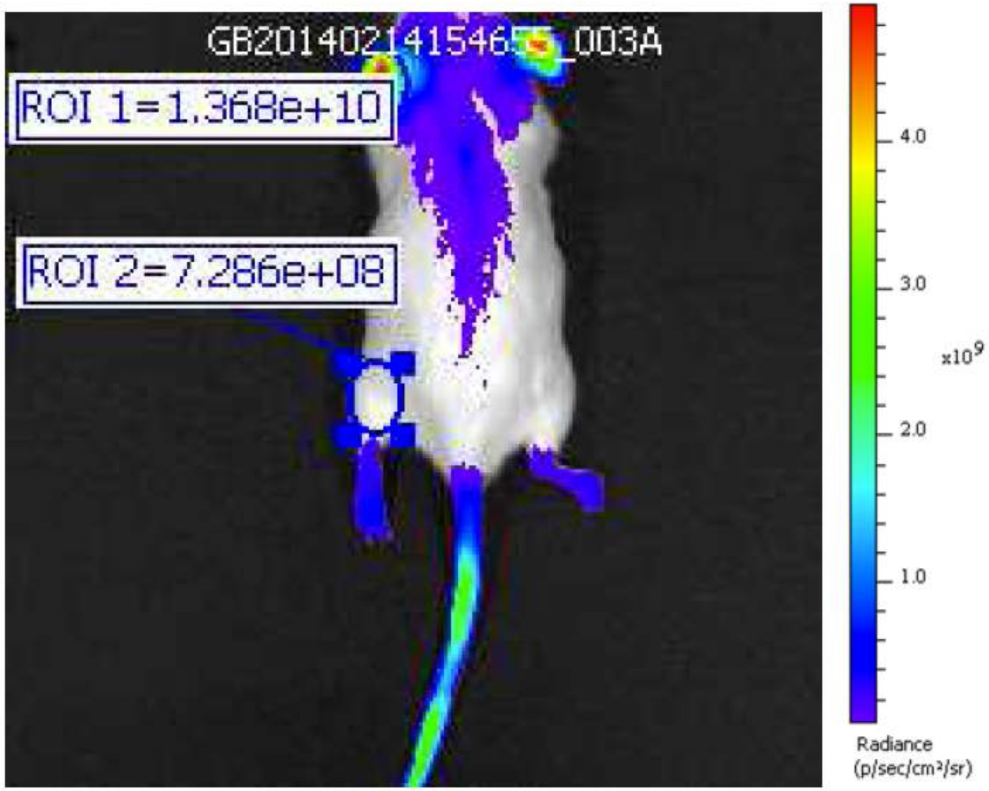
Raw TCSPC data: 640Mb/s

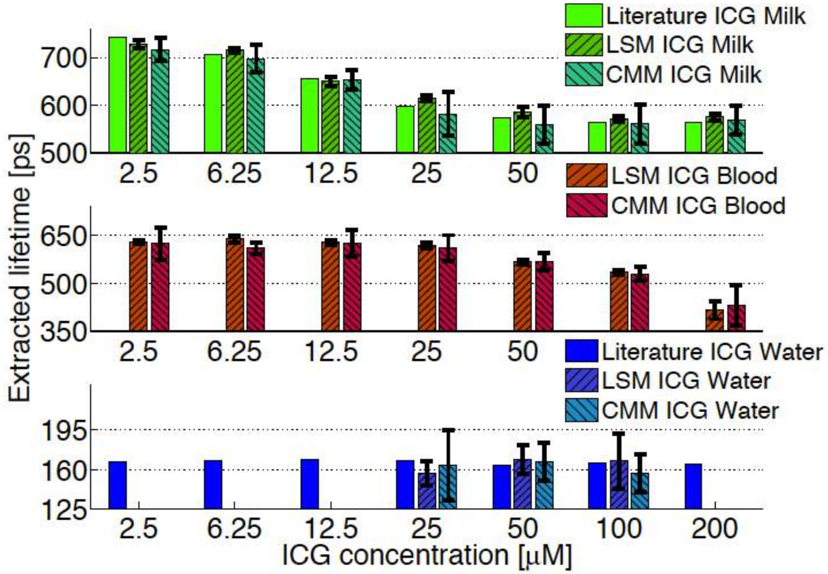
FLIM data: 20Mb/s, No FLIM software.



Courtesy David Li, Strathclyde Univ., 2016

In Vivo ICG Lifetime Measurements



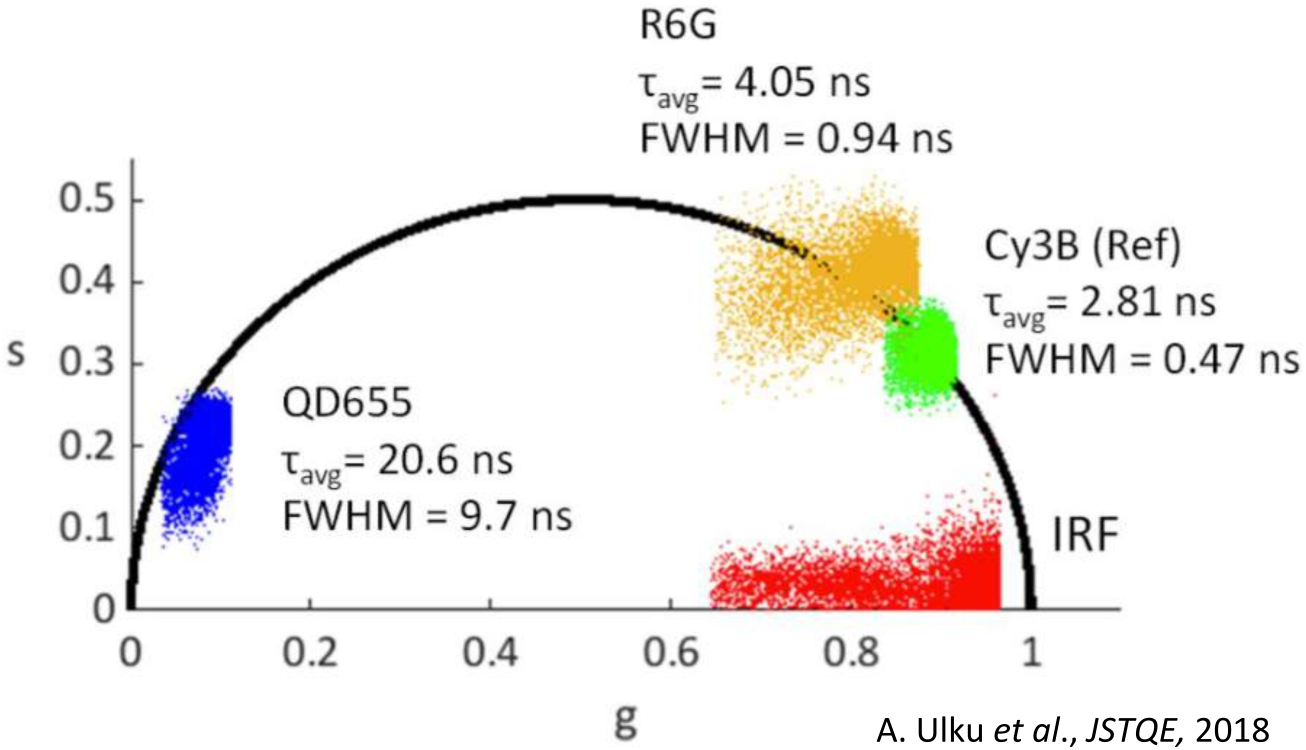


H. Homulle *et al.*, *Biomedical Optics Express,* 2015

- Comparison with literature lifetime
- Use of ICG in models for cancer enhancement

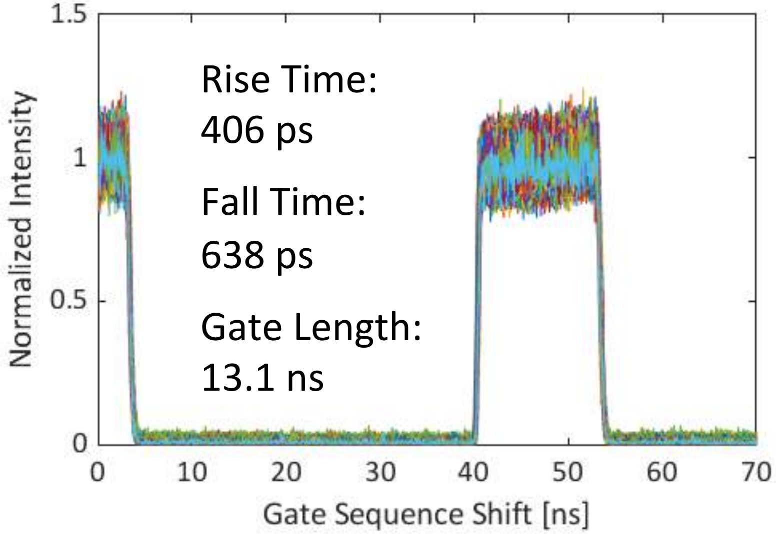
Phasor Representation

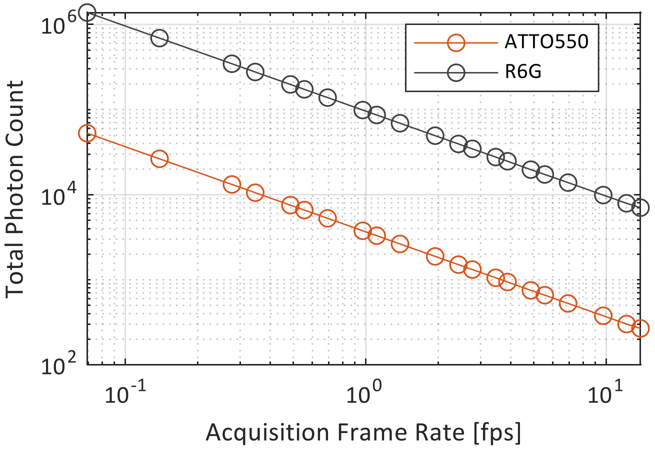
- Cosine transform of lifetime
- 2D representation of multiple fluorophores
- Easy interpretation of non-radiative energy transfer (FRET)

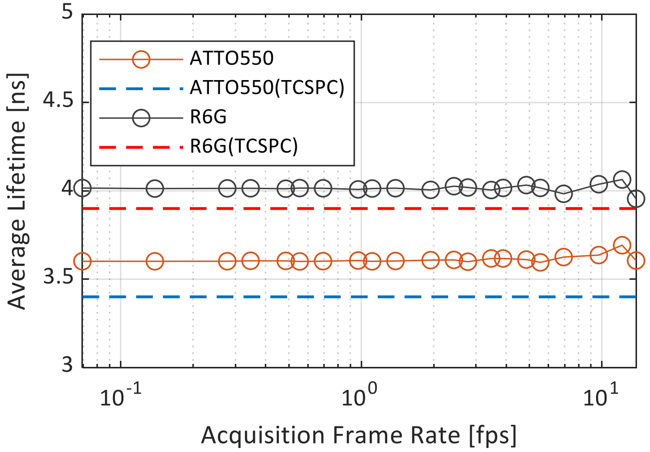


A. Ulku *et al.*, *JSTQE,* 2018

SwissSPAD-2 Gating Trials





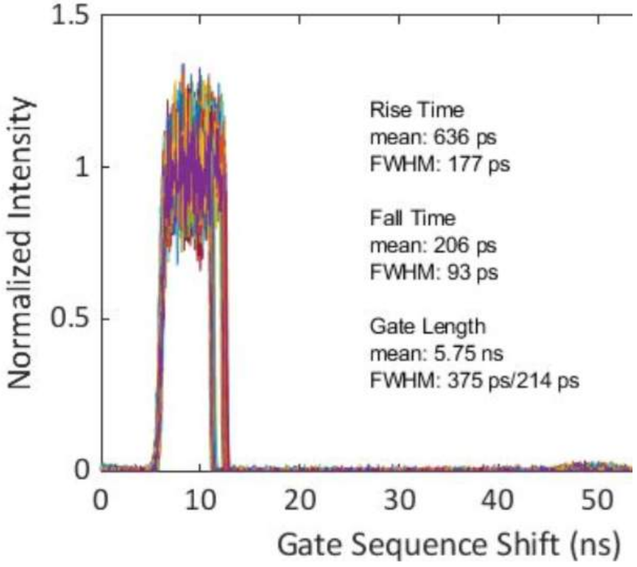


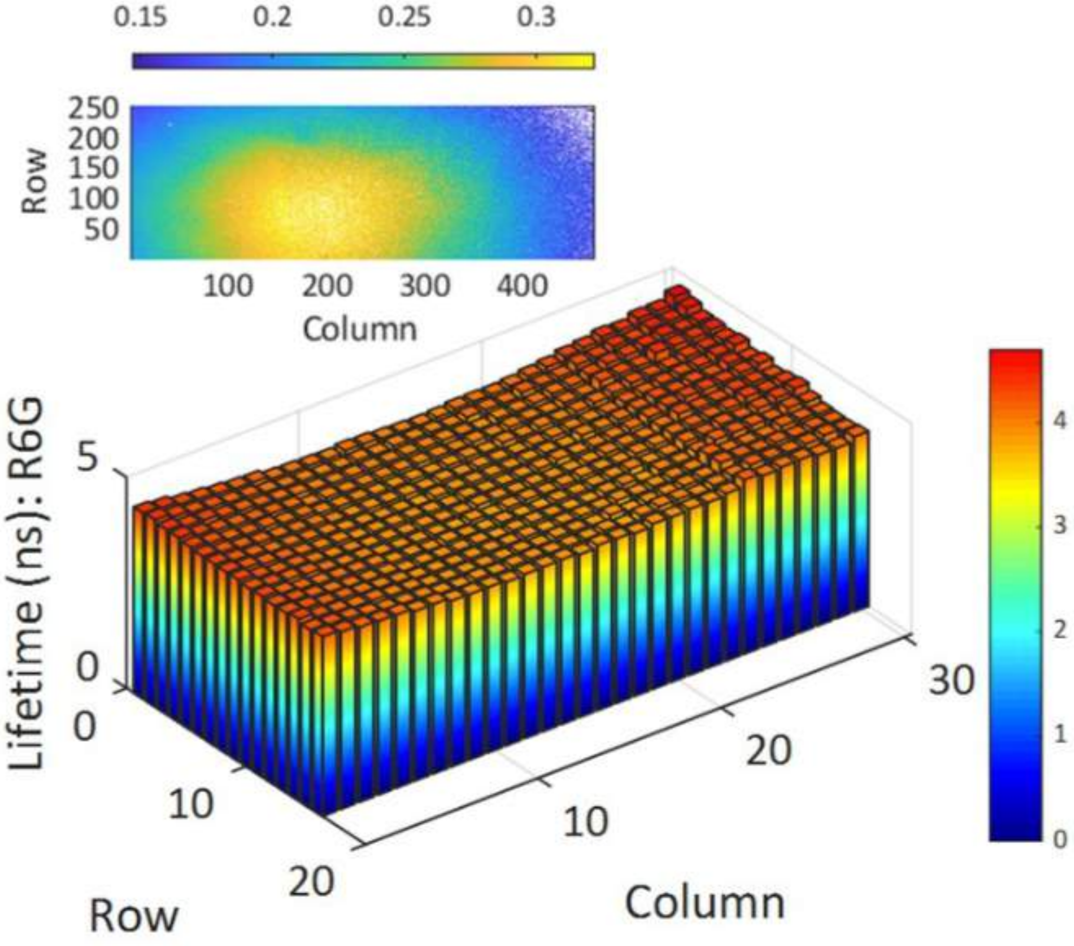
Bit Depth: 8 (Ref: 10)
Array: 472×256
Binning: 4×4
Binned Format: 118×64

Gate Length: 13.5 ns
Laser PRF: 20 MHz
Hot Pixel Removal: 1%

A. Ulku, C. Bruschini, I.M. Antolovic, S. Weiss, X. Michalet, E. Charbon, *SPIE Photonics West*, 2019

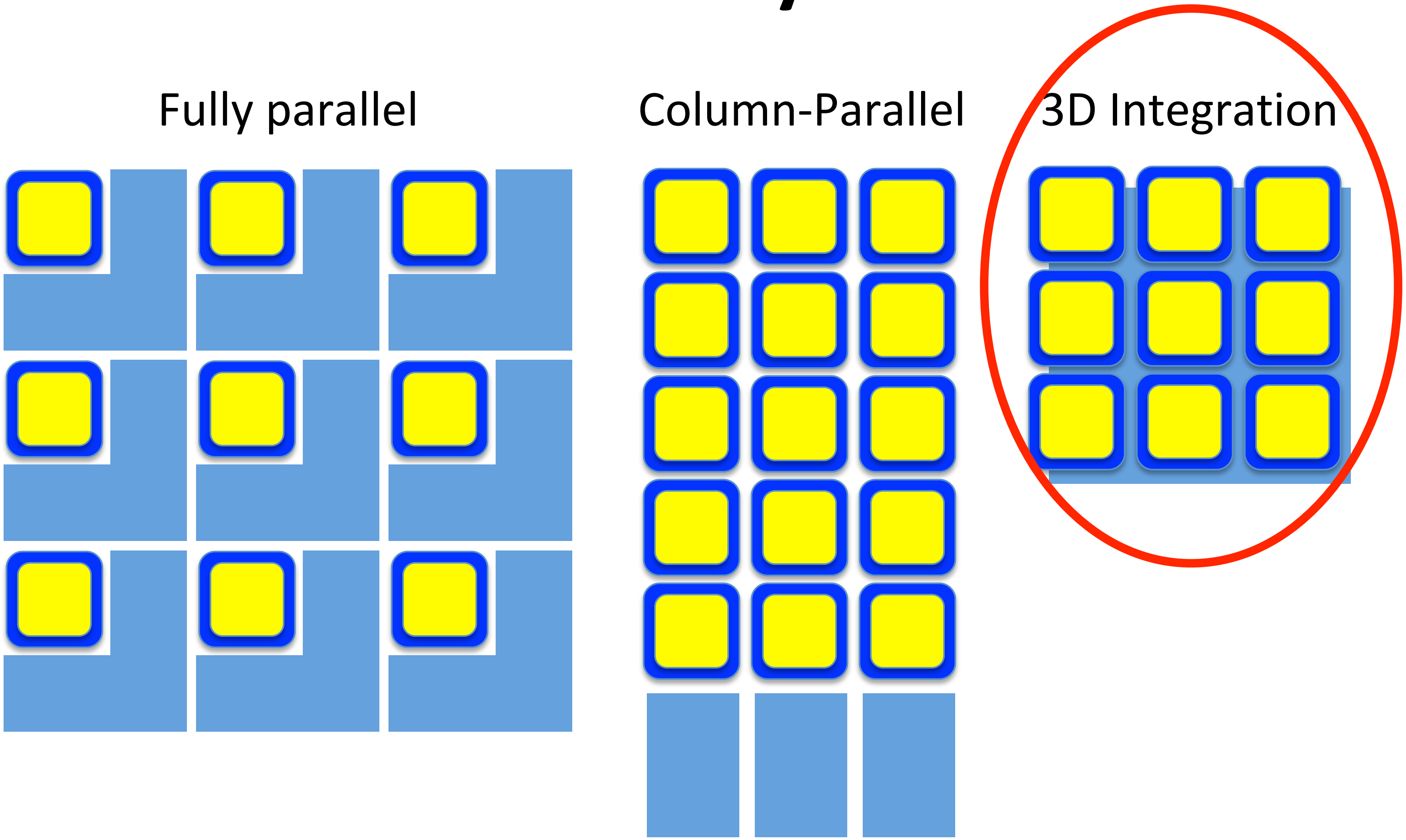
Lifetime Stability with Short Gates





A. Ulku *et al.*, *JSTQE* 2018

2D Arrays

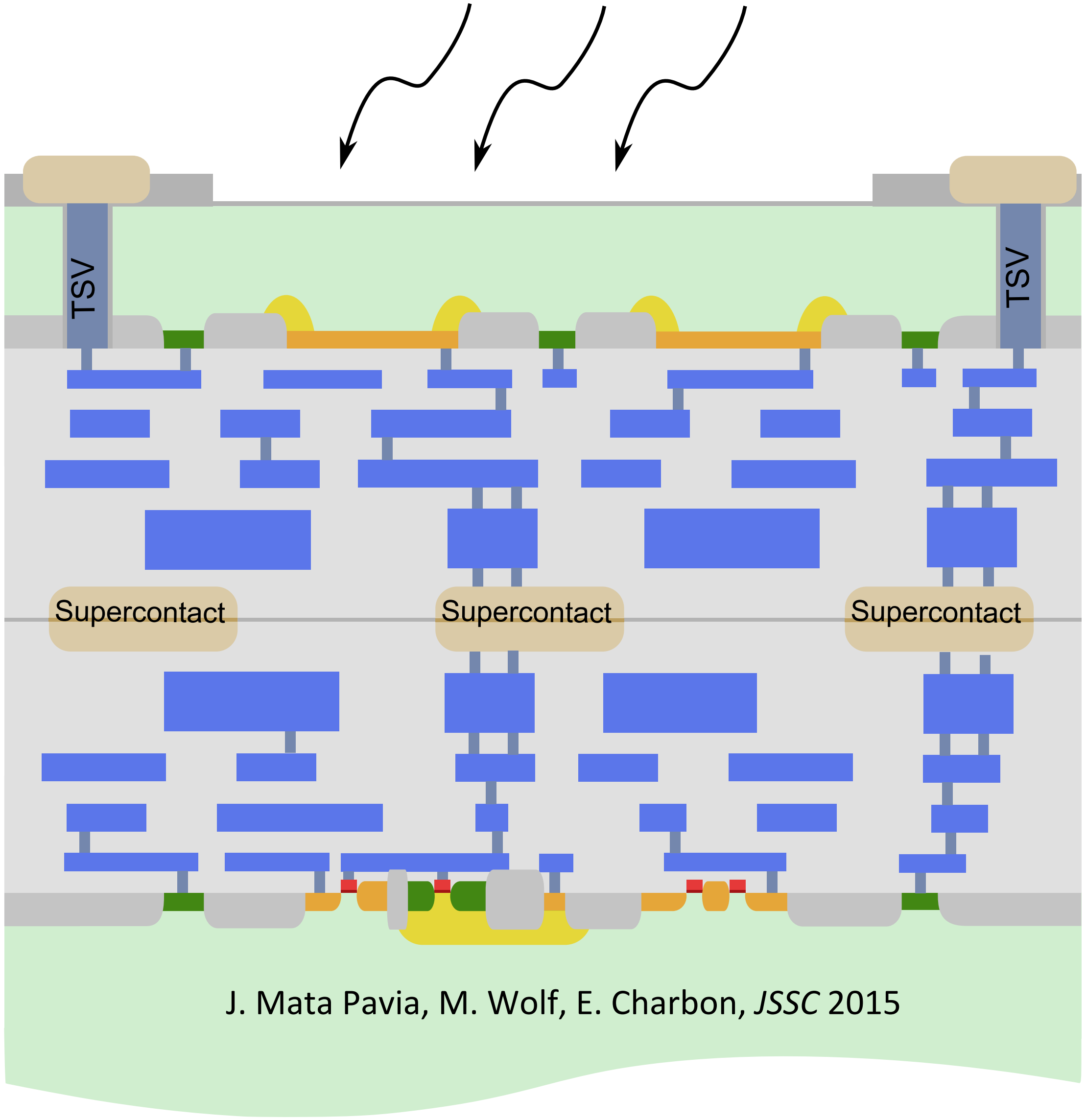


Fully parallel

Column-Parallel

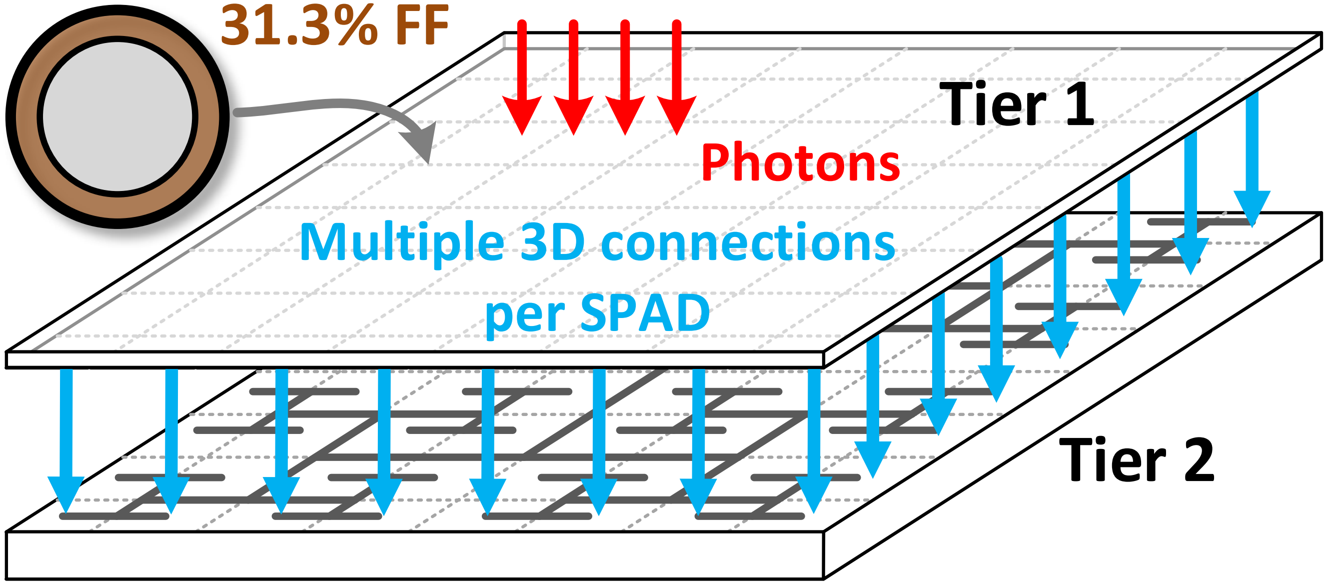
3D Integration

Backside Illumination (BSI)



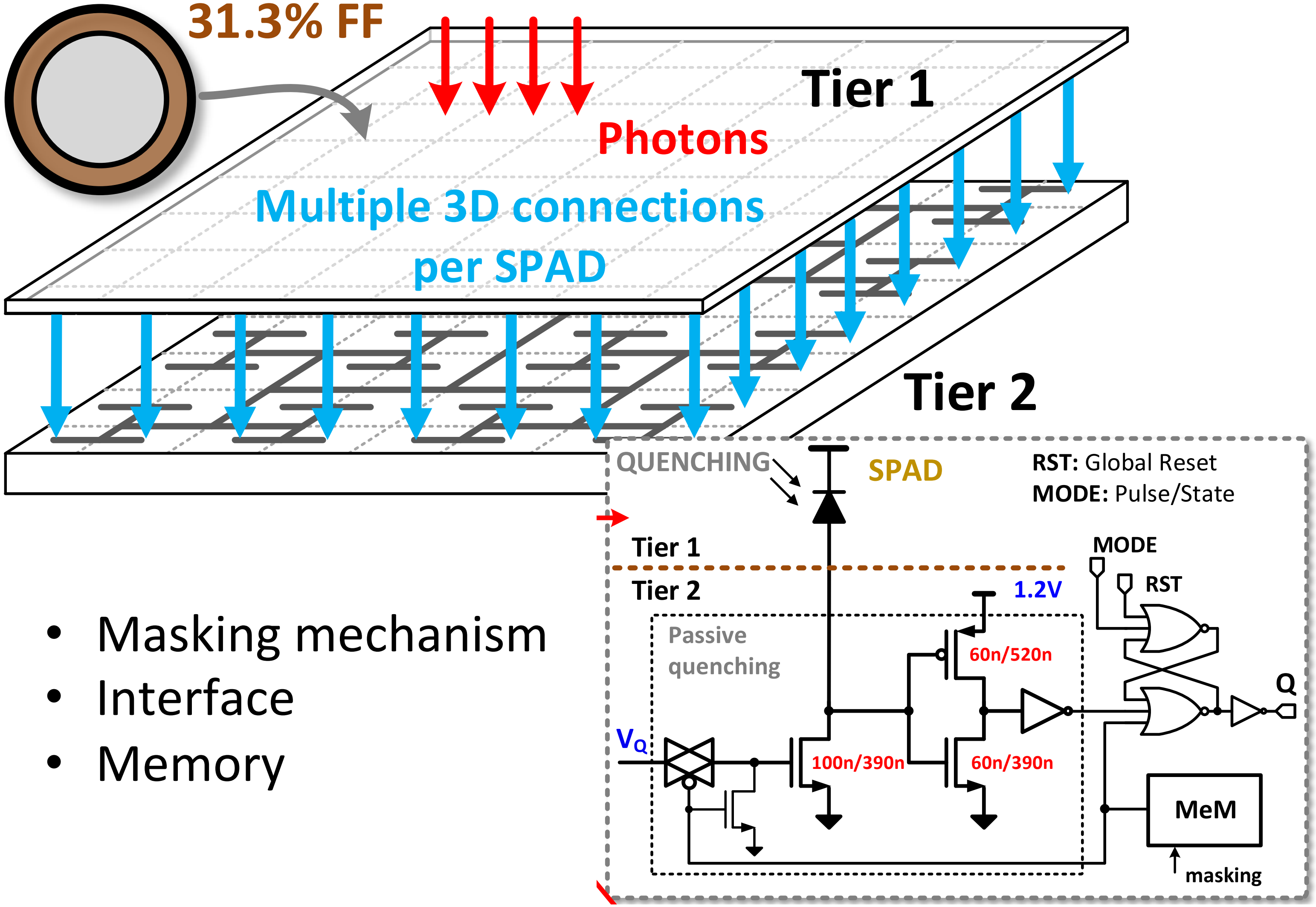
J. Mata Pavia, M. Wolf, E. Charbon, *JSSC* 2015

BSI + 3D-Stacking



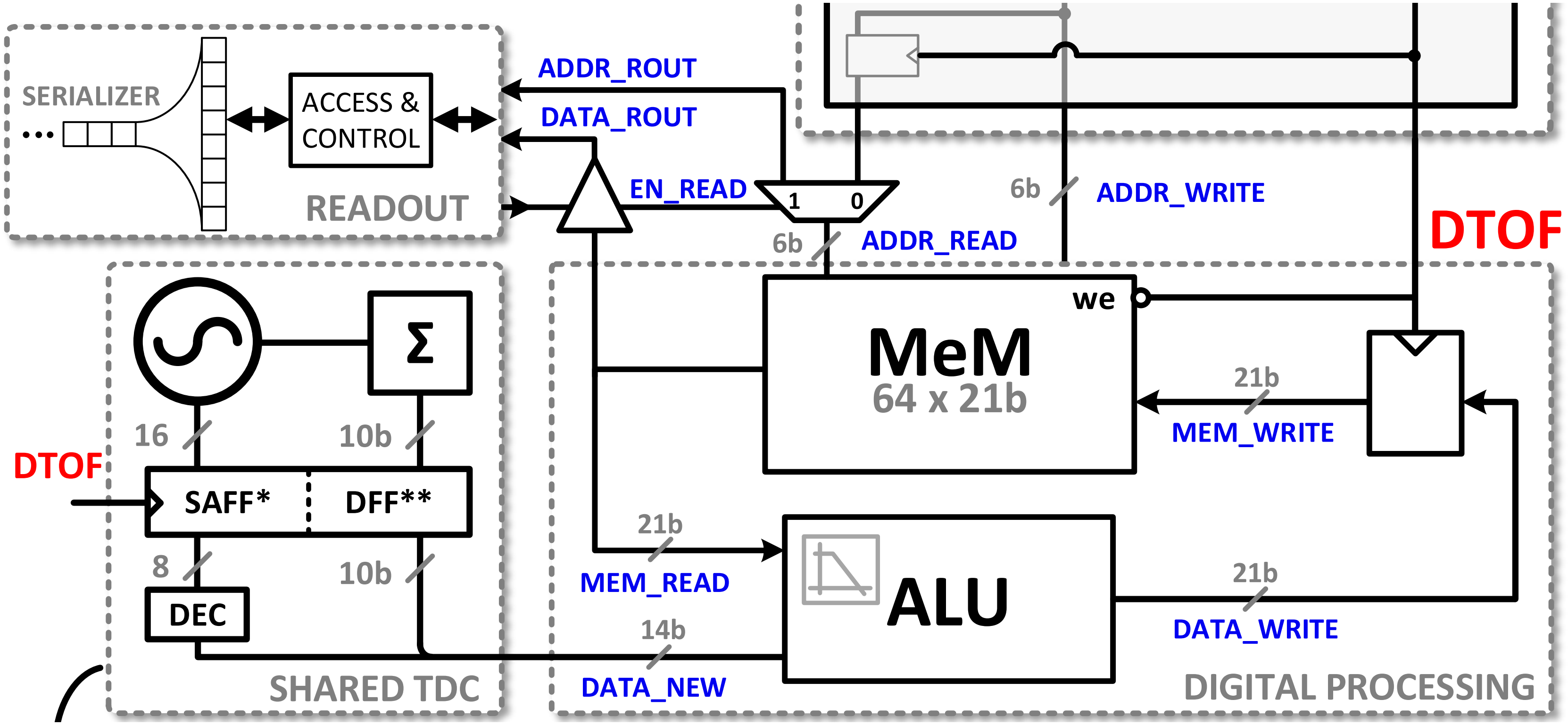
- Tier 1: SPADs + microlenses
- Tier 2: quenching, recharge, TDCs, multi-core, memories, communication unit, I/O

BSI + 3D-Stacking



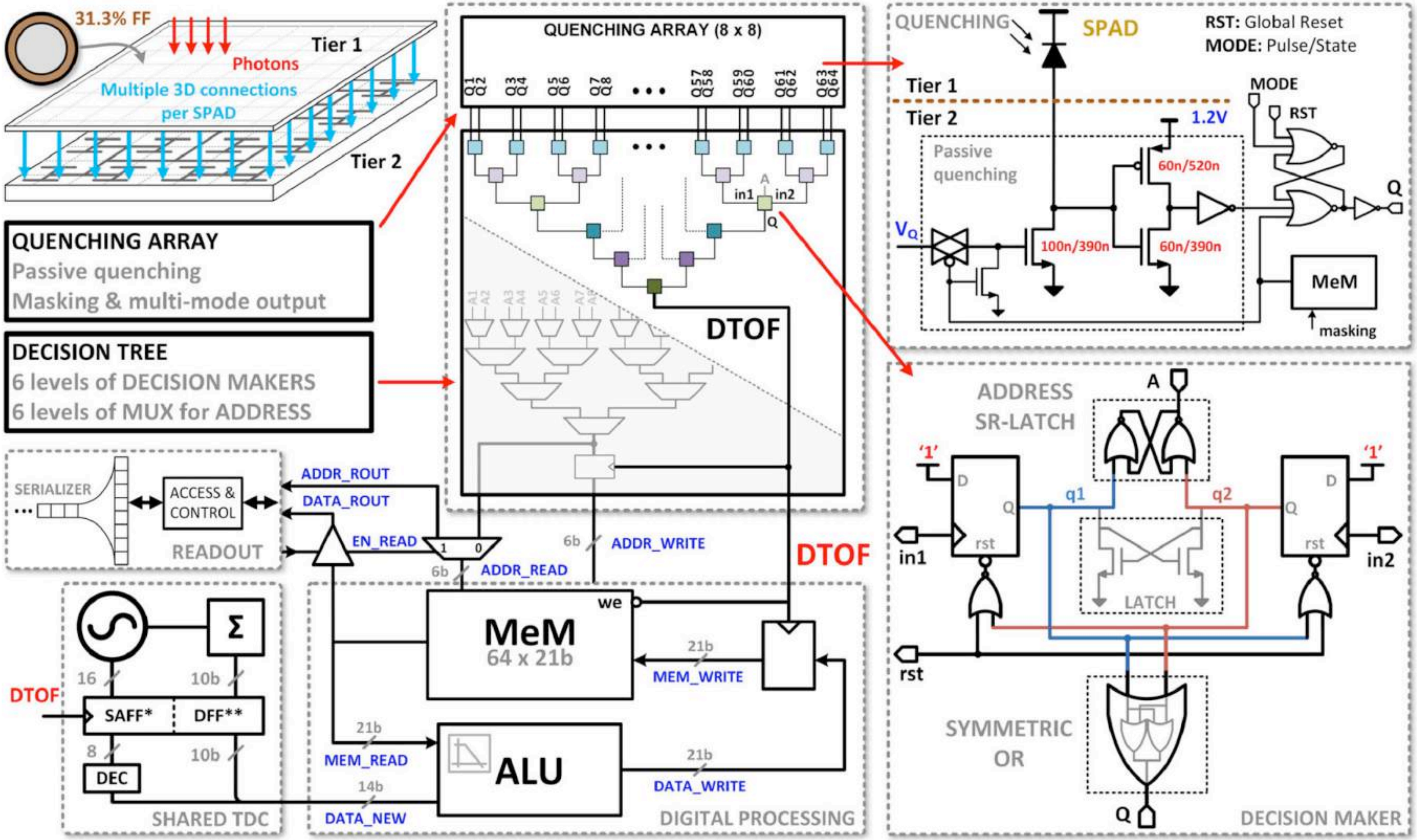
- Masking mechanism
- Interface
- Memory

BSI + 3D-Stacking



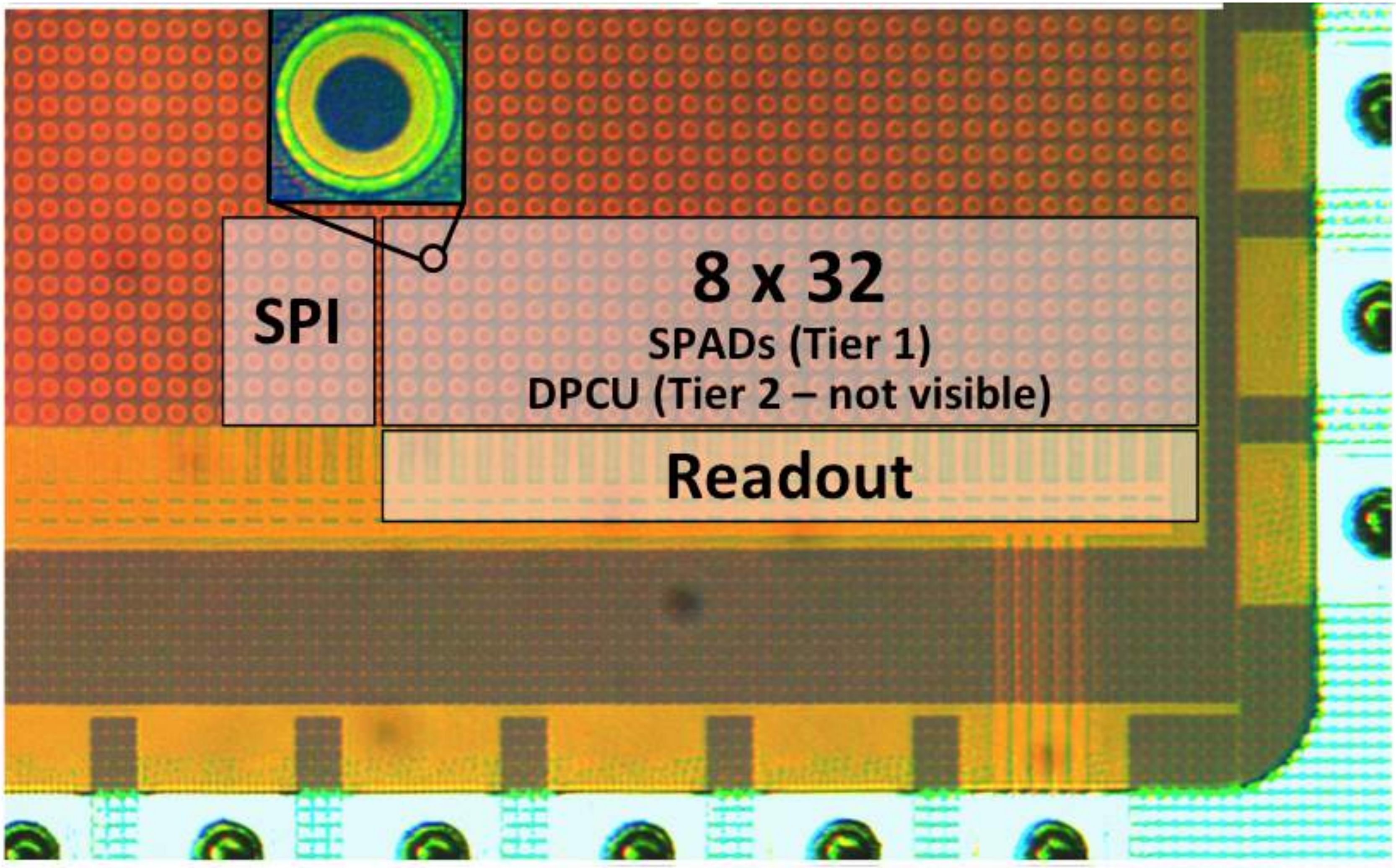
A.R. Ximenes, P.Padmanabhan *et al.*, *ISSCC*, 2018

BSI + 3D-Stacking

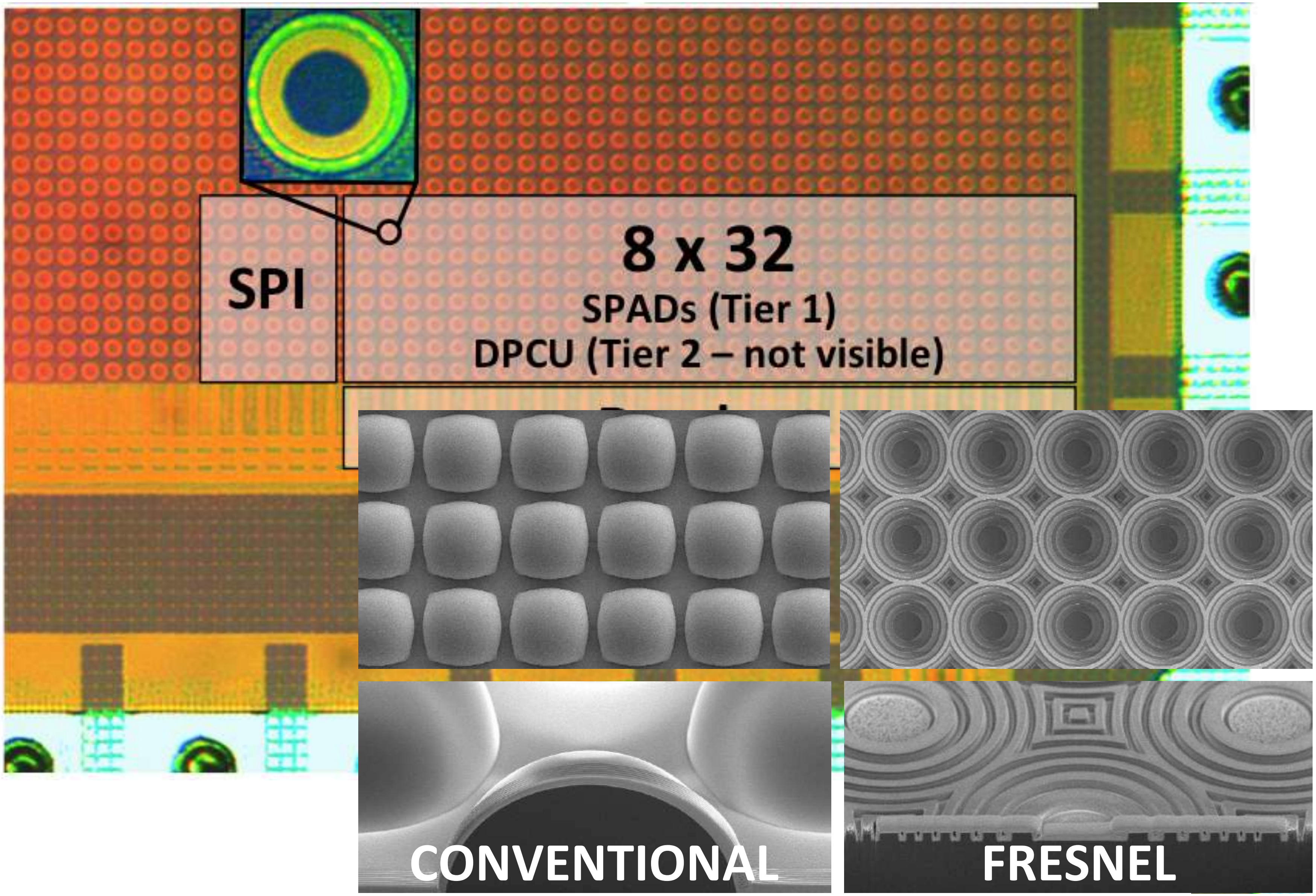


A.R. Ximenes, P.Padmanabhan *et al.*, *ISSCC*, 2018

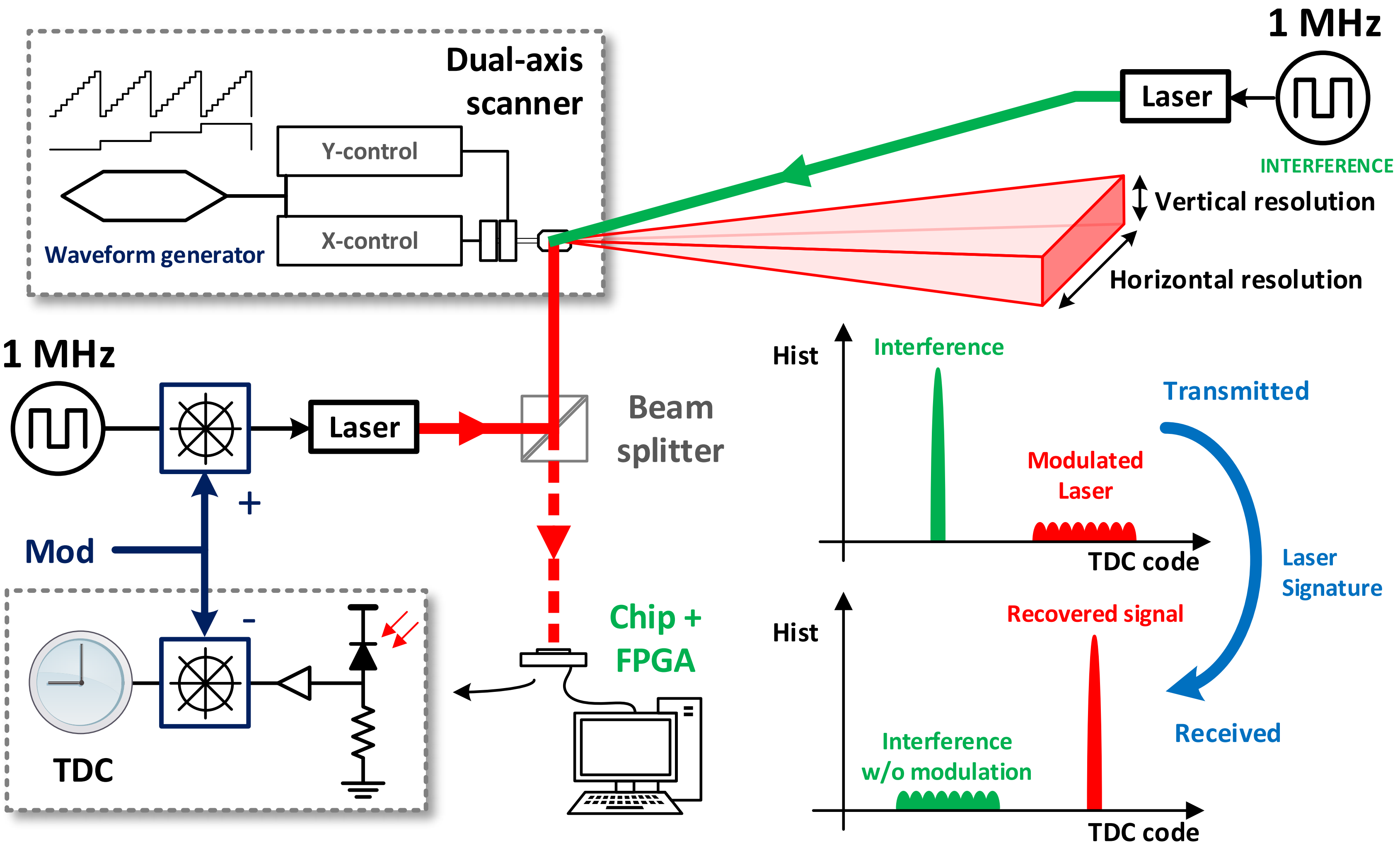
3D-Stacked Chip Micrograph



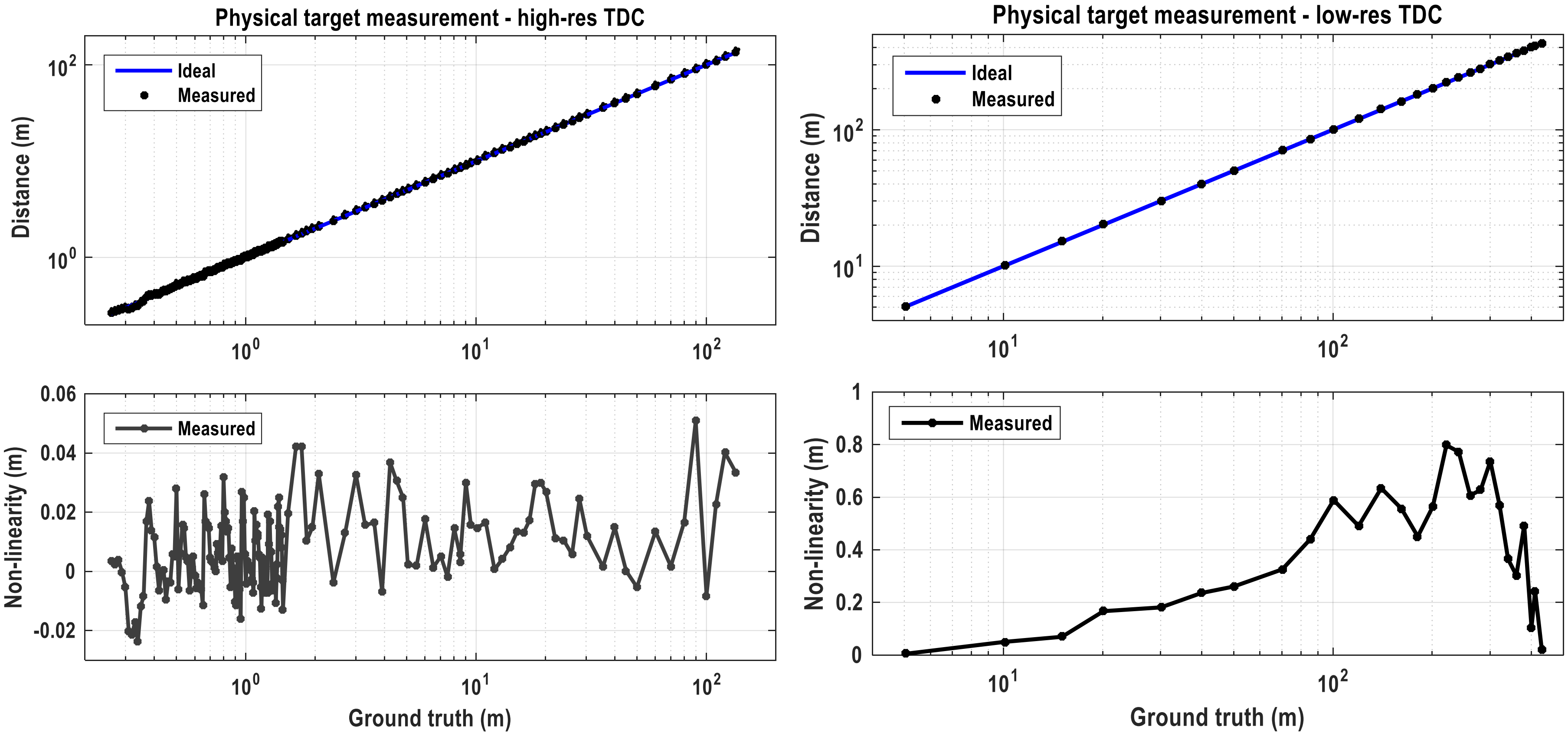
3D-Stacked Chip Micrograph



The LiDAR System



Distance Measurements



A.R. Ximenes, P.Padmanabhan *et al.*, *ISSCC*, 2018

Interference Suppression