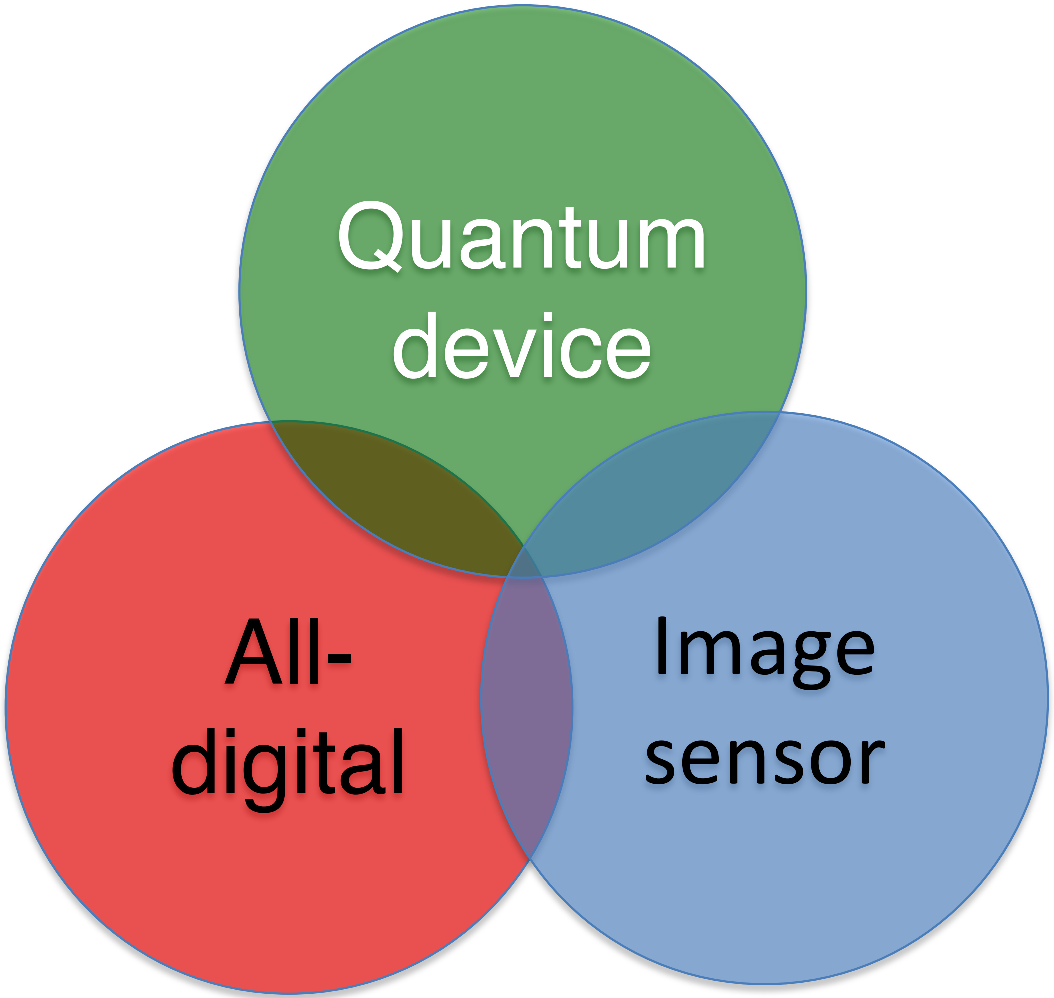
From SPADs to Quantum Computing

Edoardo Charbon

EPFL

Les Diablerets, Switzerland

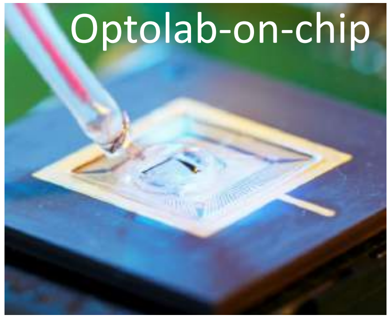
Single-Photon Avalanche Diodes (SPADs) Are:



The Goals of this Talk

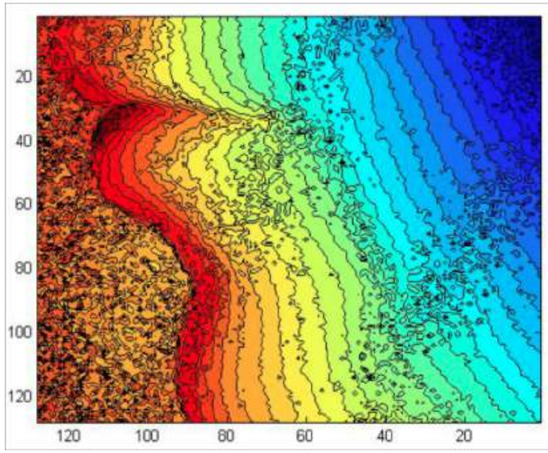
- To convince you that SPADs are quantum devices and that they can be used for quantum applications
- Modularity is an important ingredient to large photonic systems and even the technology of a cellphone camera will do
- To demonstrate that one can actually make a product (and money) out of SPADs

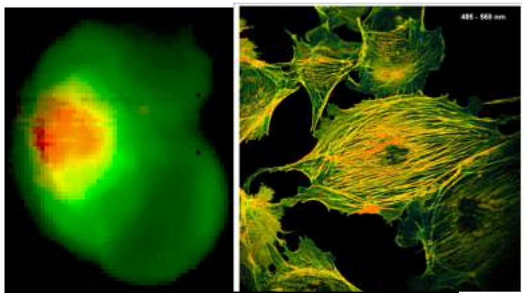
Some SPAD Applications

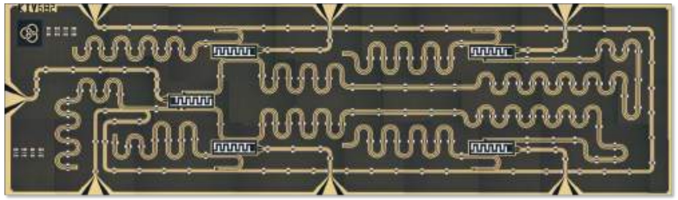

Optolab-on-chip

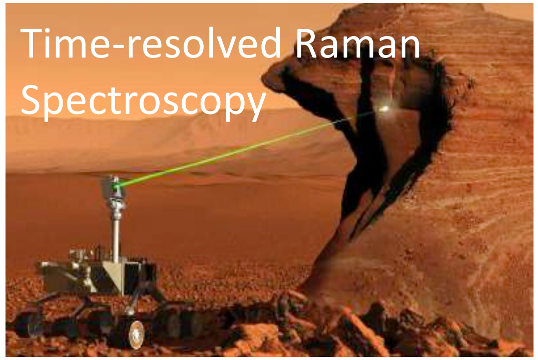

3D Vision

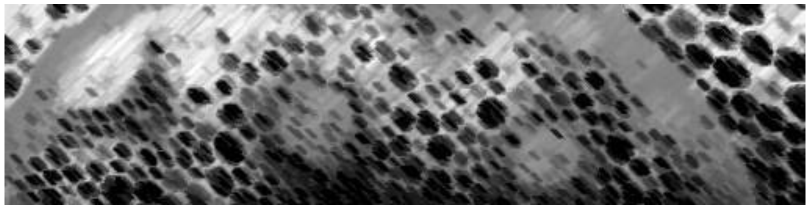
Near Infrared Imaging (NIRI)




Fluorescence Lifetime Imaging Microscopy (FLIM)

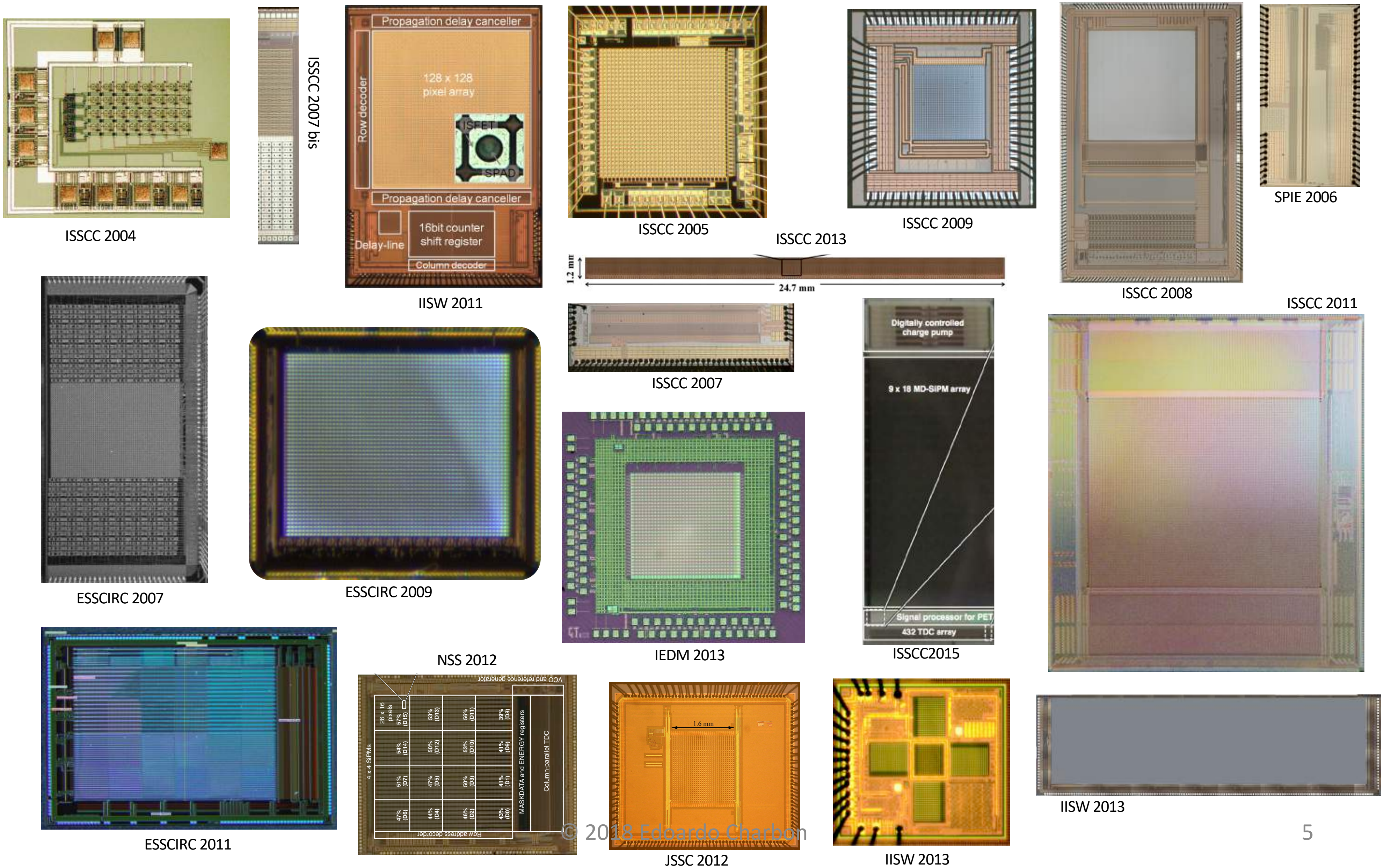

Quantum Computing
QRNG


Time-resolved Raman Spectroscopy

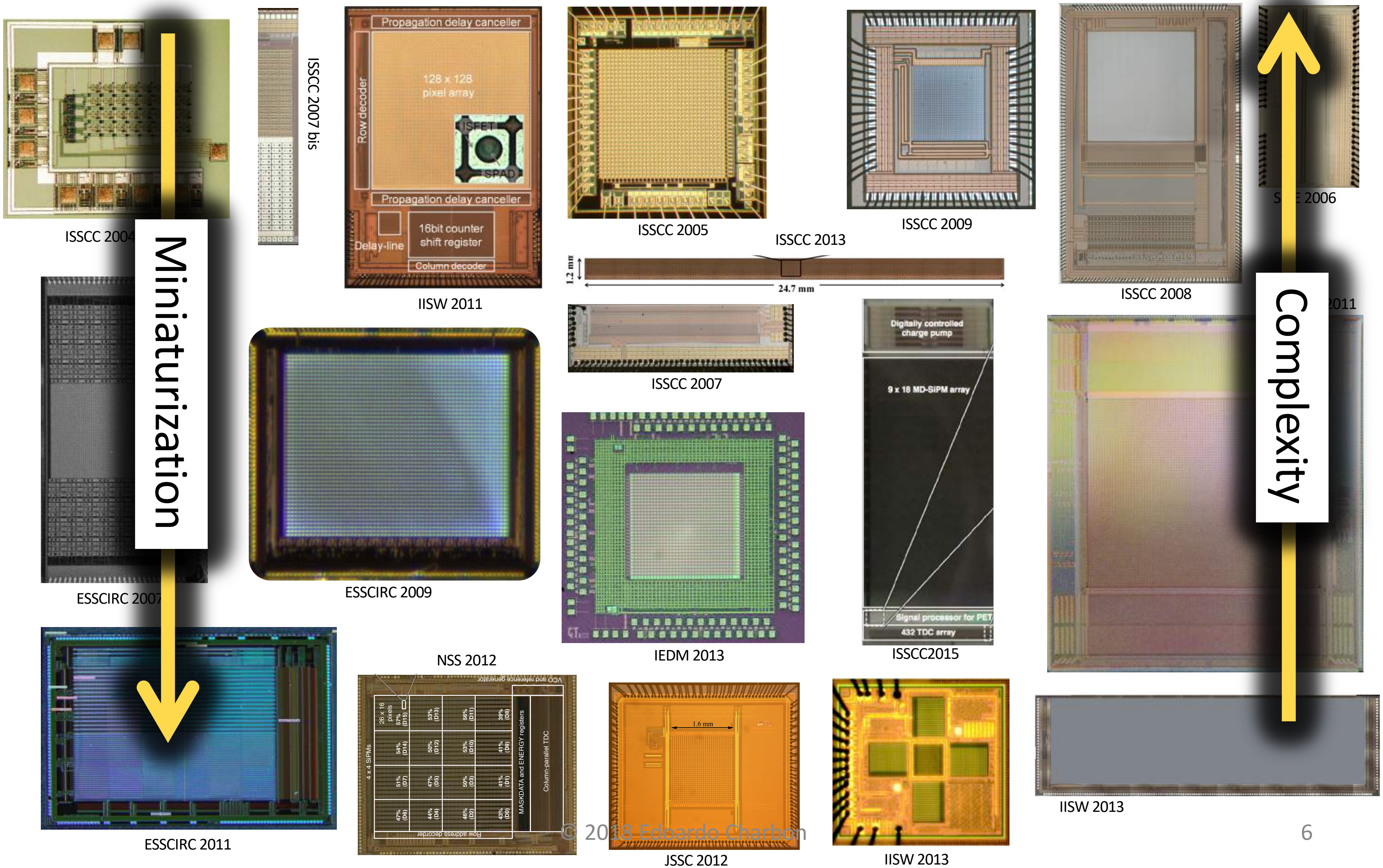

Super-resolution (GSDIM)

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

SPAD Image Sensors Targeted to Apps

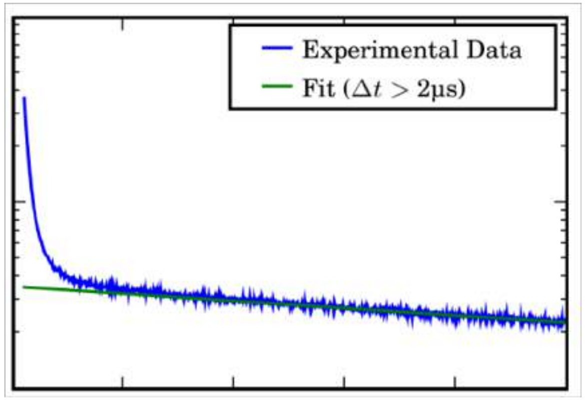


SPAD Image Sensors Targeted to Apps

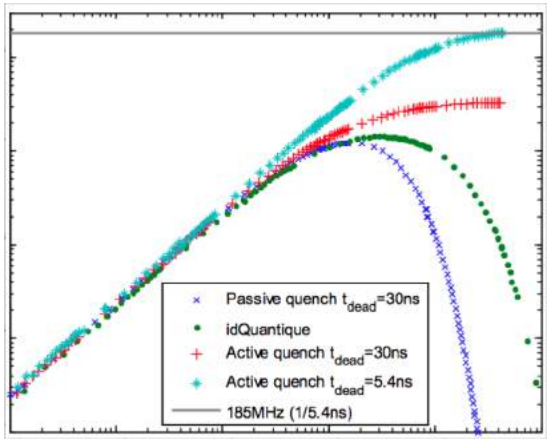


SPAD Non-idealities

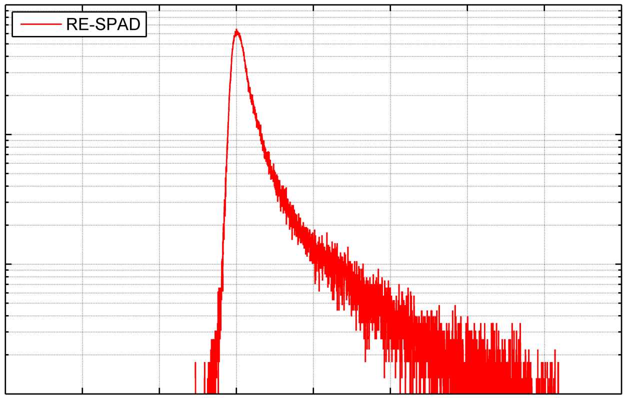
Afterpulsing



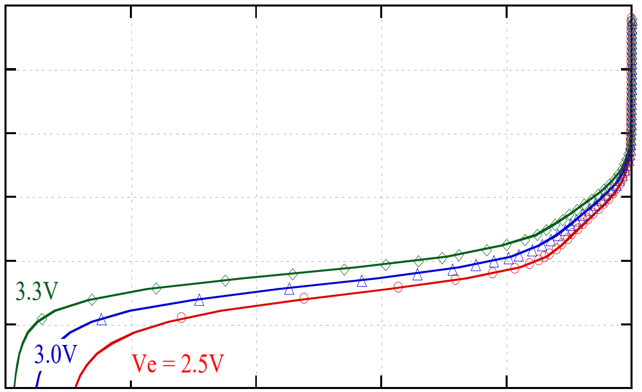
Dynamic Range



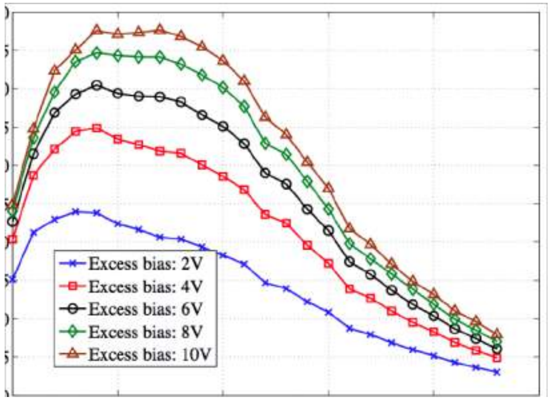
Jitter



DCR

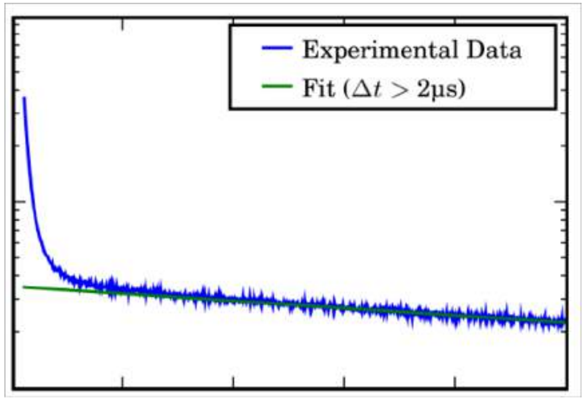


PDP/PDE

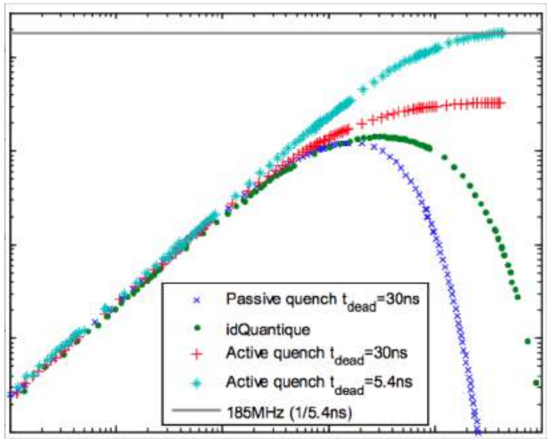


SPAD Image Sensor Non-idealities

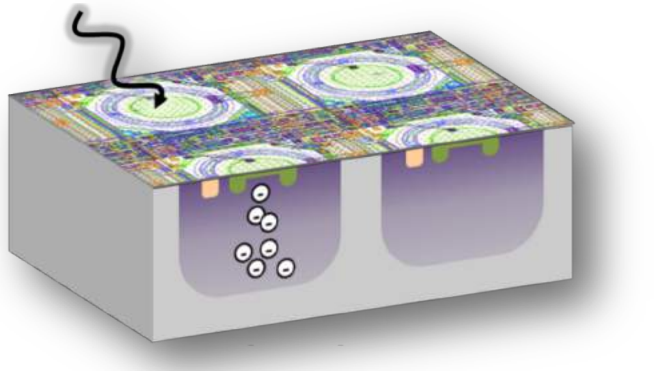
Afterpulsing
non-uniformity



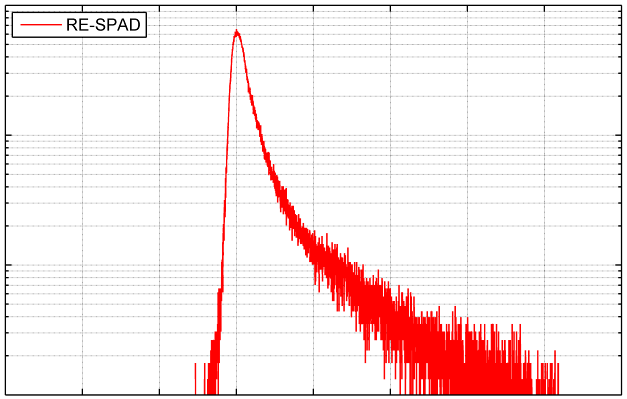
Dynamic Range
non-uniformity



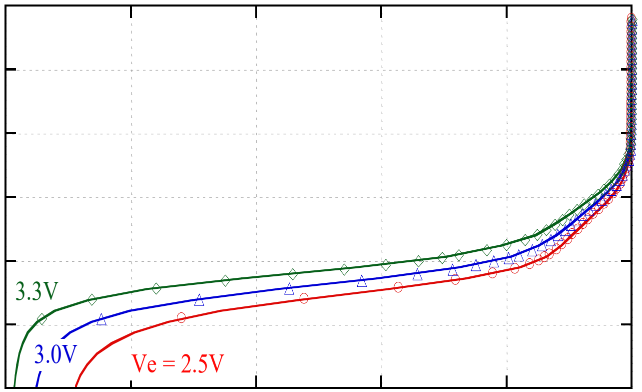
Crosstalk



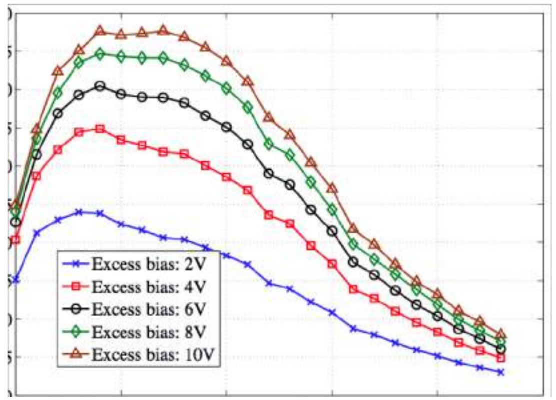
Jitter
non-uniformity



DCR
non-uniformity

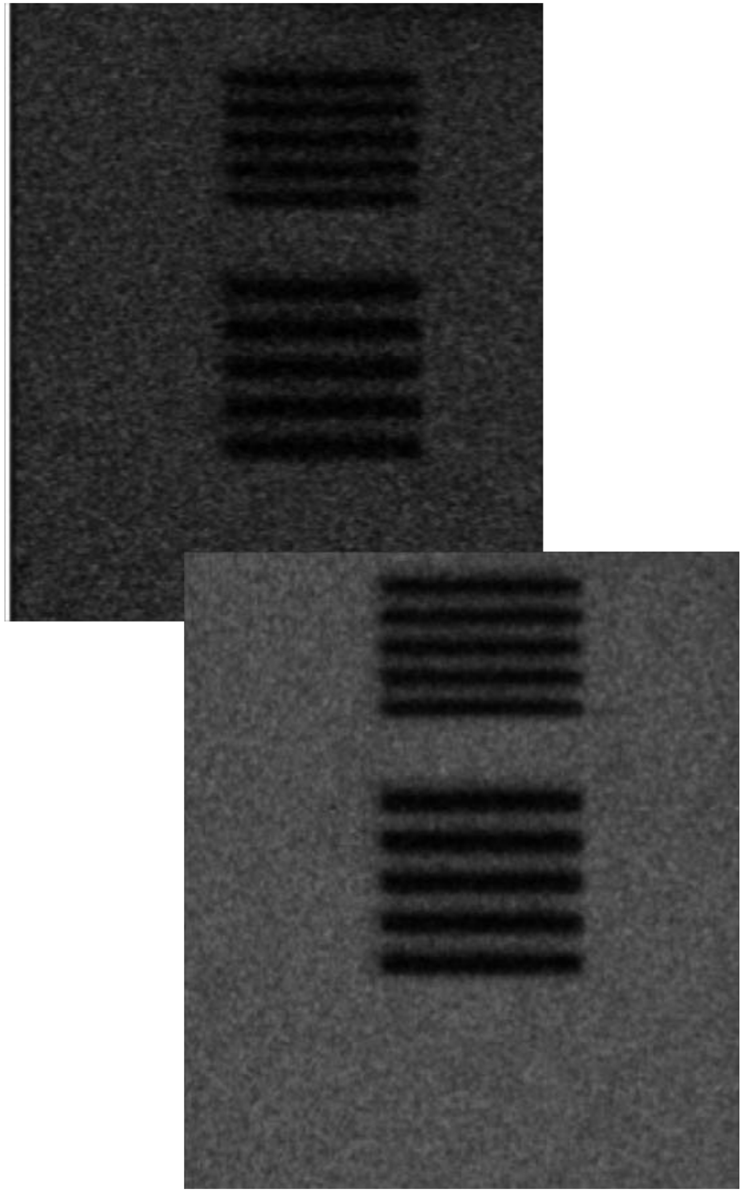


PDP/PDE
non-uniformity

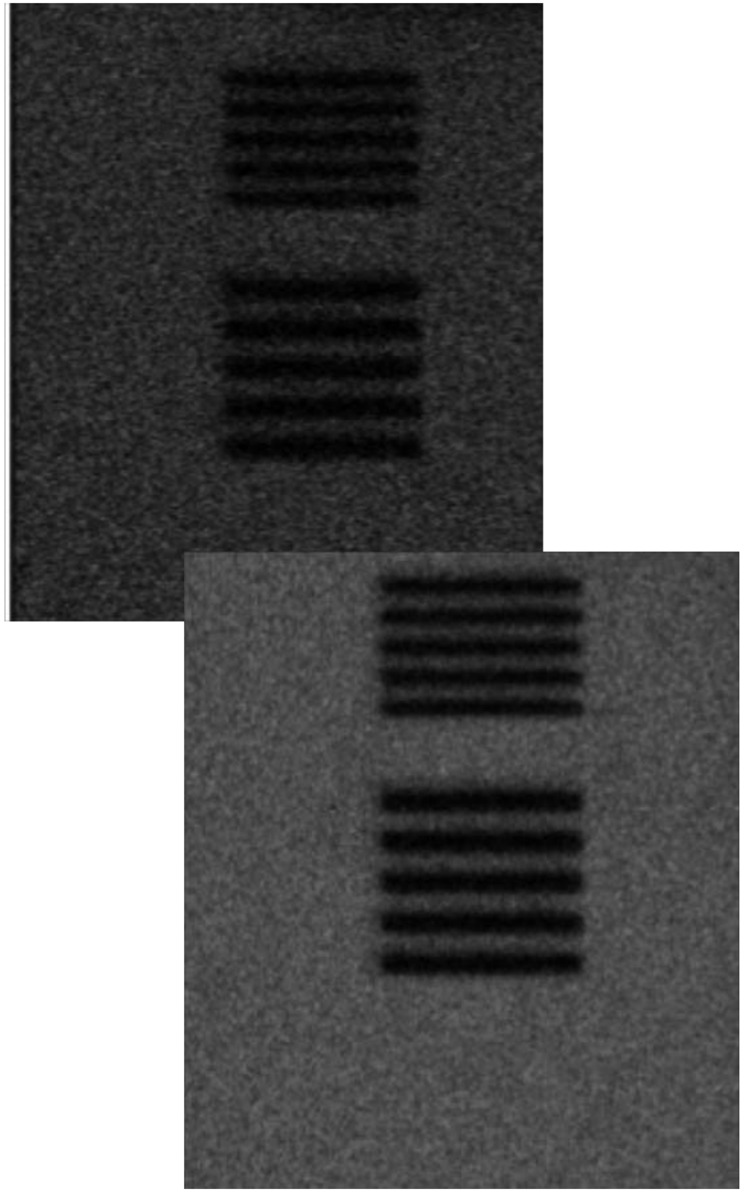


How to Deal with Non-uniformity?

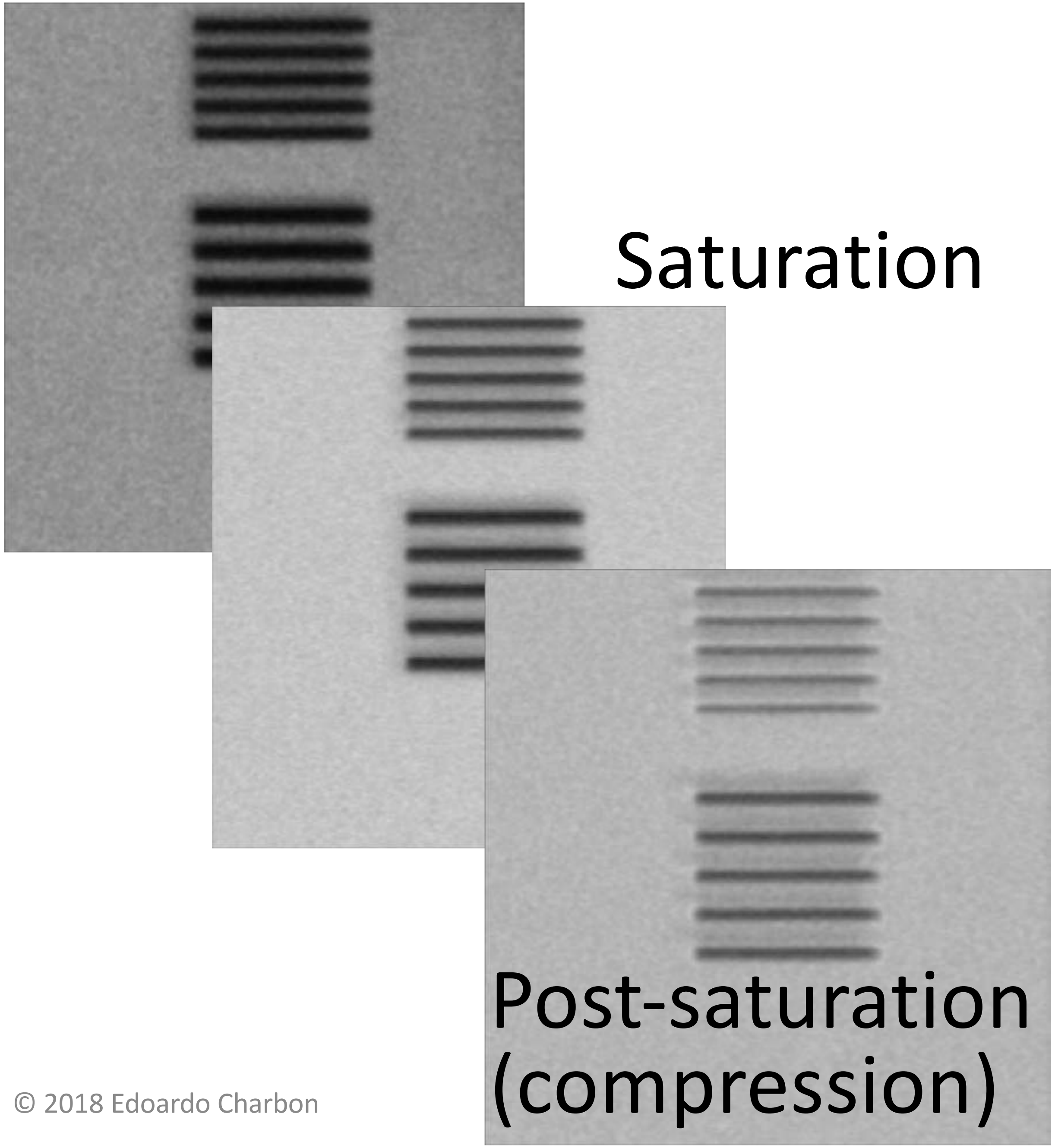
Afterpulsing, Dynamic Range NU



Afterpulsing, Dynamic Range NU

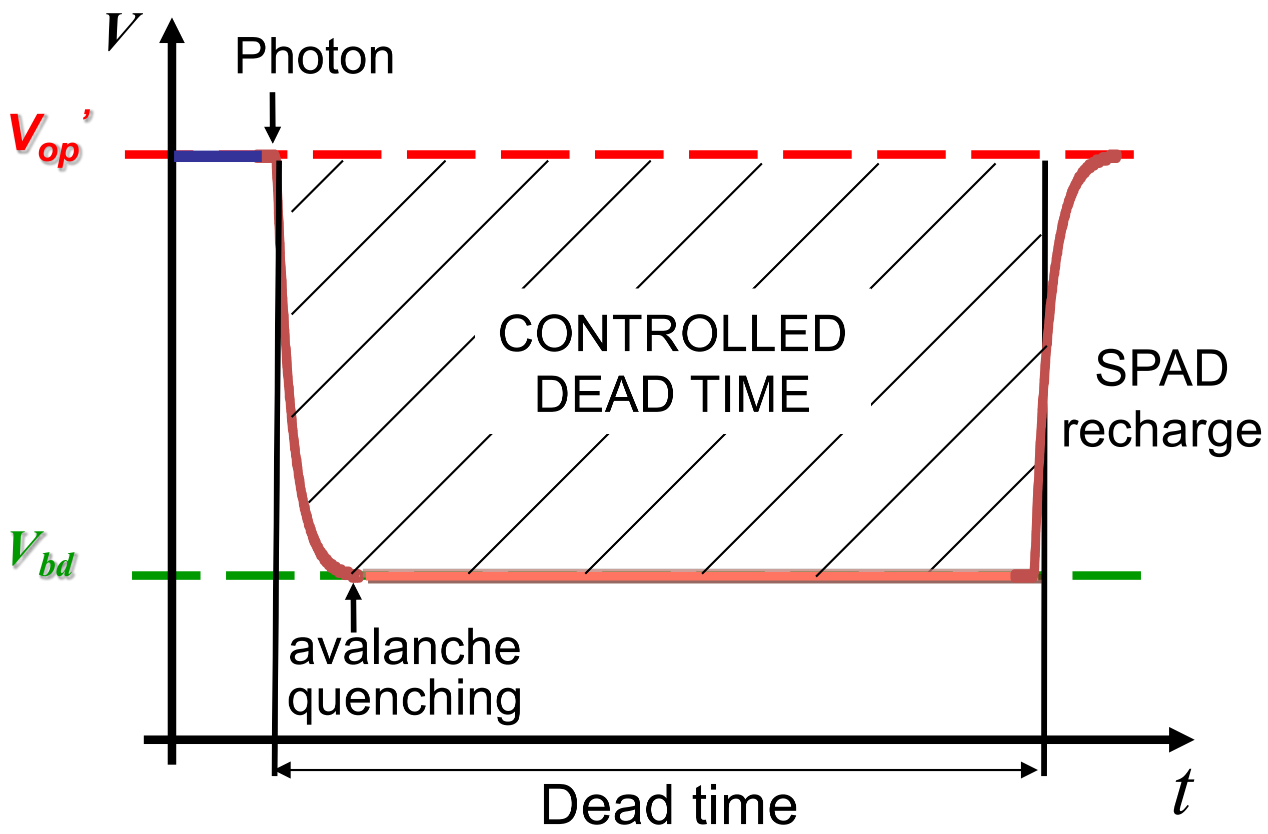


Saturation

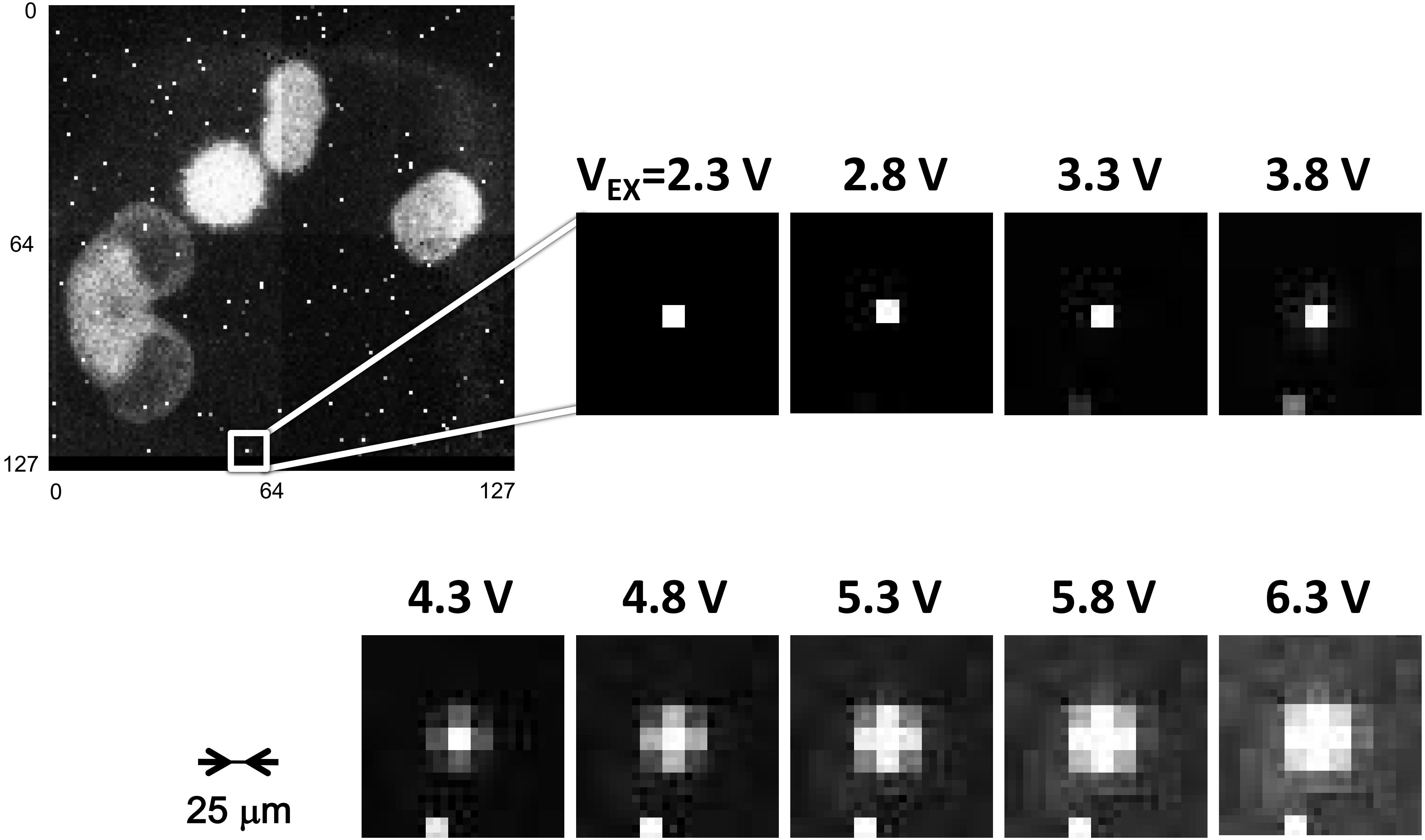


Solution

- Accelerate quenching (and minimize quenching current) with active quenching
- Control dead time with active recharge



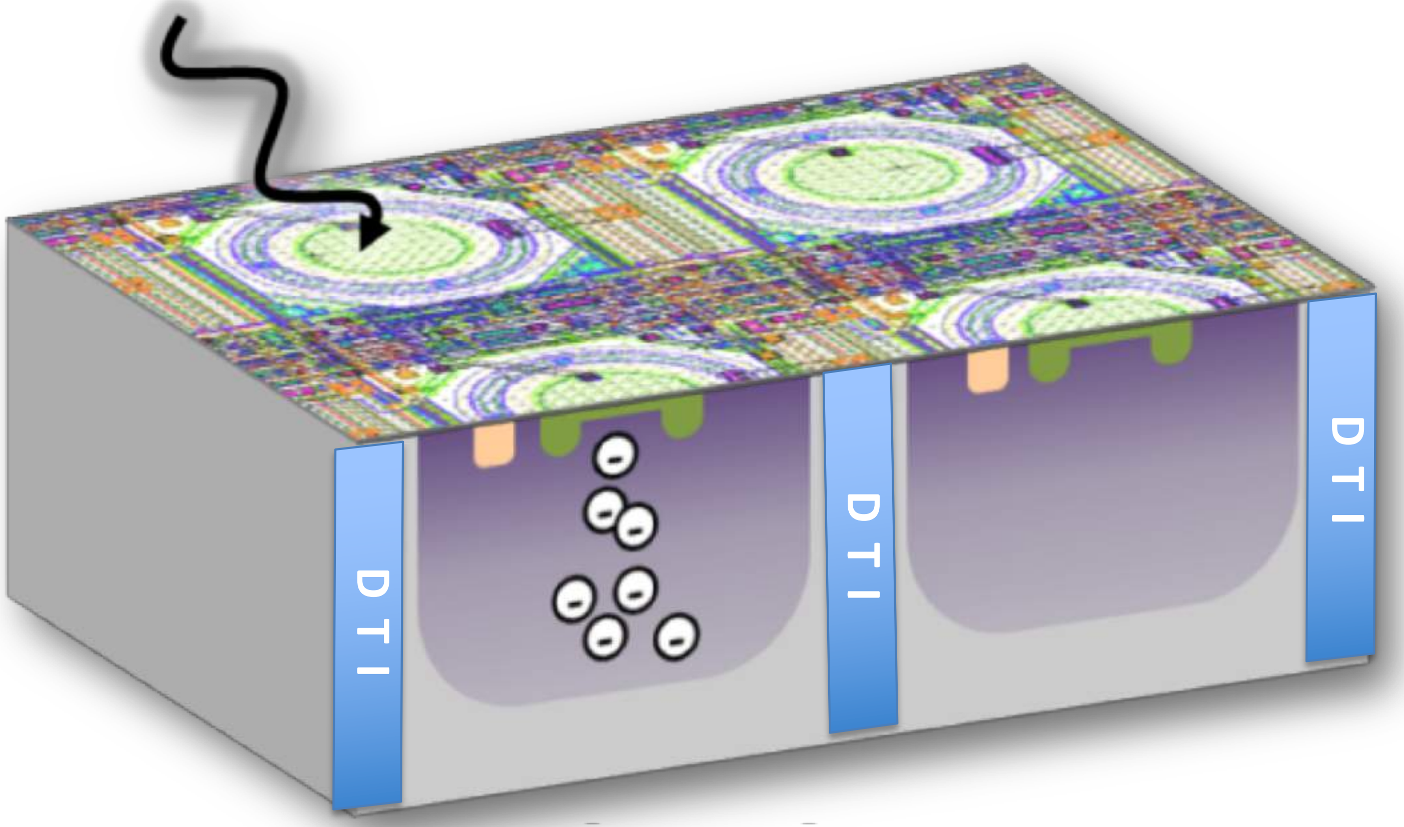
Crosstalk (Evidenced by Hot Pixels)



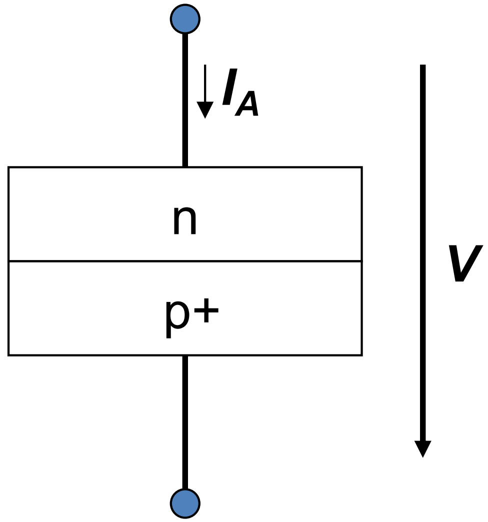
Y. Maruyama et al, *IISW* 2011

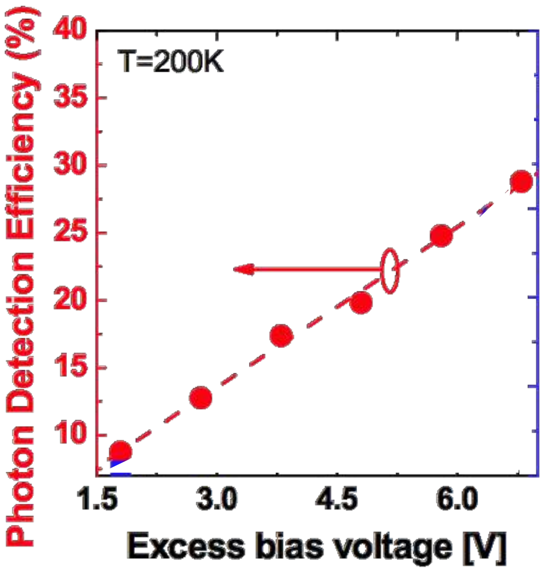
Solution

- Accelerate quenching (and minimize photon emission) with active quenching
- Add opaque deep trench isolations

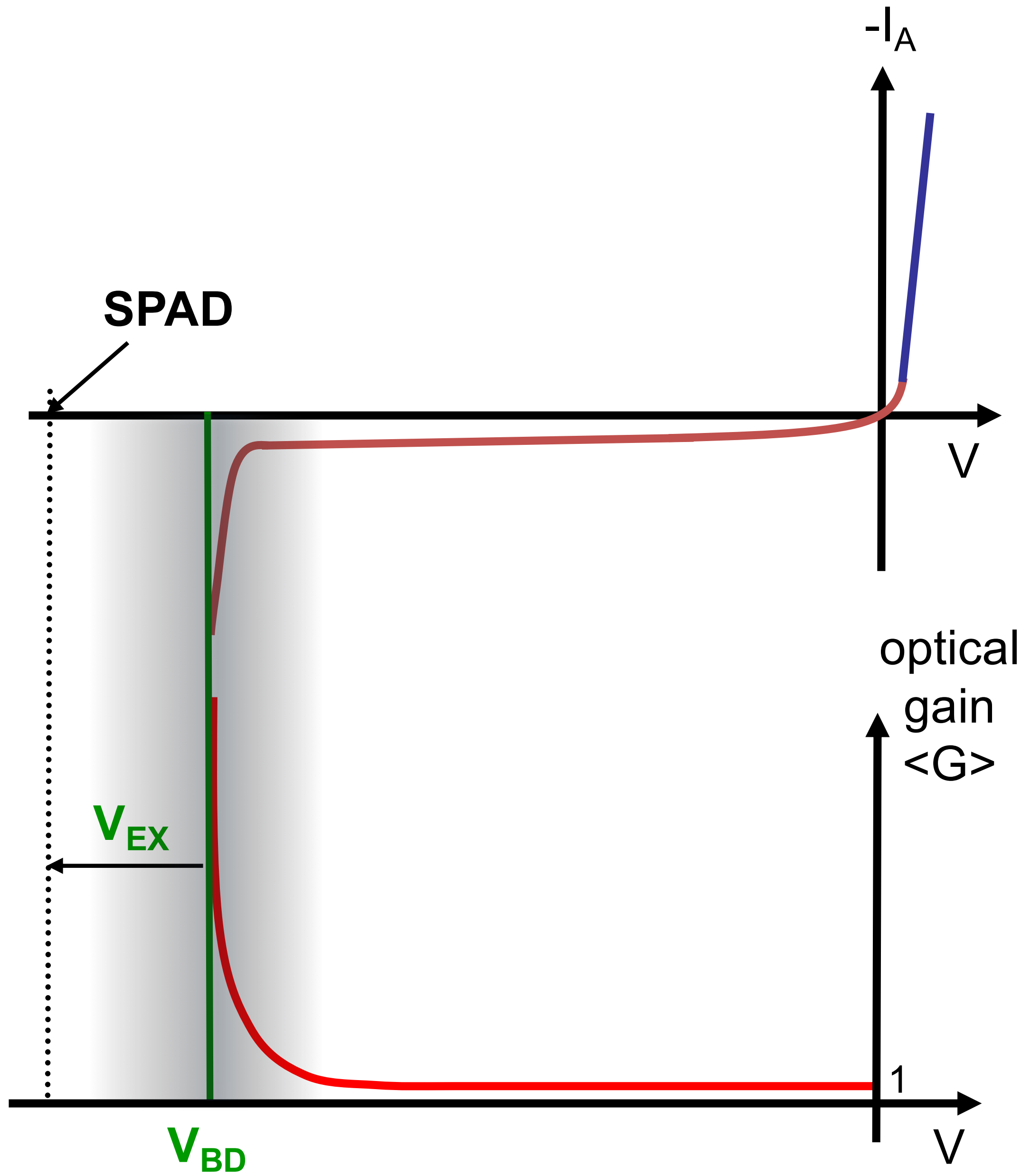


PDP/PDE NU



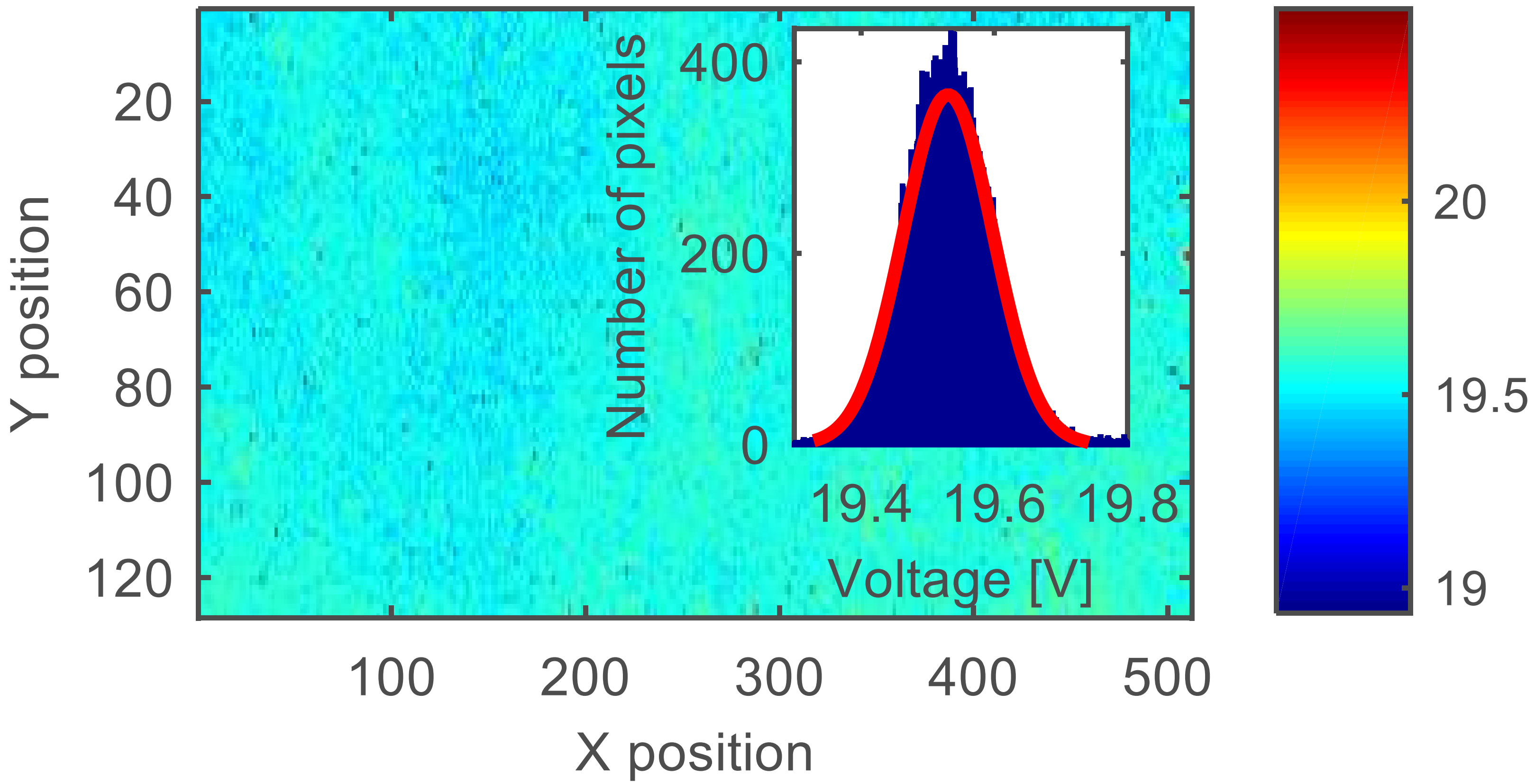


Tosi *et al.*, 2009



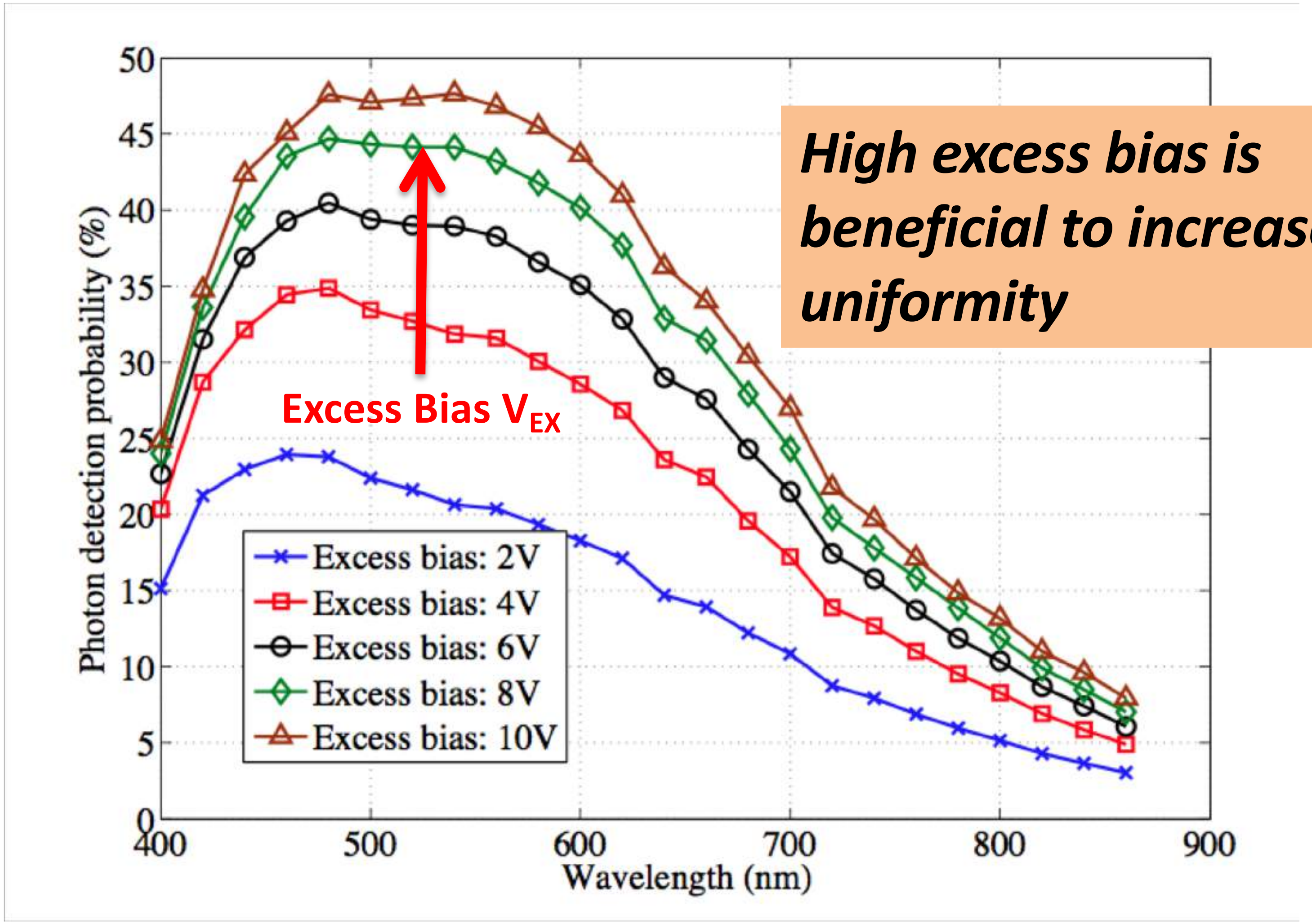
Breakdown Distribution

V_{BD} distribution



I.M. Antolovic, PhD. Thesis 2017

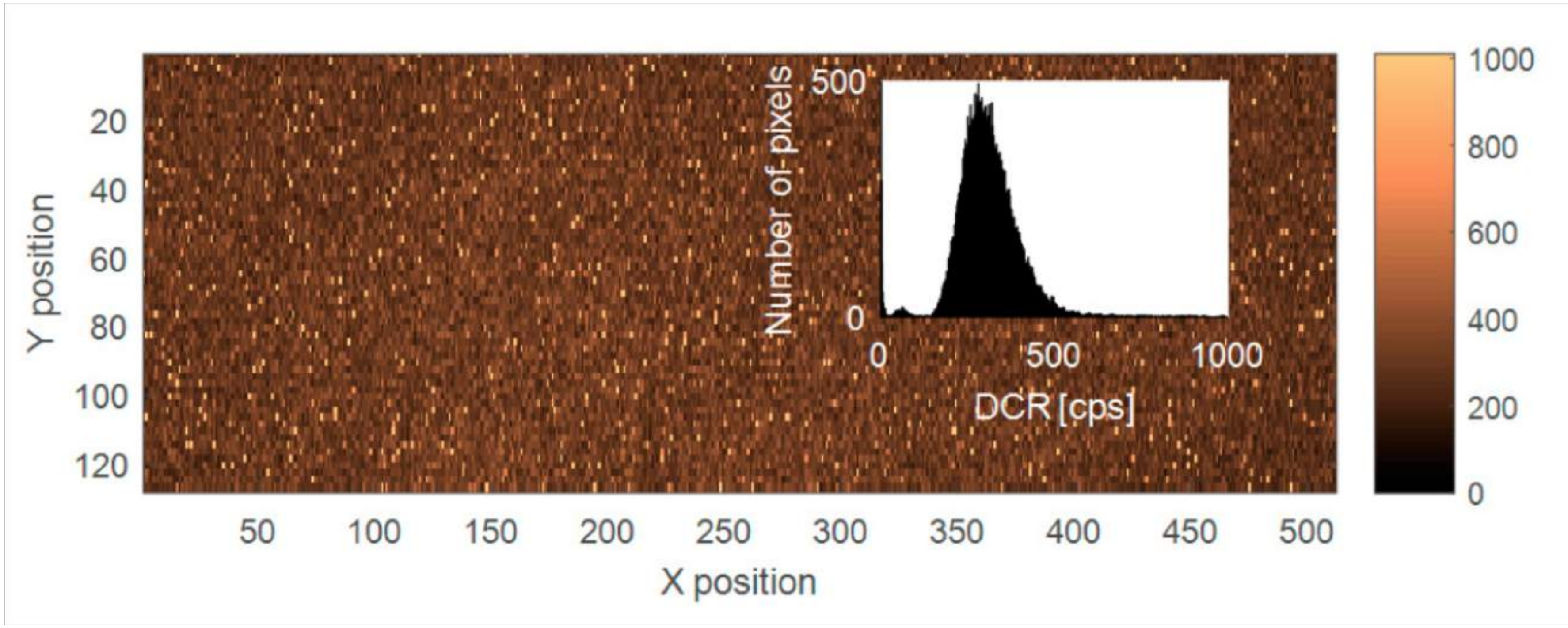
Solution



High excess bias is beneficial to increase PDE uniformity

C. Veerappan and E. Charbon, JSTQE 2014

Jitter, DCR NU

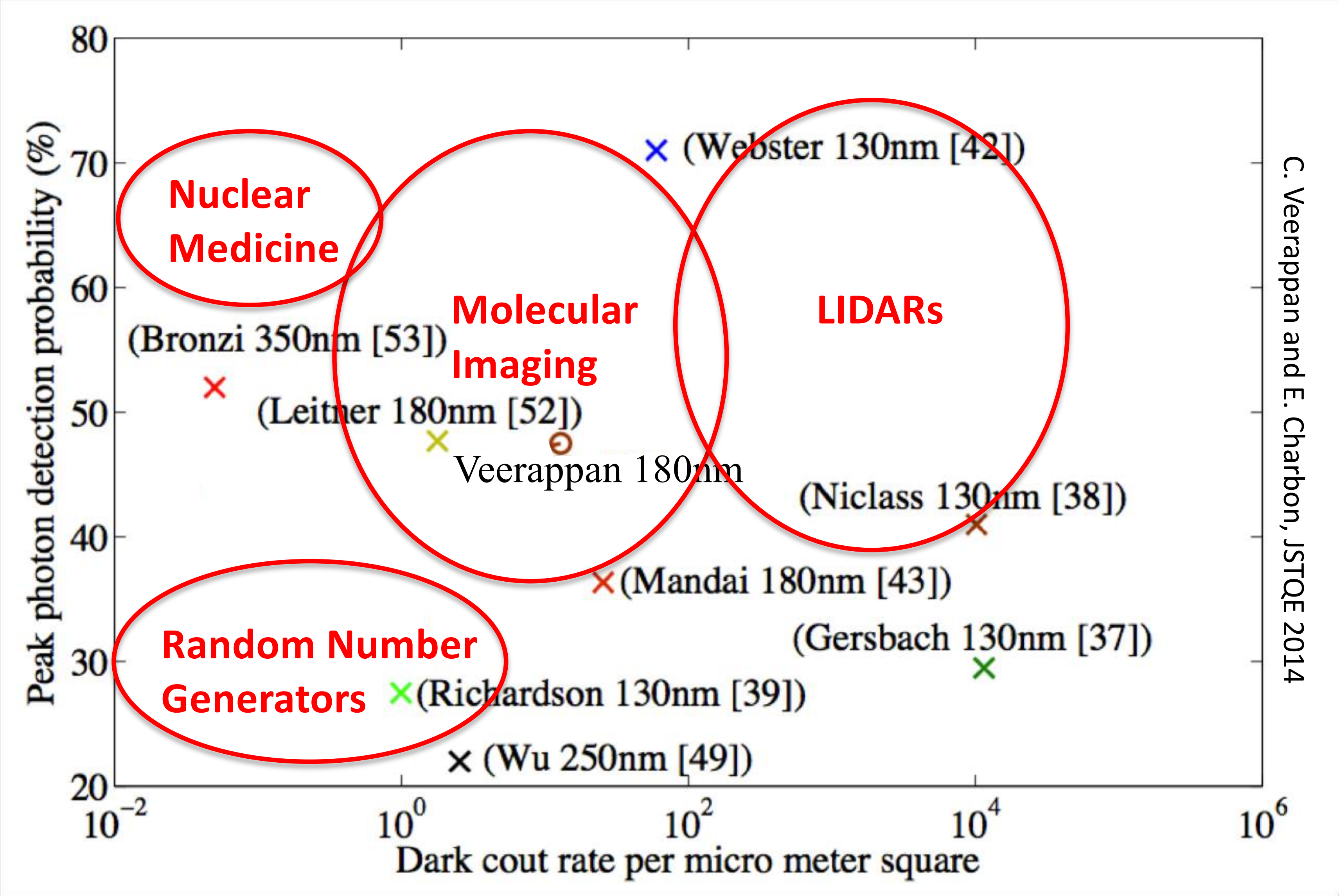


I.M. Antolovic, S. Burri, R. Hoebe, Y. Maruyama, C. Bruschini, E. Charbon, MDPI Sensors, **16**, 1005, 2016

Solution: not much to do, except

- reduce jitter & DCR
- reduce temperature

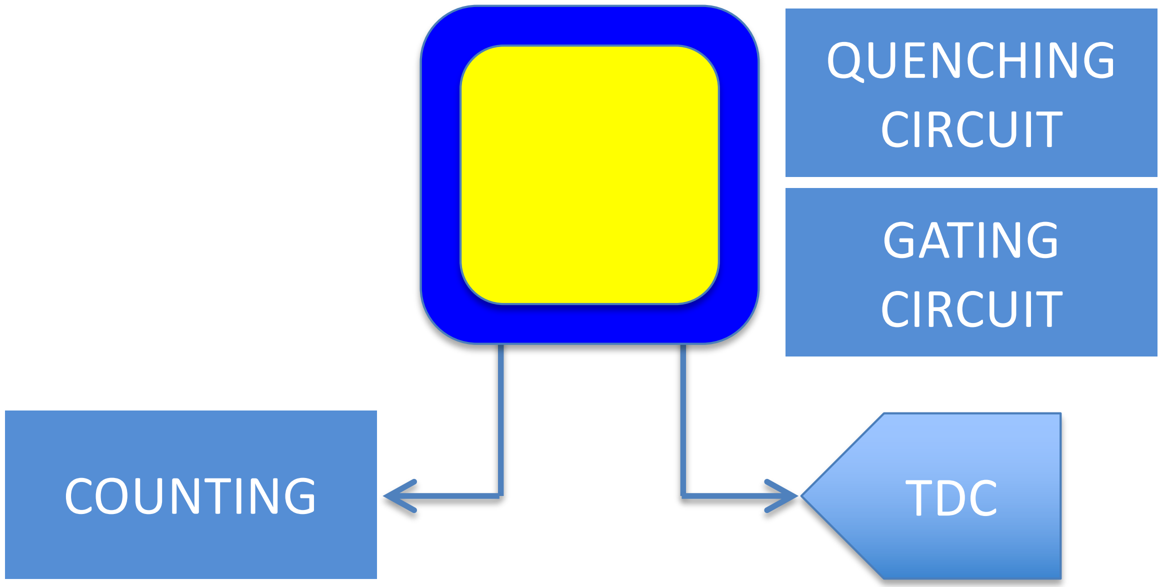
Sensitivity vs. DCR Issue



C. Veerappan and E. Charbon, JSTQE 2014

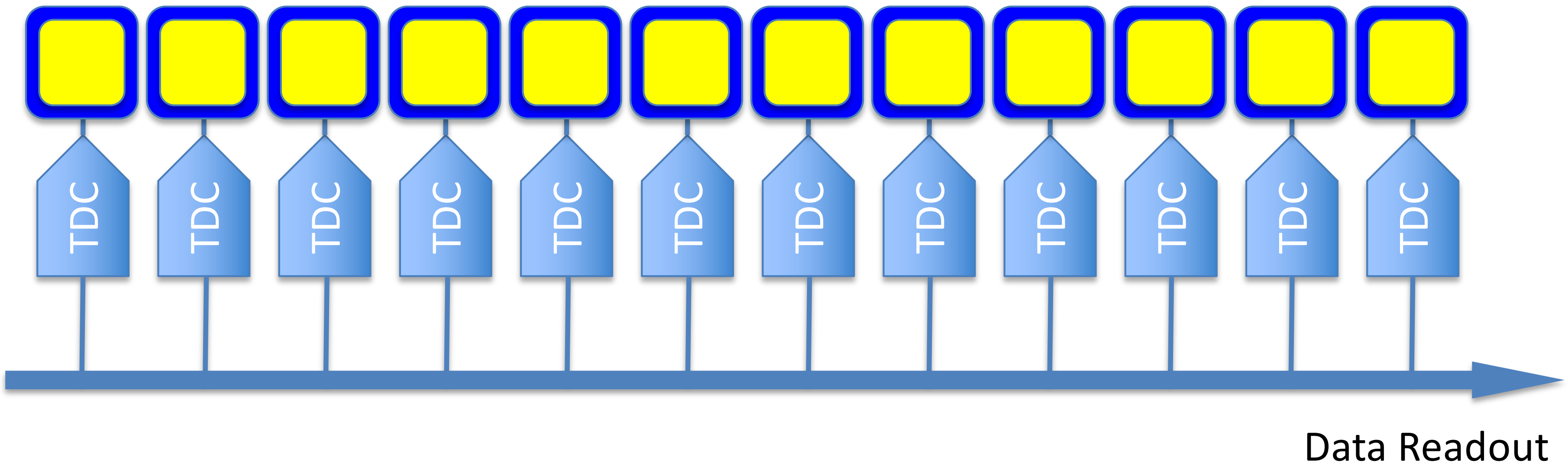
Architectures
and Quantum Applications

First, Let Us Define the Pixel



1D Arrays

- No sharing of resources
- High fill factor
- Reconfigurability of pixel



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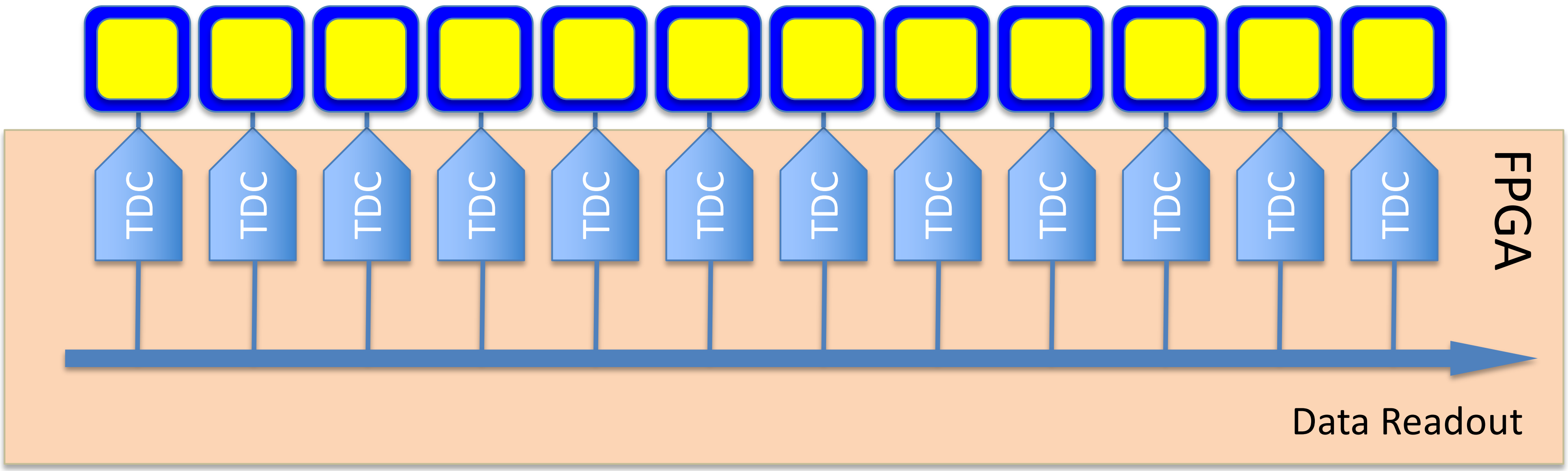
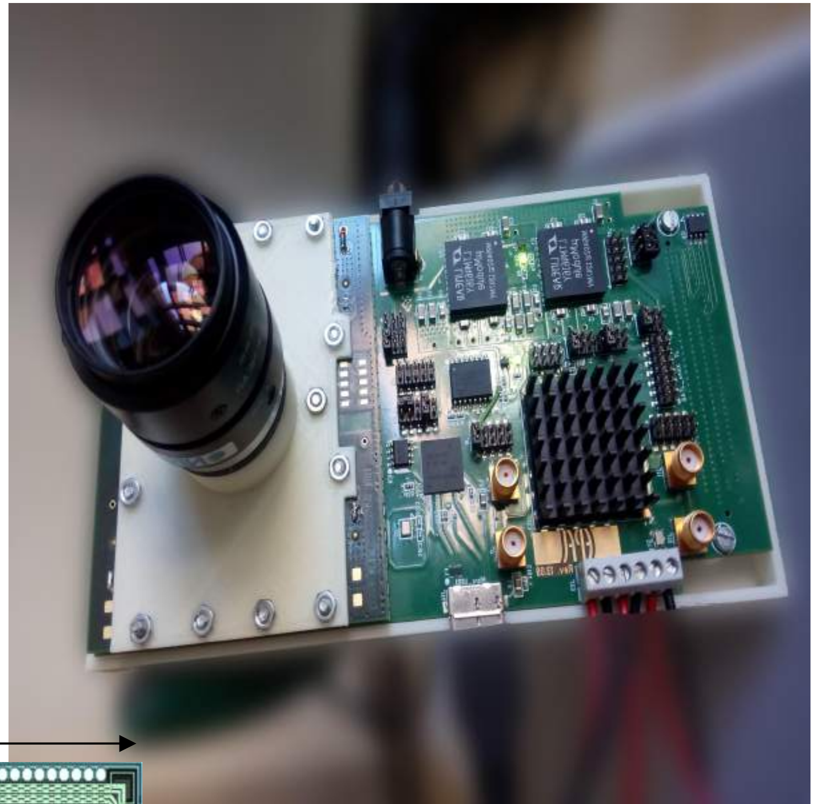
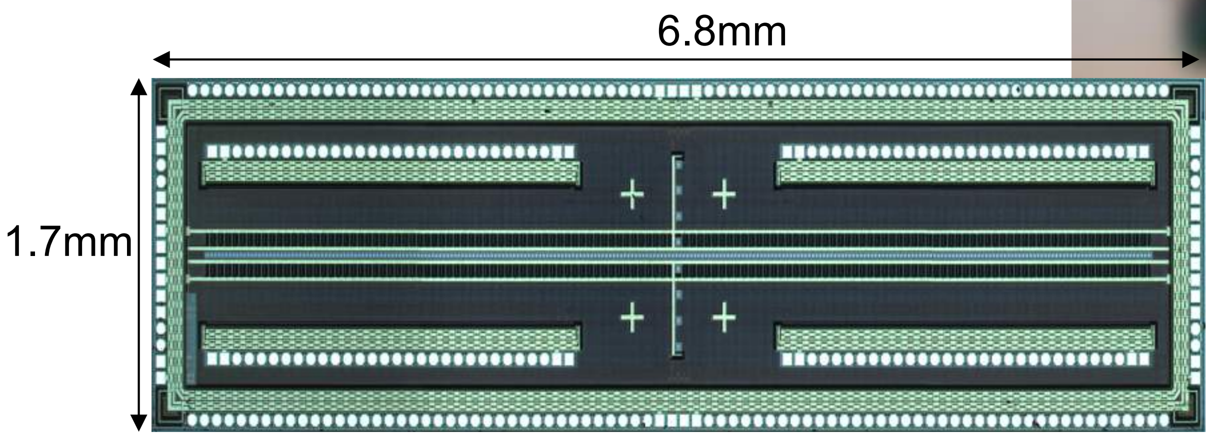


LinoSPAD: Time-resolved Camera

- 1x256 SPAD pixels
- Single-photon sensitivity
- Flexible timing and counting (64 TDCs on FPGA)
- Versatile, compact and modular time-resolved system



8cm x 16cm

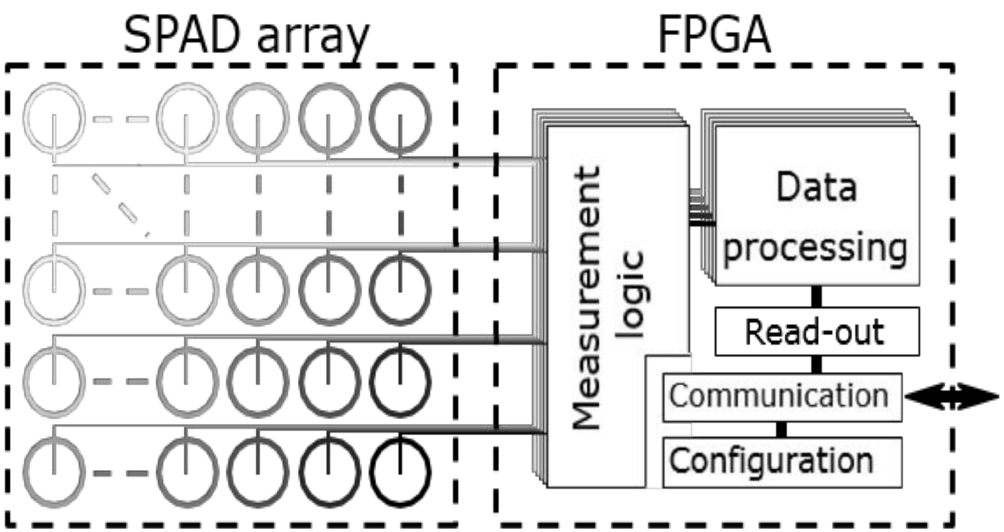


S. Burri, C. Bruschini, E. Charbon, *SPIE Photonics West* 2018, San Francisco

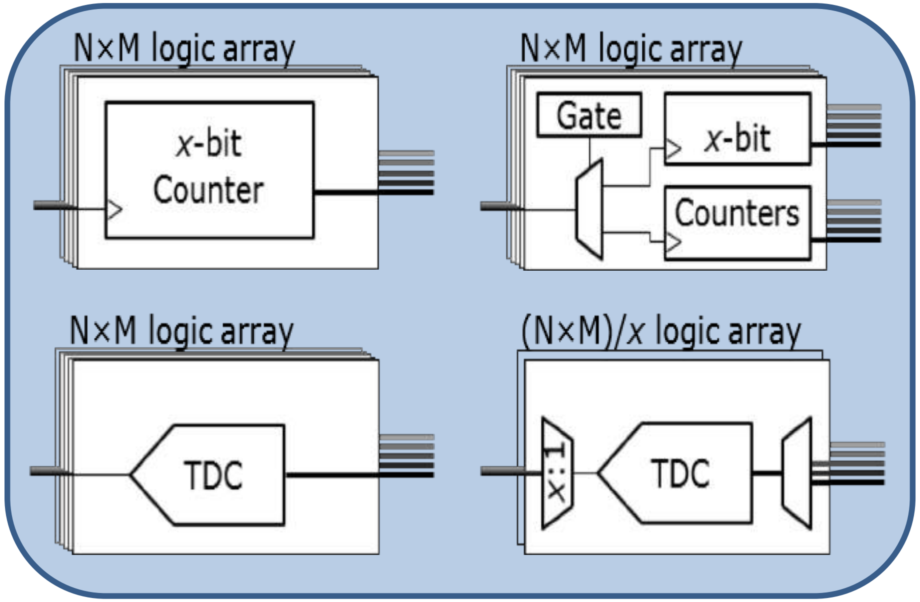
S. Burri et al., *MDPI Instruments* 2017

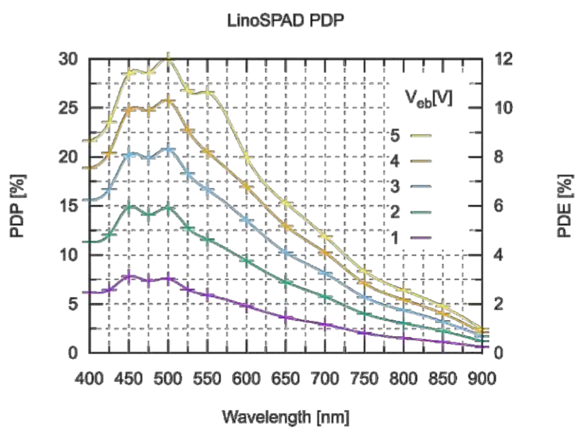
LinoSPAD Modularity

Combine options for pixel logic and processing

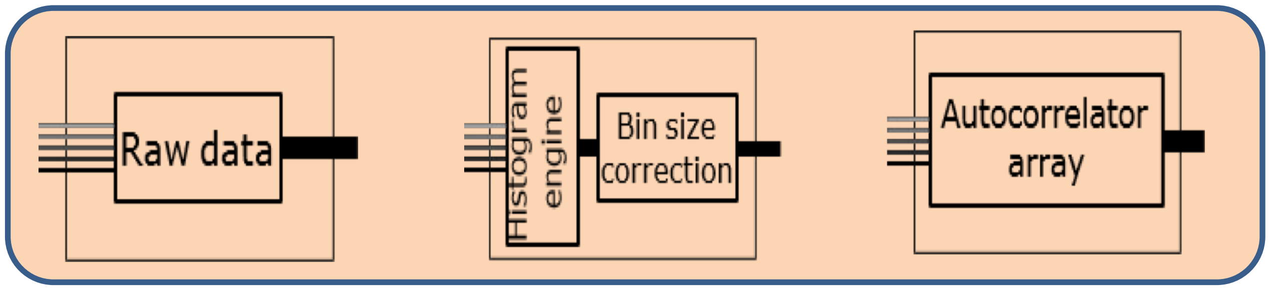


Measurement blocks





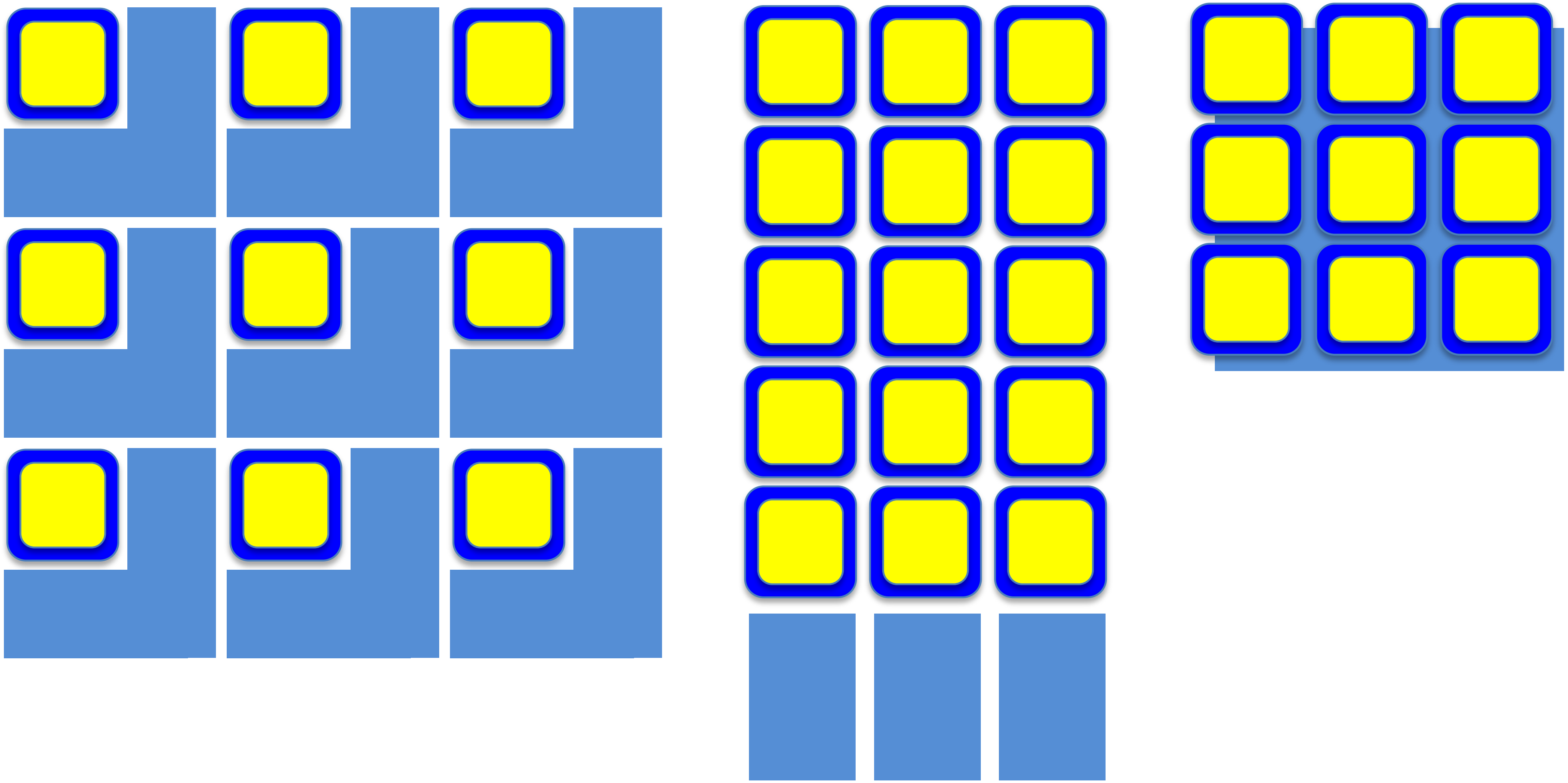
Processing blocks



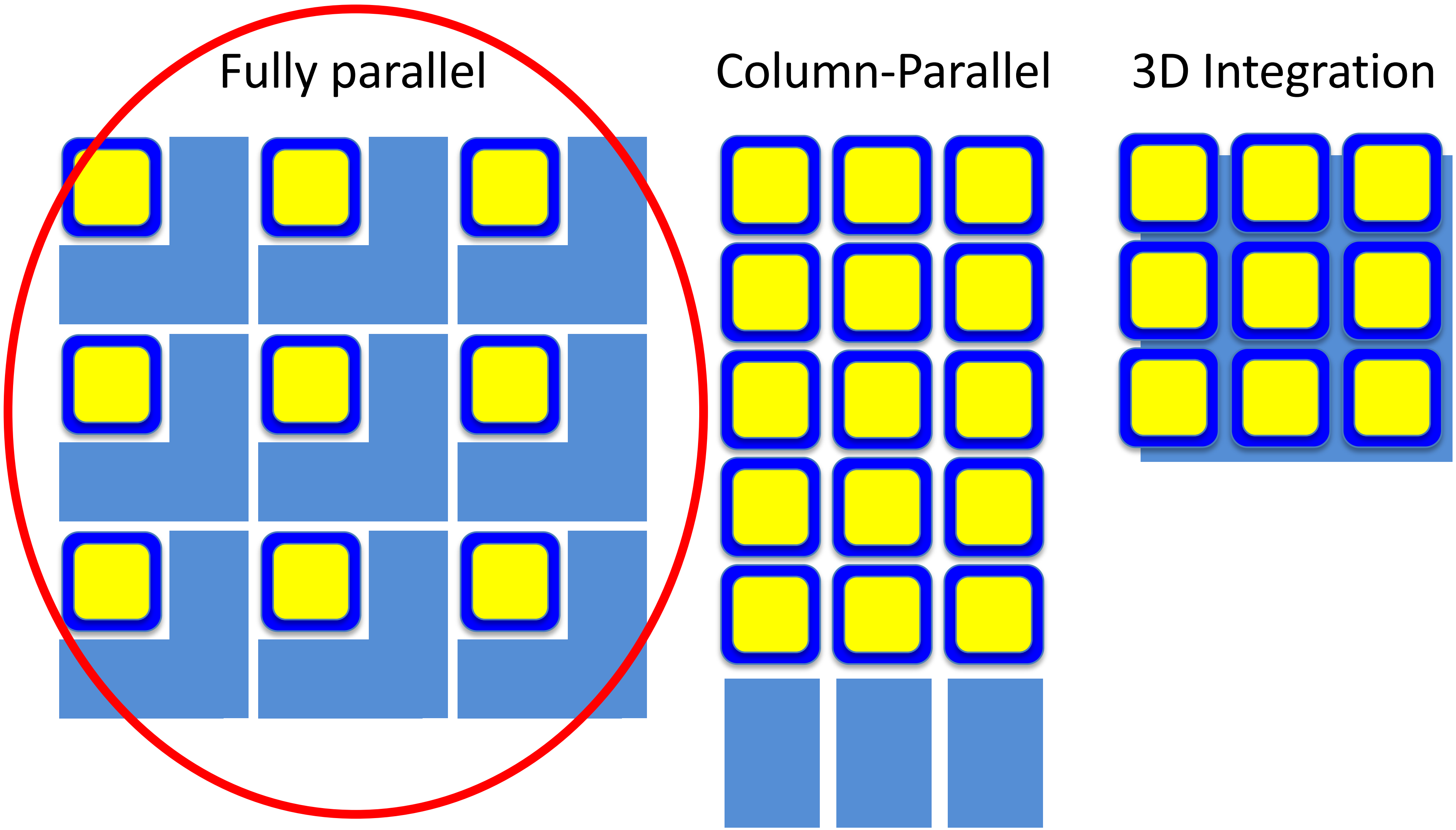
Illustrations: H. Homulle

2D Arrays

Fully parallel | Column-Parallel | 3D Integration



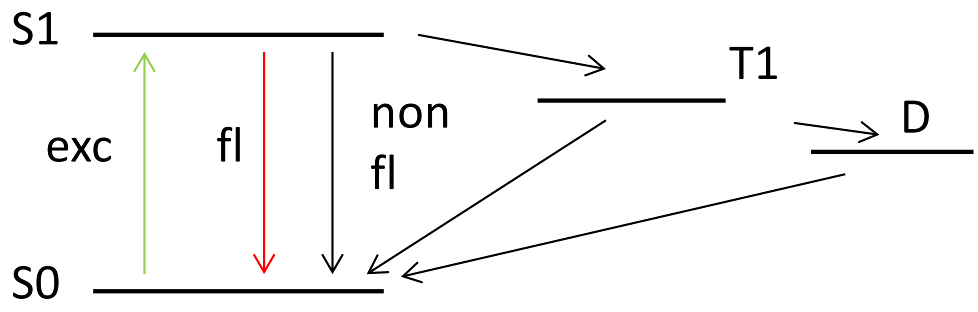
2D Arrays

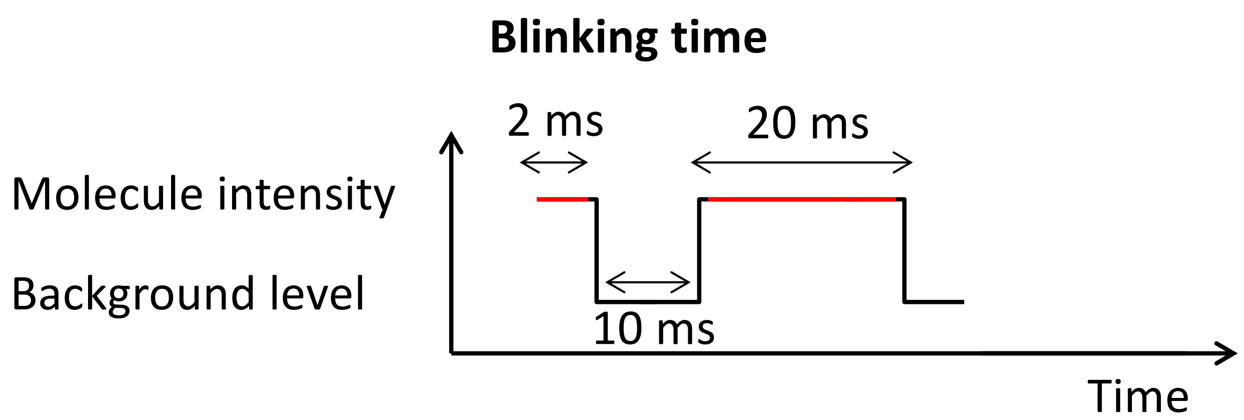


The GSDIM Super-resolution Project

Localization Super-resolution

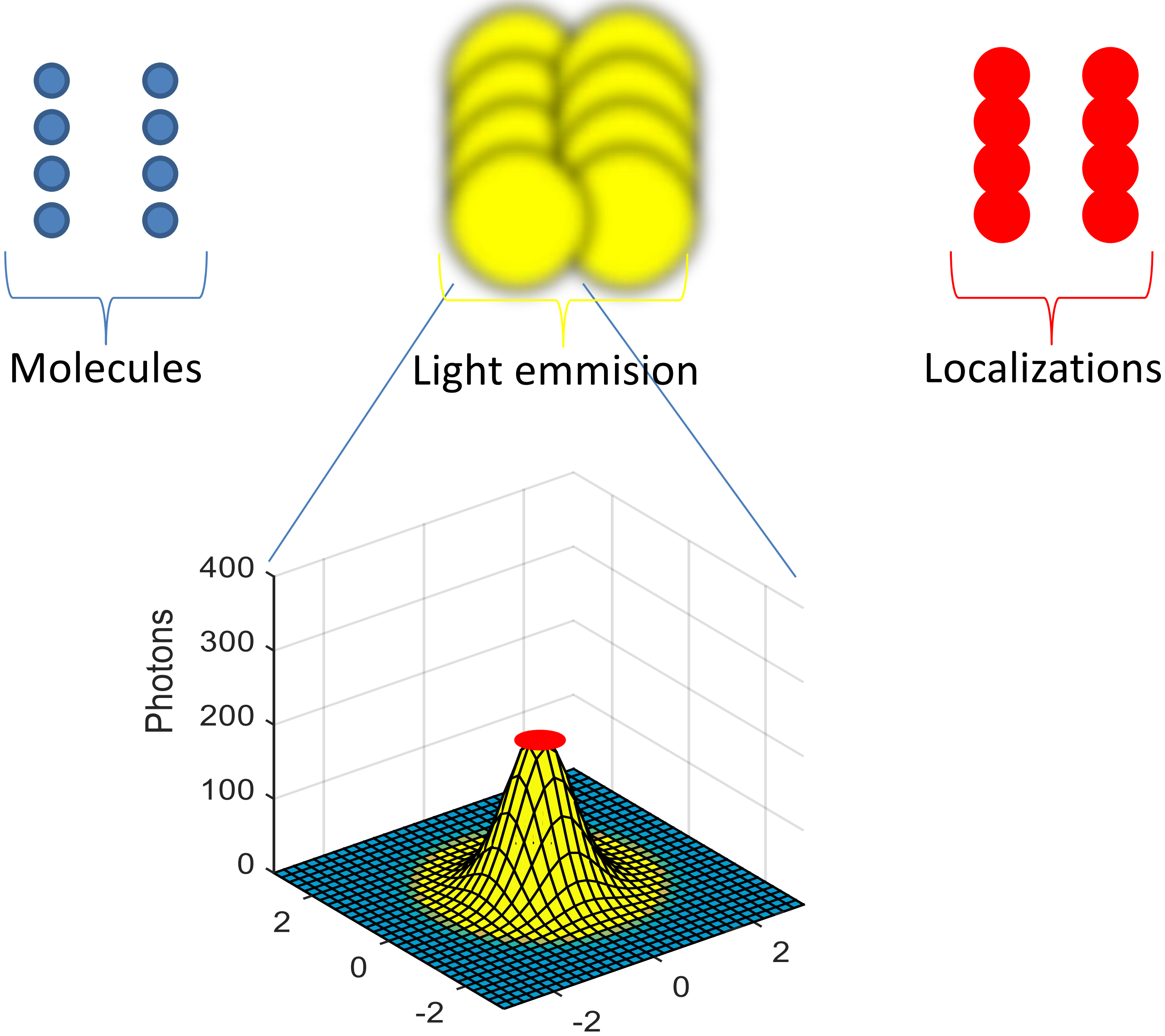
- PALM
- STORM
- dSTORM/GSDIM*



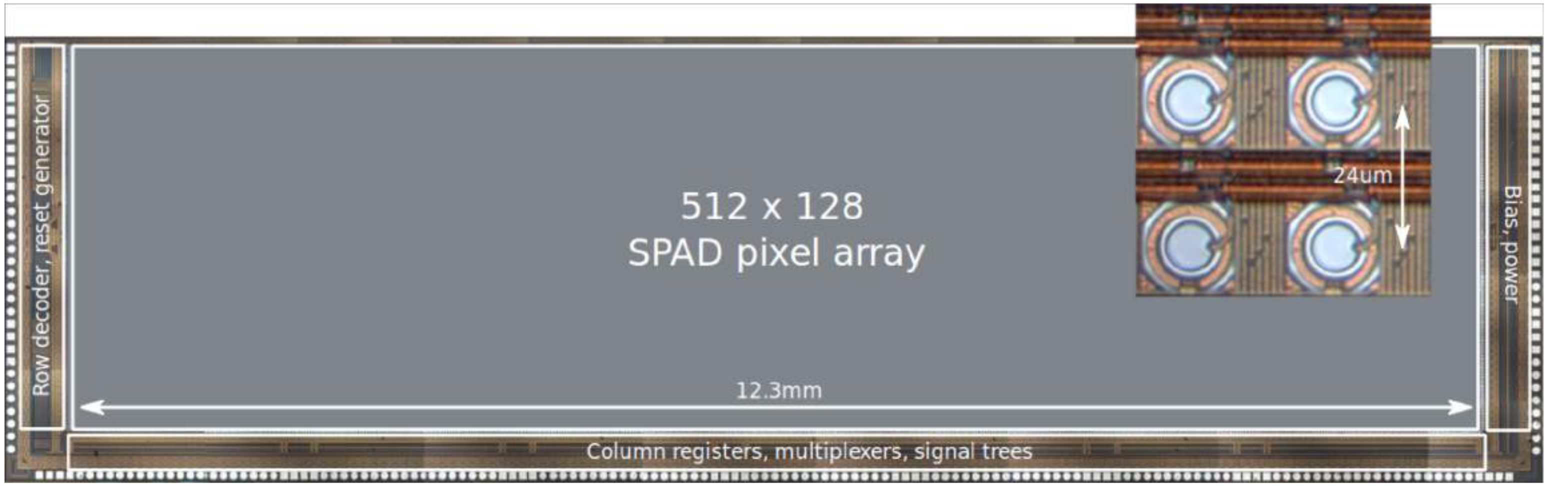


*) GSDIM = Ground-state depletion and single-molecule return

Localization Super-resolution

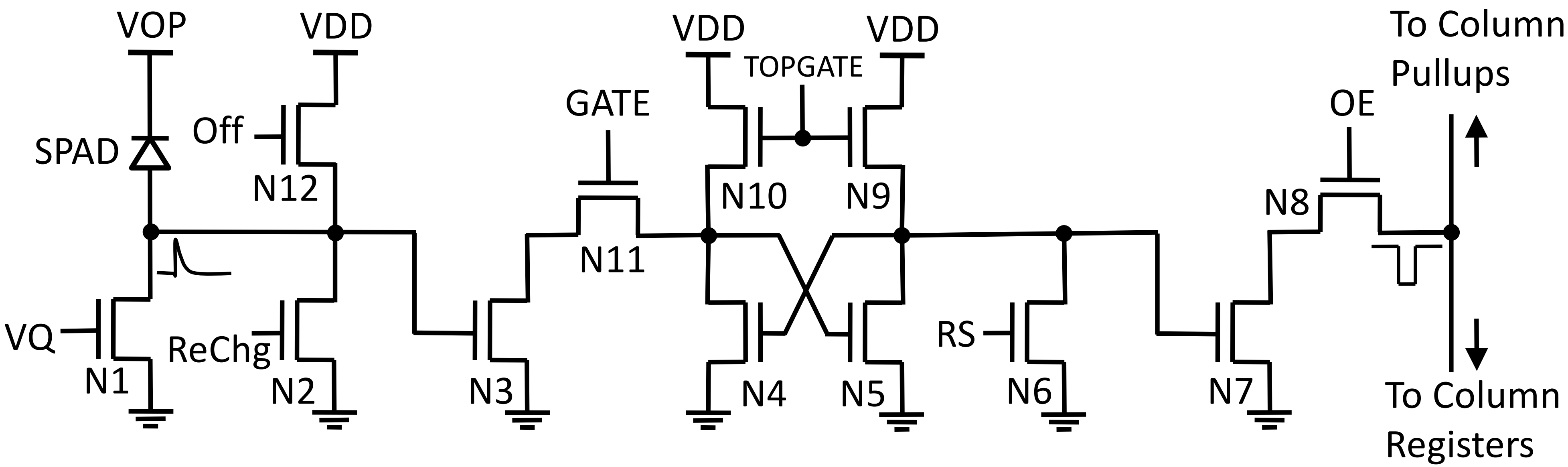


SwissSPAD



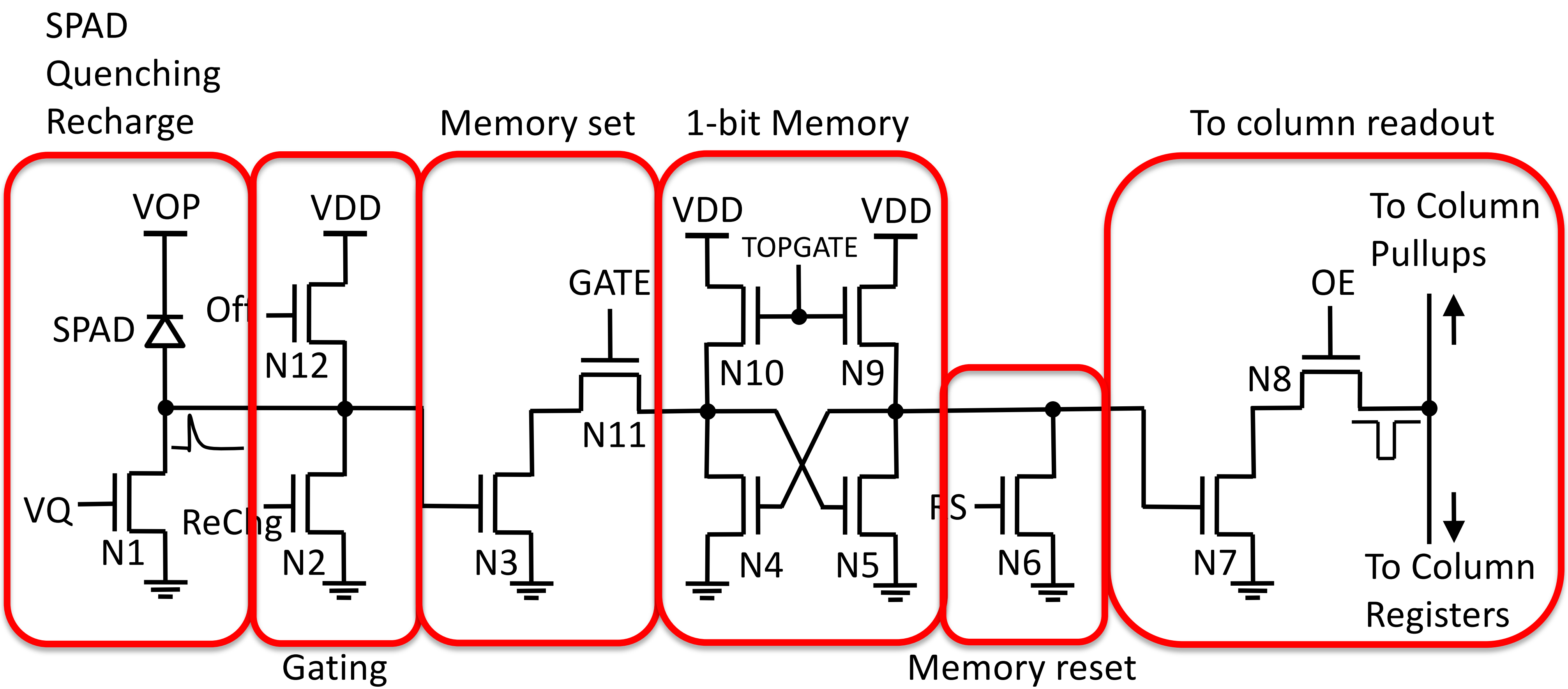
Burri et al., Optics Express 2014

Pixel Architecture



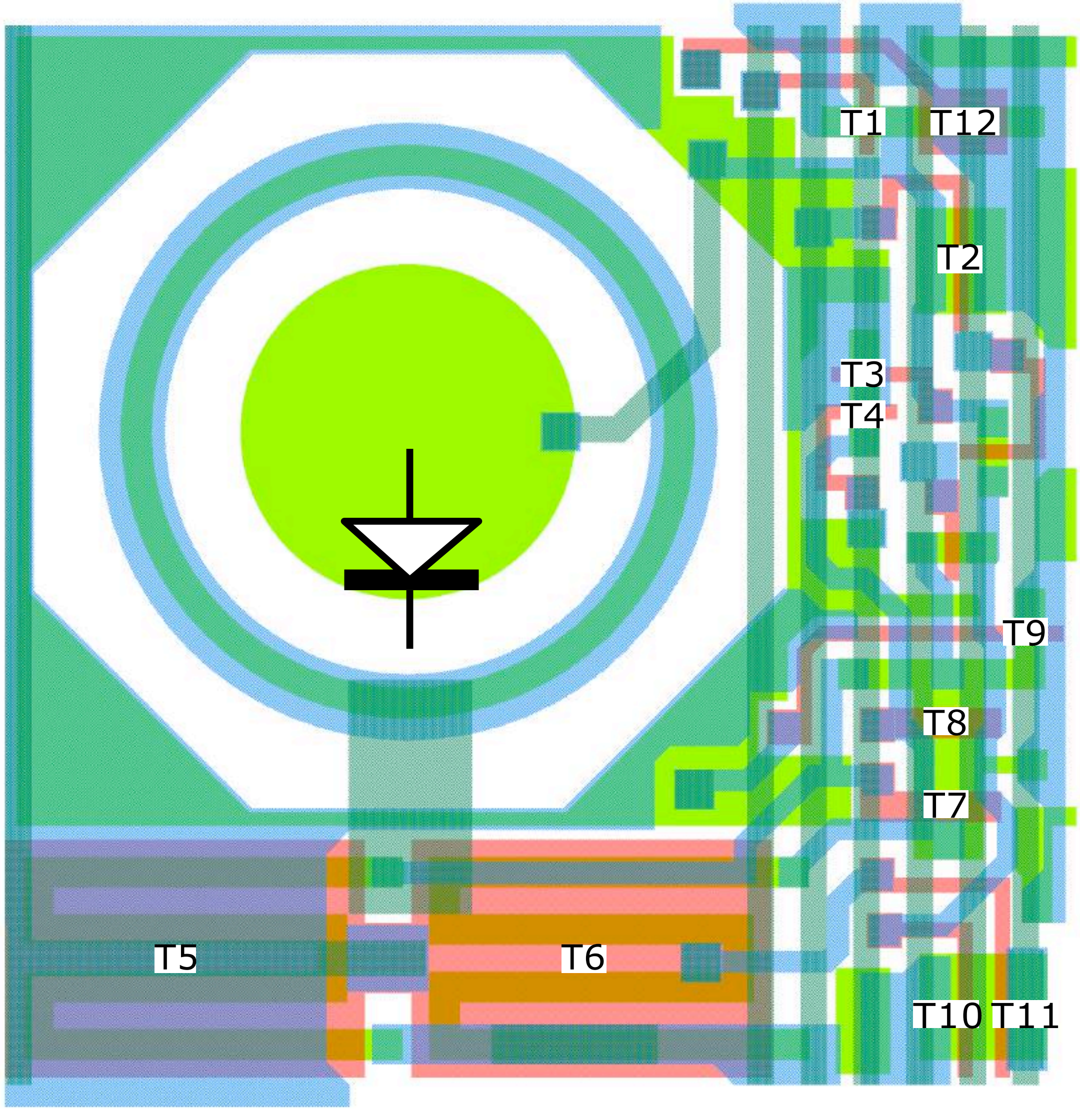
Burri et al., Optics Express 2014

Pixel Architecture

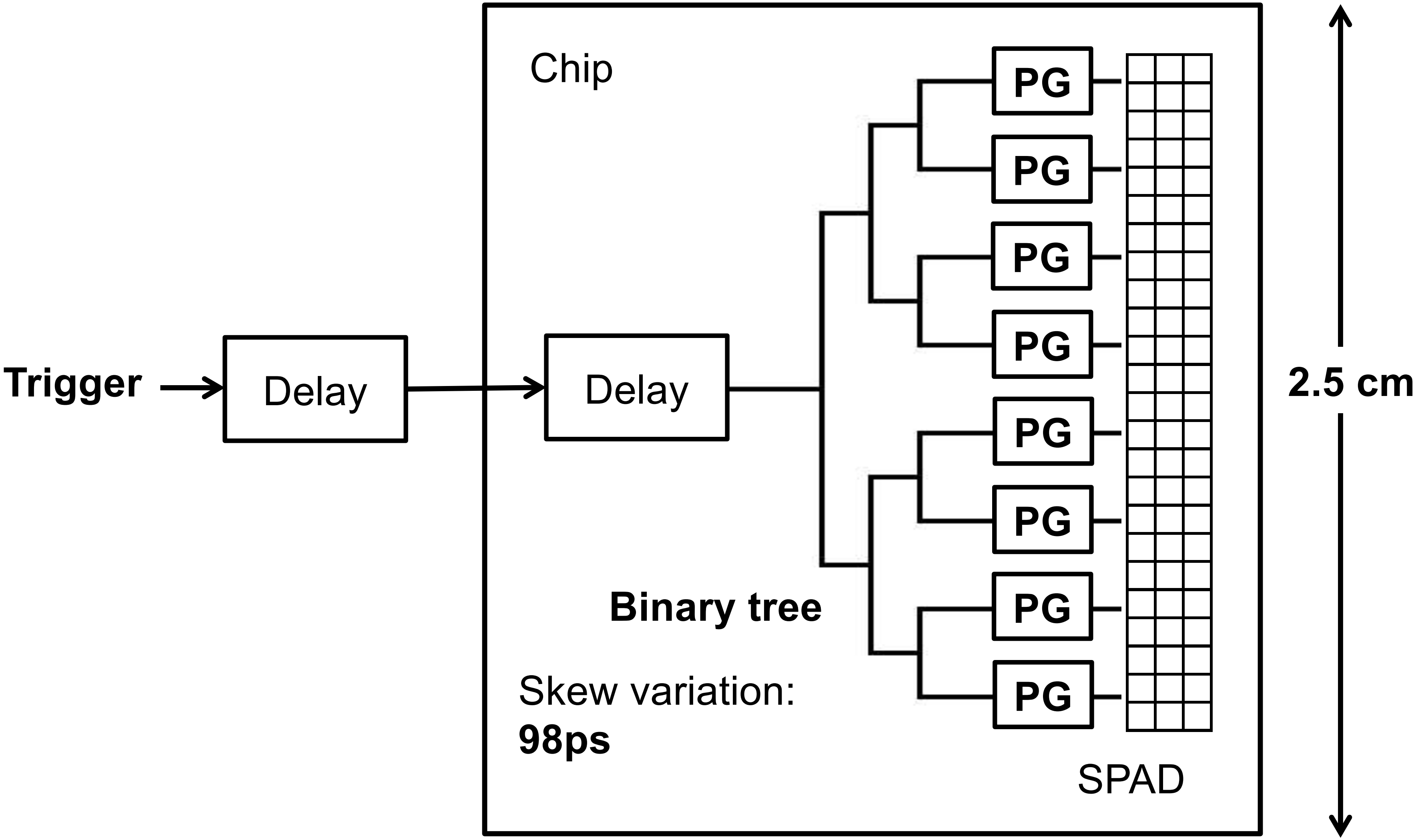


Burri et al., Optics Express 2014

Pixel Layout



Gating Synchronization: B-Trees

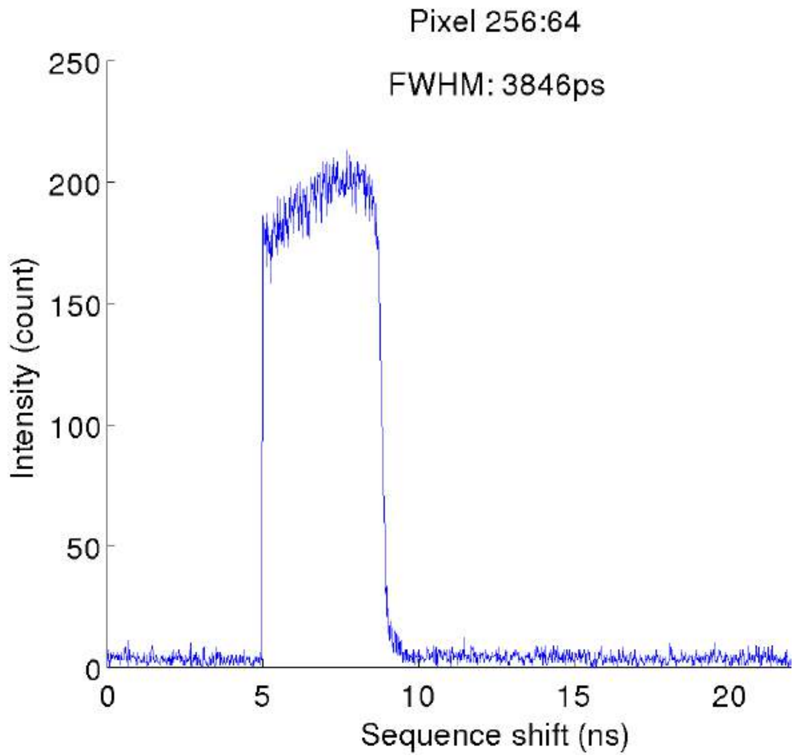


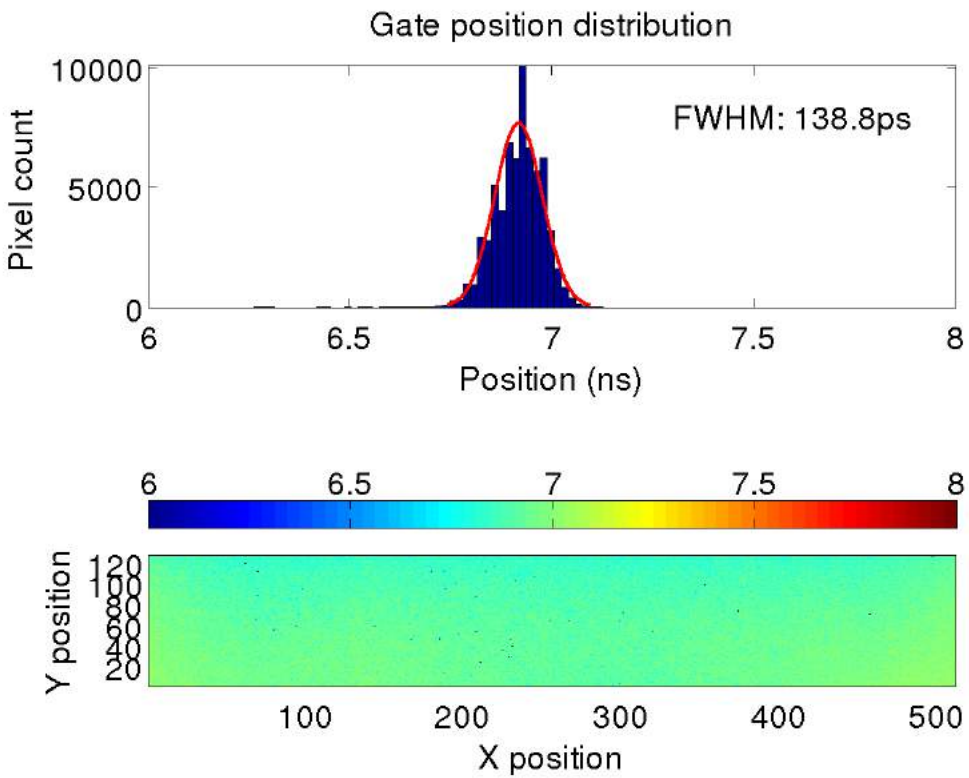
PG: Pulse Generator

Courtesy: Yuki Maruyama

Gate Accuracy and Uniformity

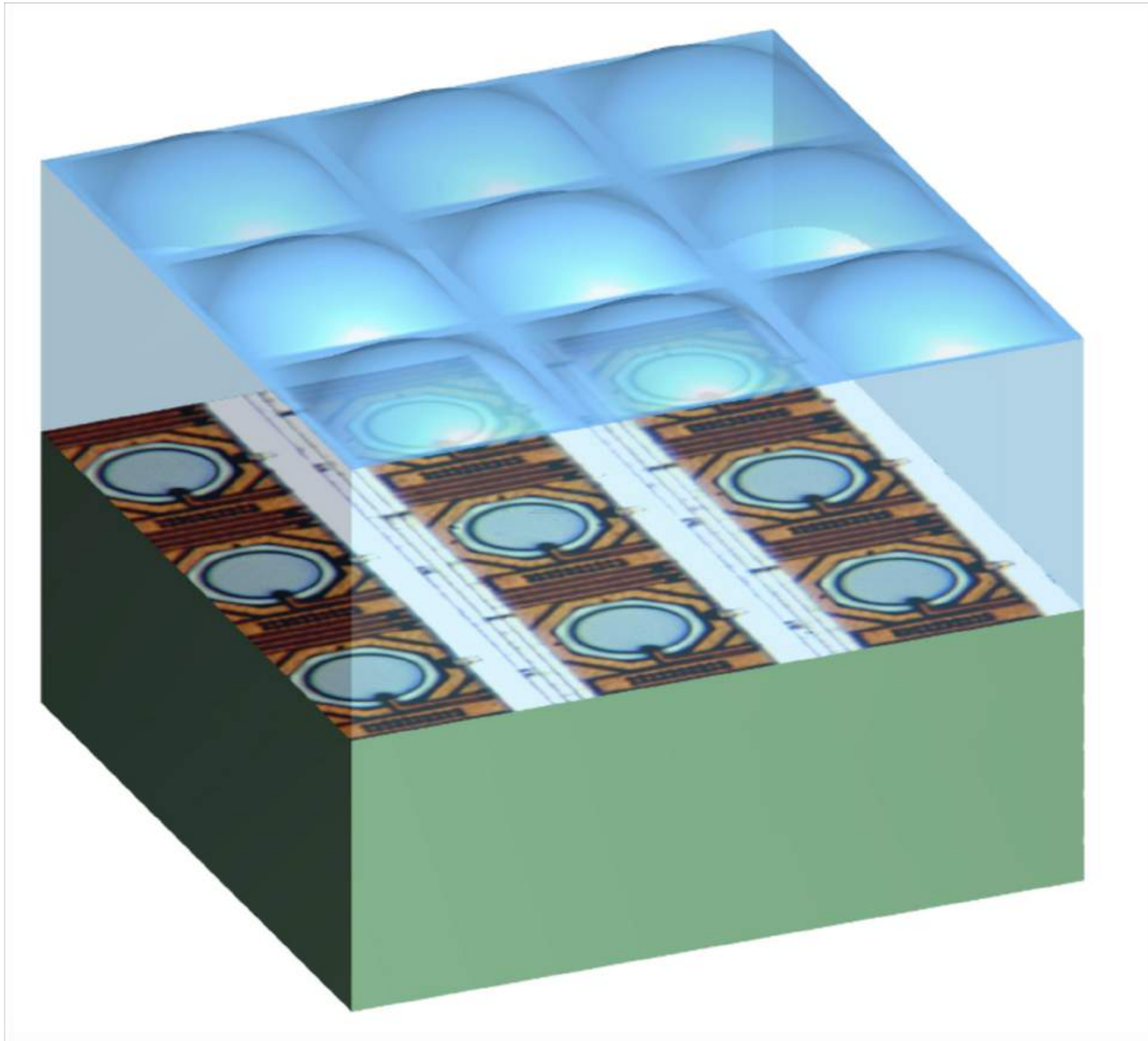
- 4ns gating (138ps FWHM)
- 156kfps frame rate



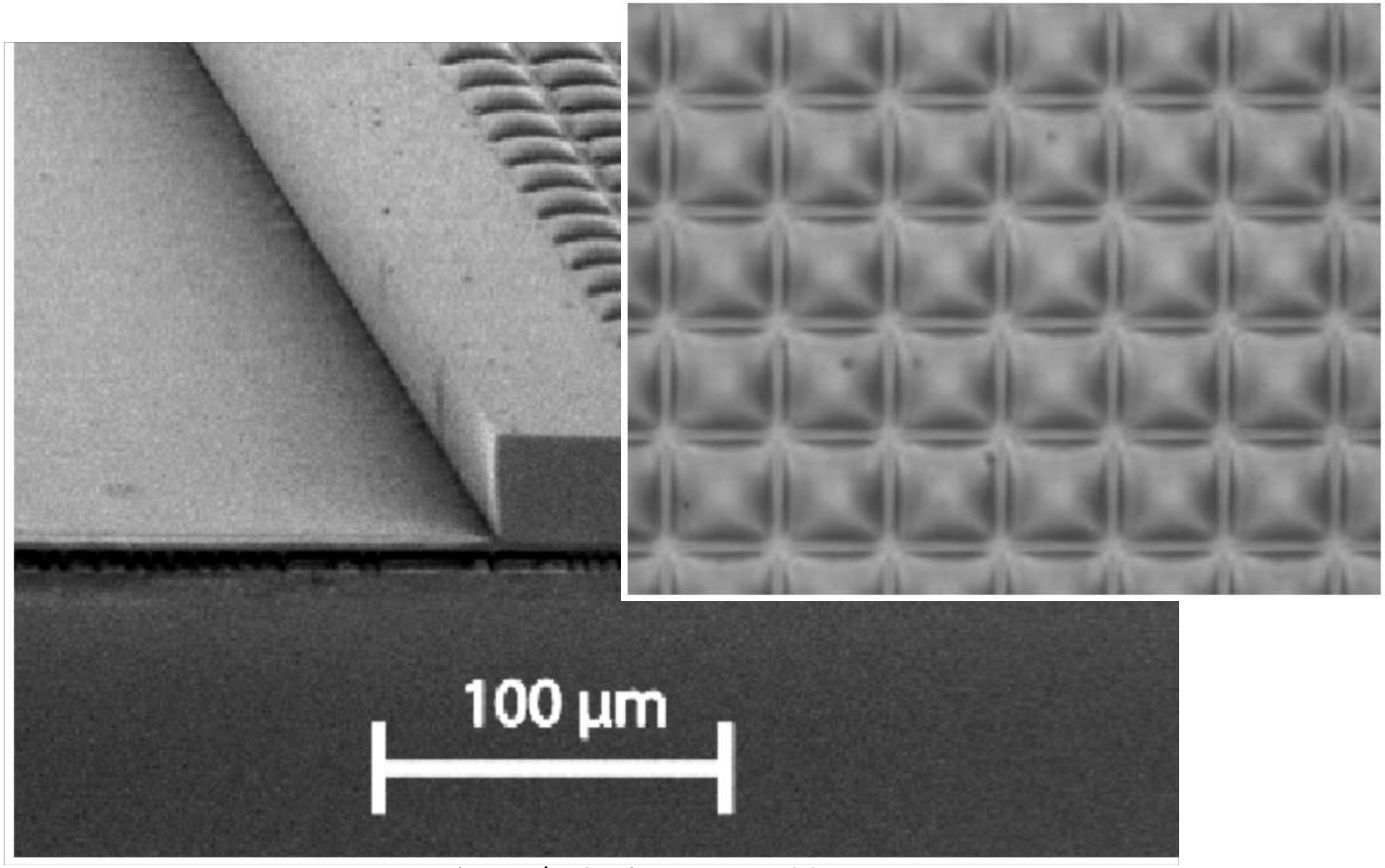


Burri et al., Optics Express 2014

Fill Factor Recovery: Microlenses

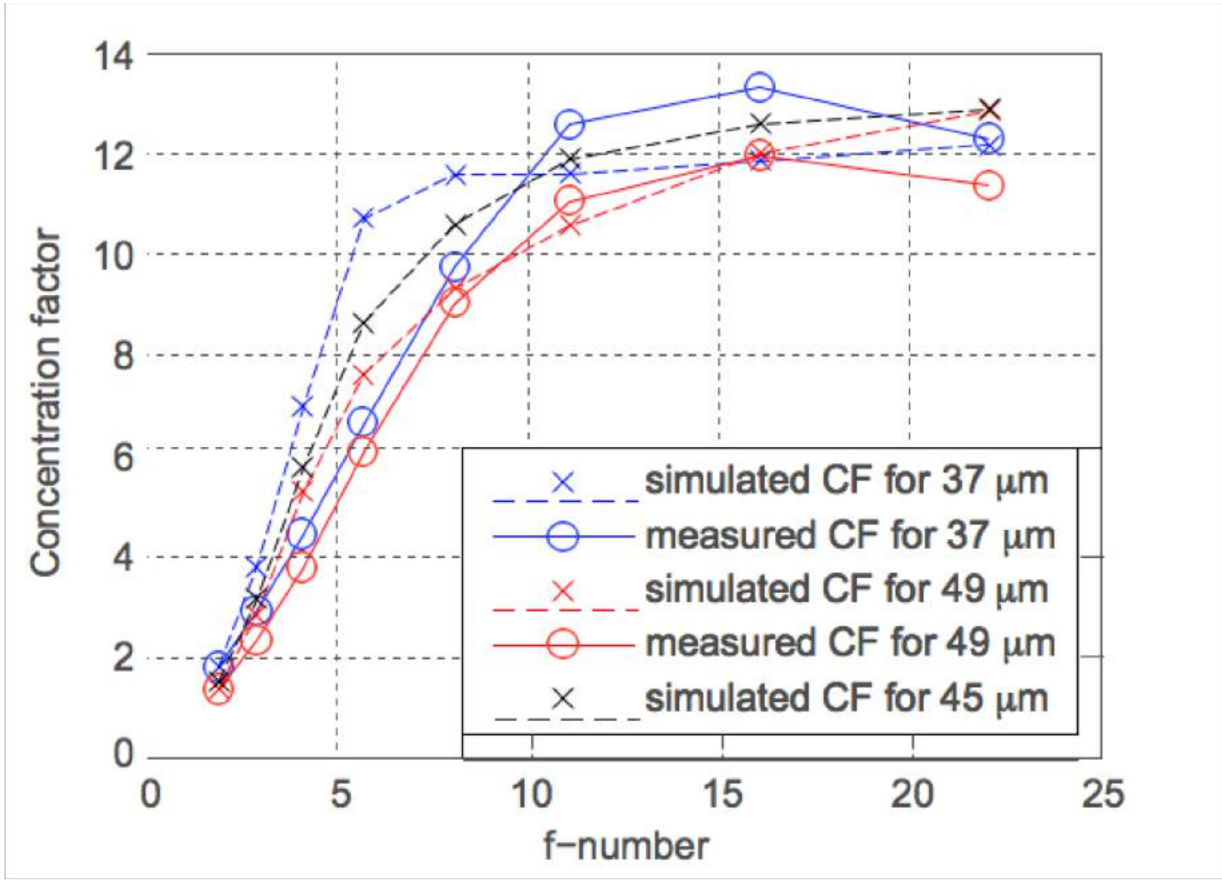


Fill Factor Recovery: Microlenses



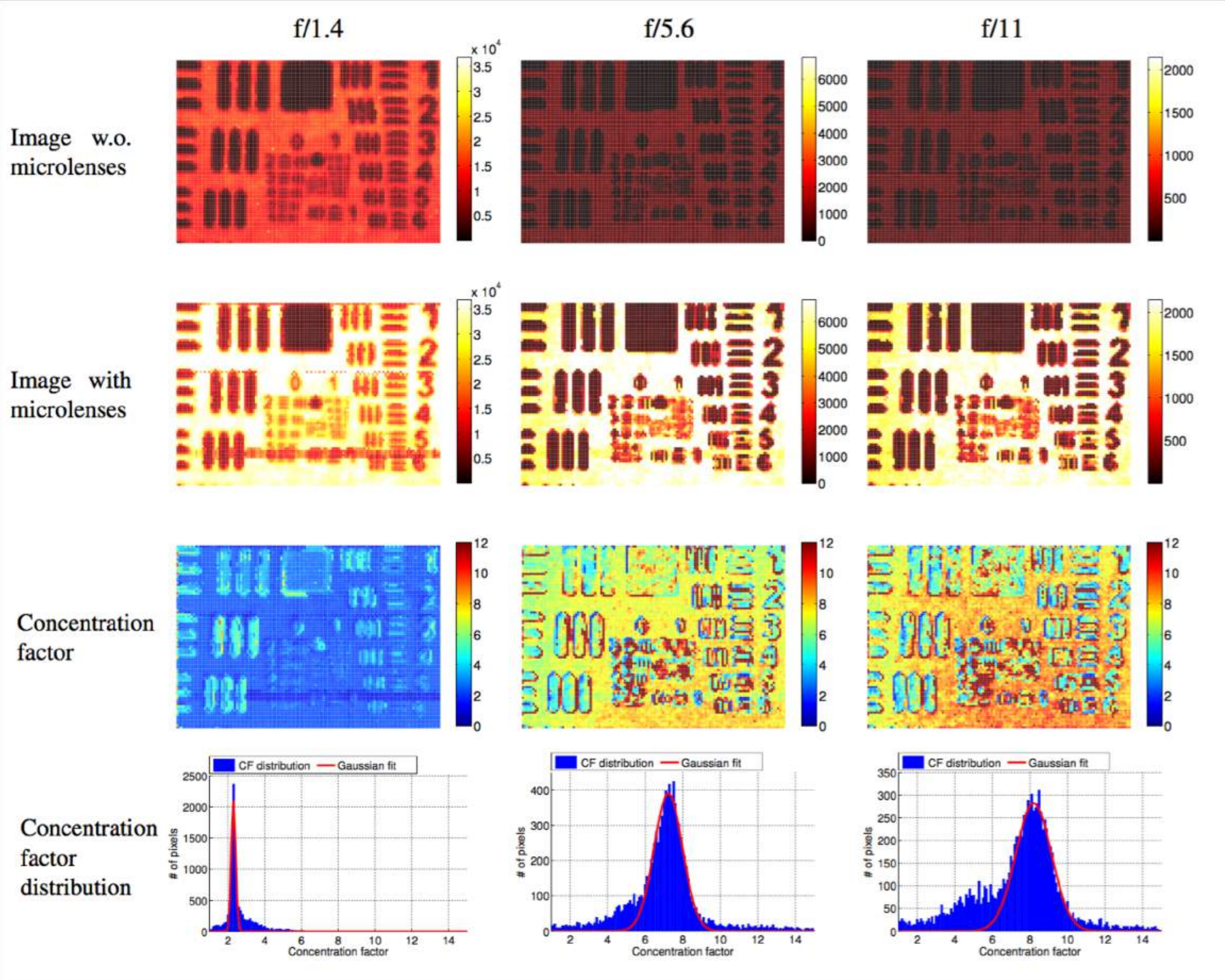
J. Mata Pavia et al., Optics Express 2014

Fill Factor Recovery: Microlenses



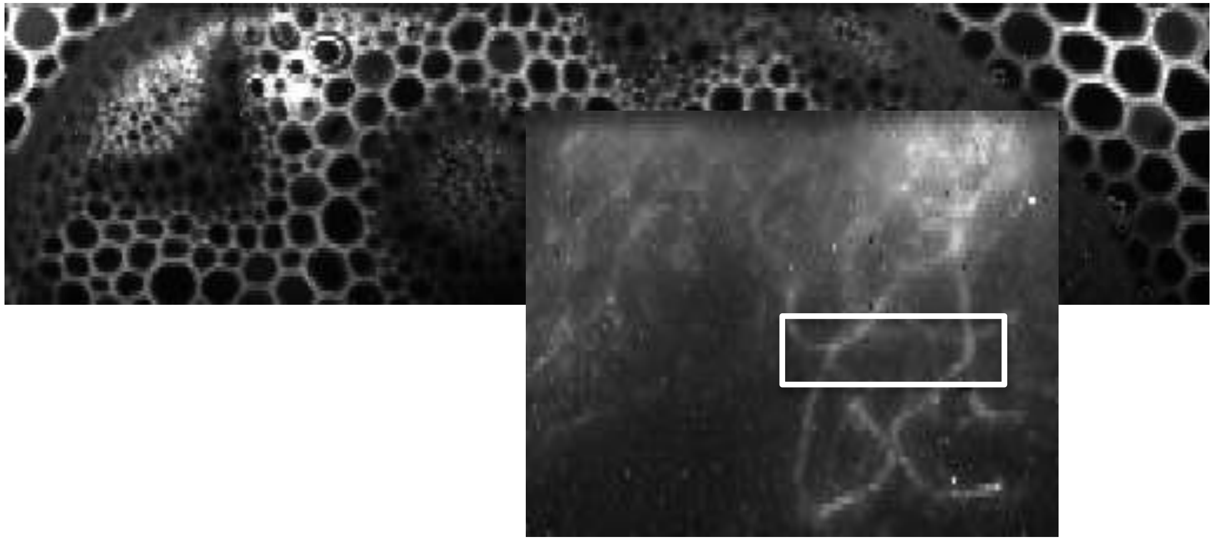
J. Mata Pavia et al., Optics Express 2014

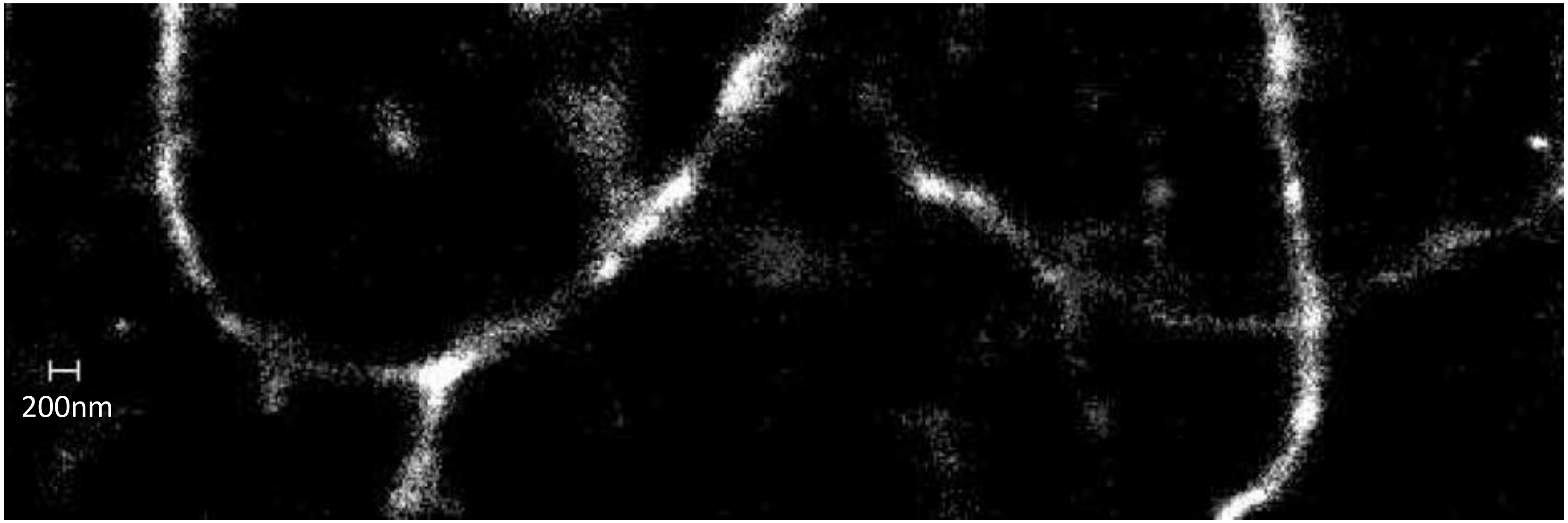
Fill Factor Recovery: Microlenses



J. Mata Pavia et al., Optics Express 2014

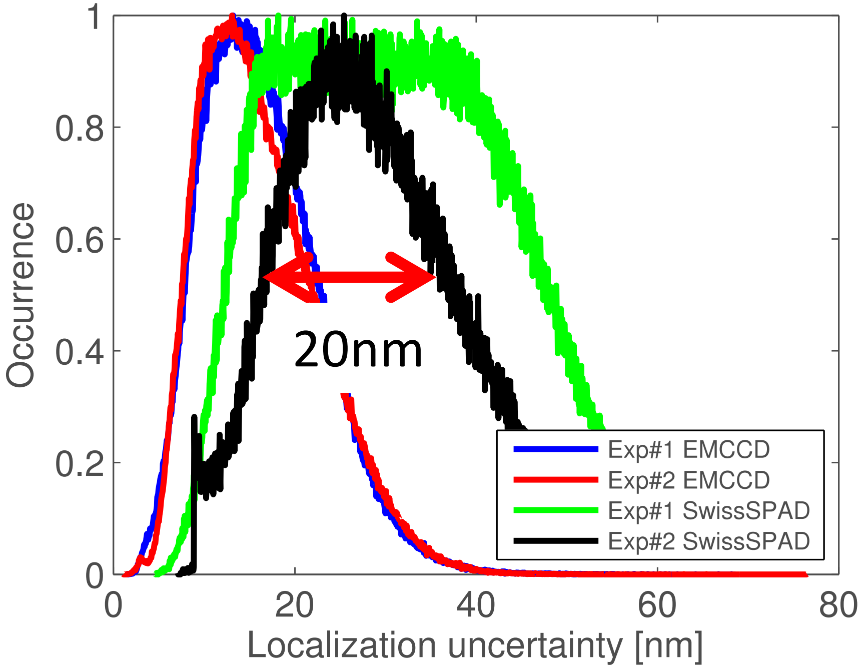
GSDIM Images

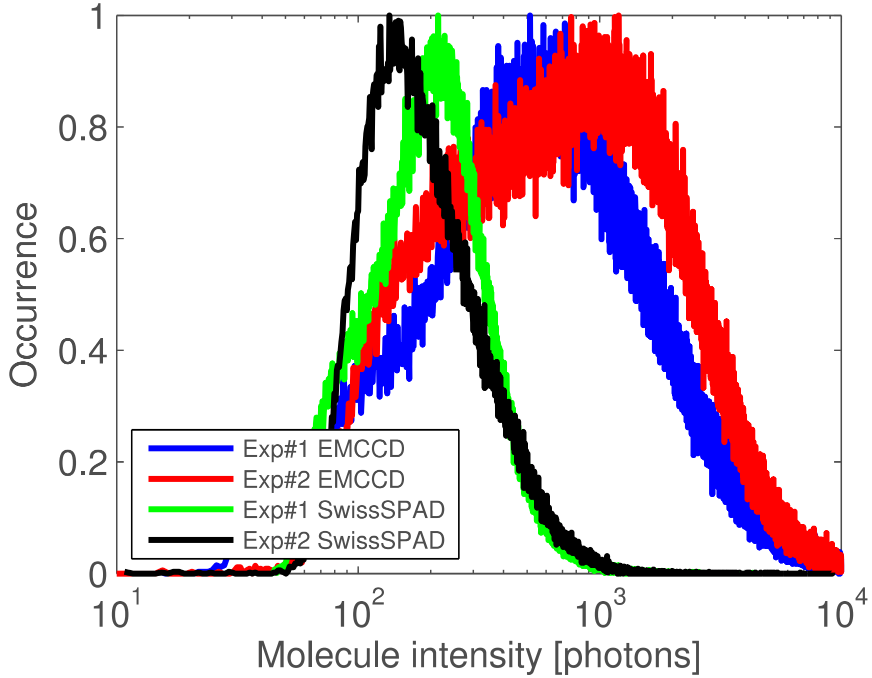




I.M. Antolovic, S. Burri, R. Hoebe, Y. Maruyama, C. Bruschini, E. Charbon, MDPI Sensors, **16**, 1005, 2016

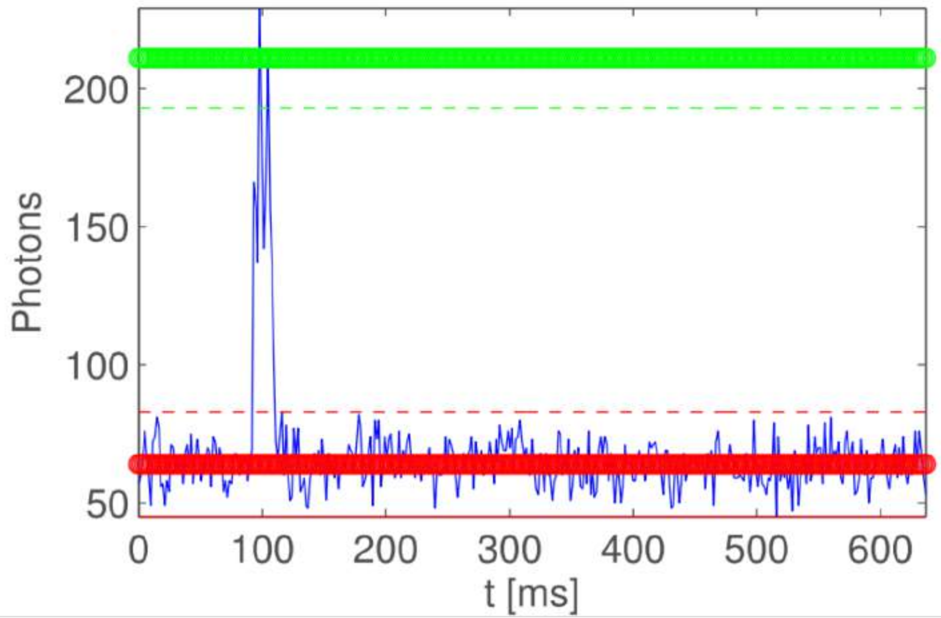
Localization Accuracy



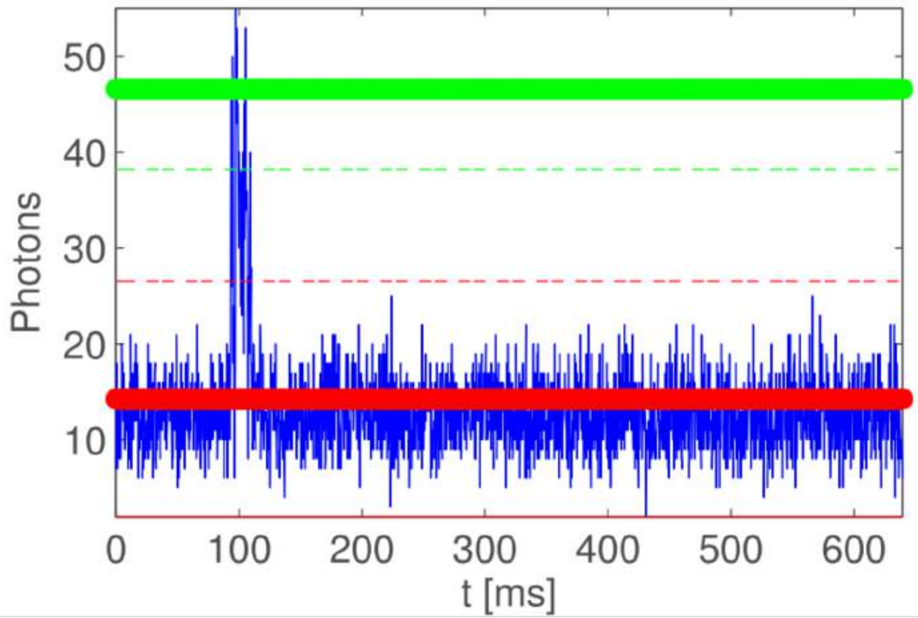


Blinking Statistics

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



1.6ms resolution



0.3ms resolution

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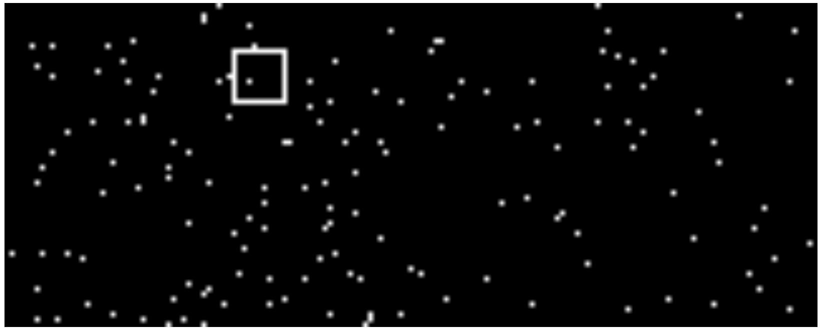
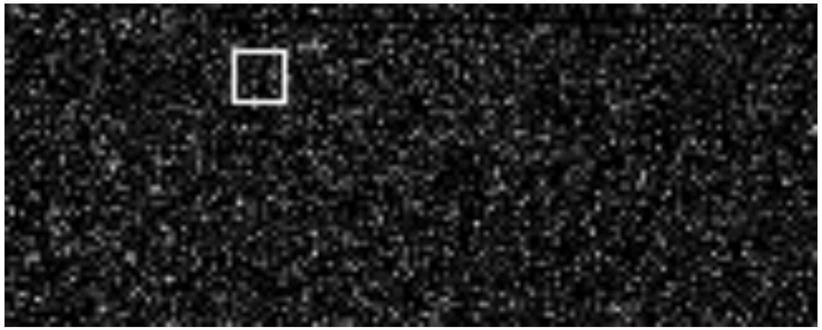
Blinking Effects

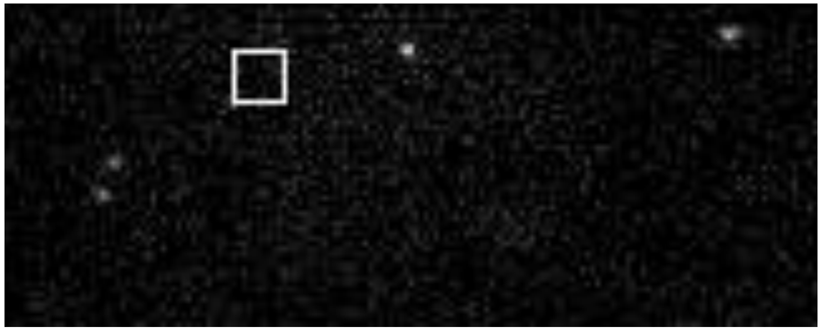


6.4 μs frame time

1.6 ms frame time

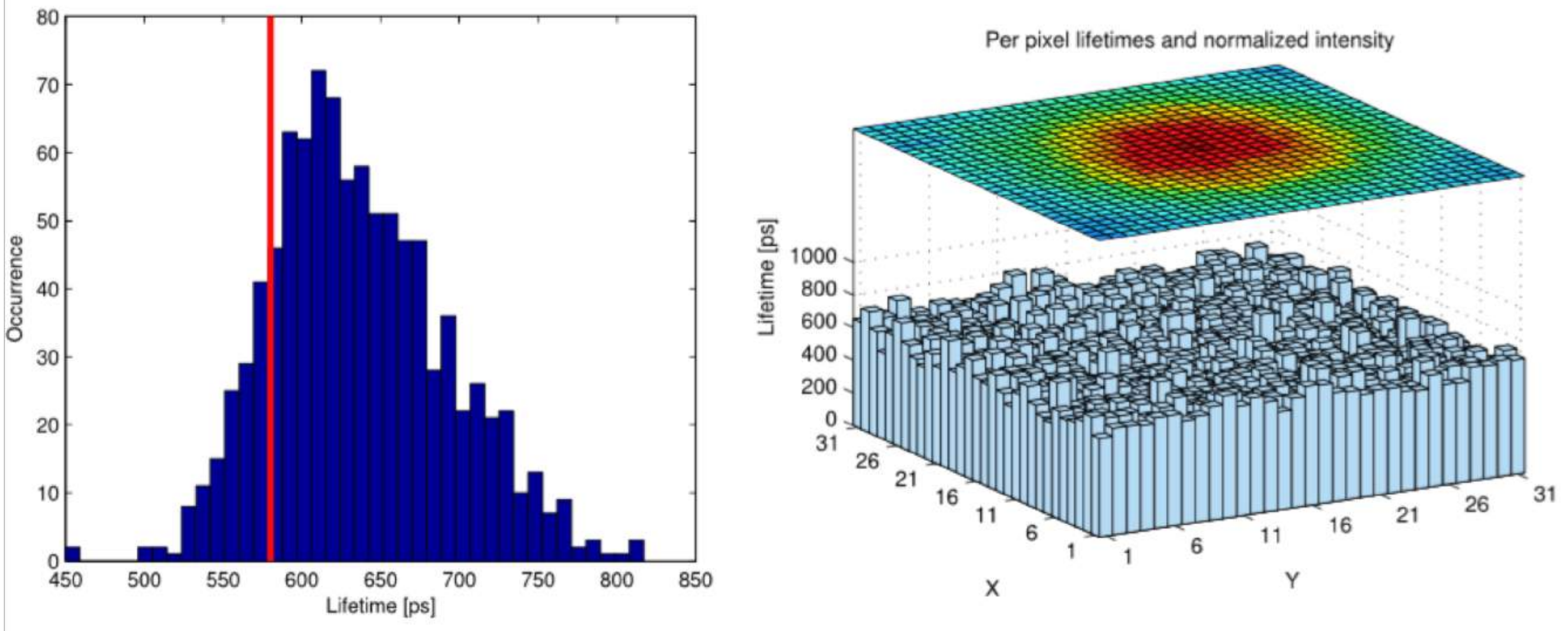


0.3 ms frame time



10 ms frame time

Fluorescence Lifetime Microscopy (FLIM)



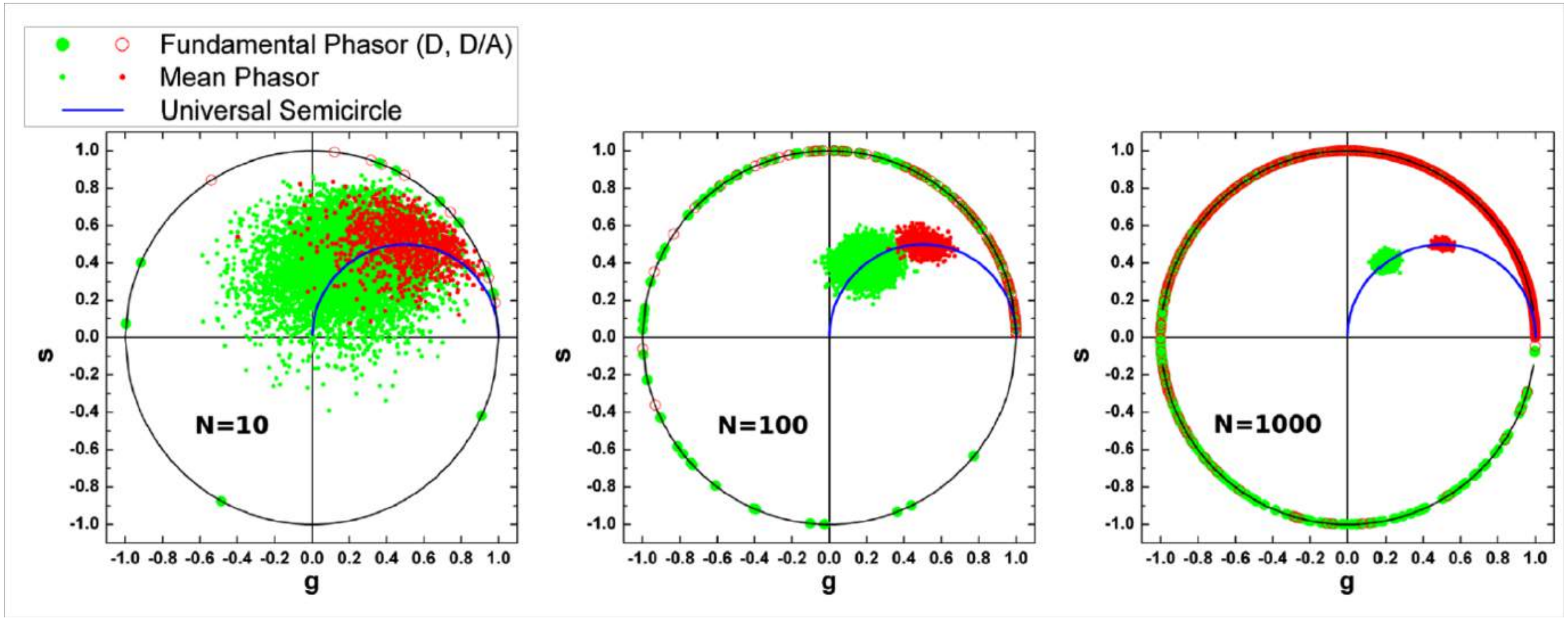
(a) (b)

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.

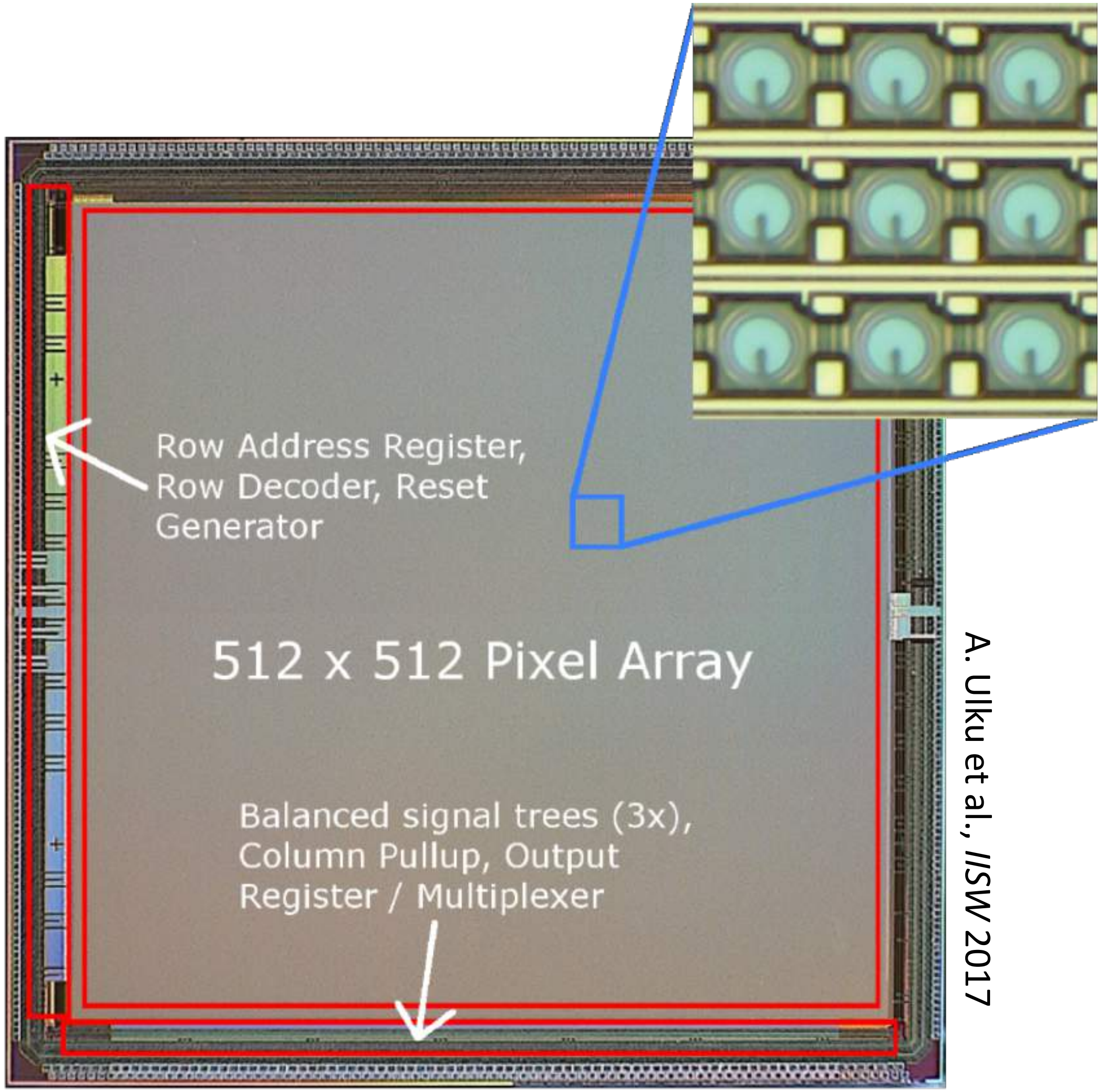
I.M. Antolovic, S. Burri, R. Hoebe, Y. Maruyama, C. Bruschini, E. Charbon, MDPI Sensors, **16**, 1005, 2016

Phasor Representation

- Real-time FLIM has demanding processing requirements resulting from the following stages:
  - Histogram generation
  - Fitting algorithms to find fluorescence lifetime
- These steps are eliminated by using phasor analysis.

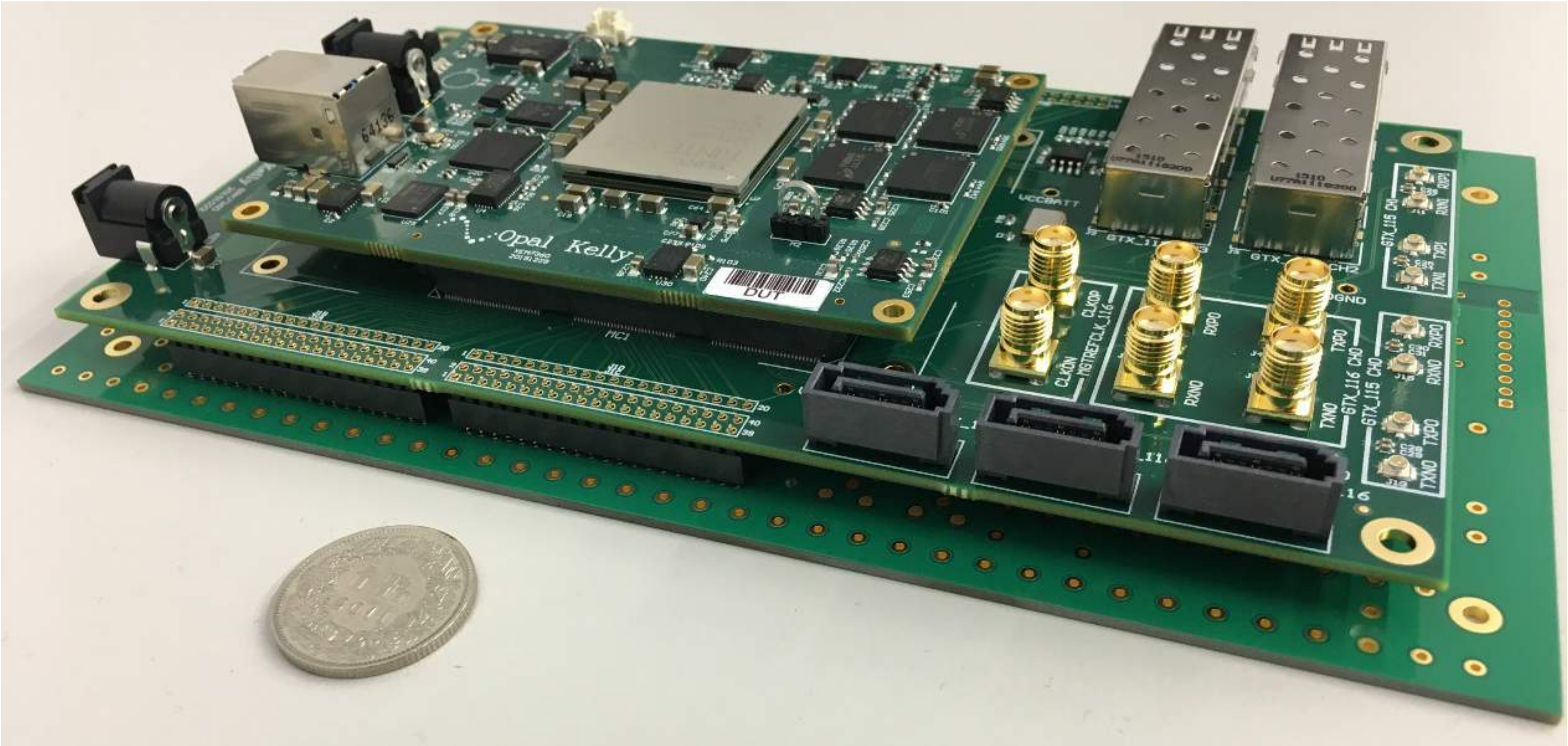


SwissSPAD2



A. Ulku et al., *IISW* 2017

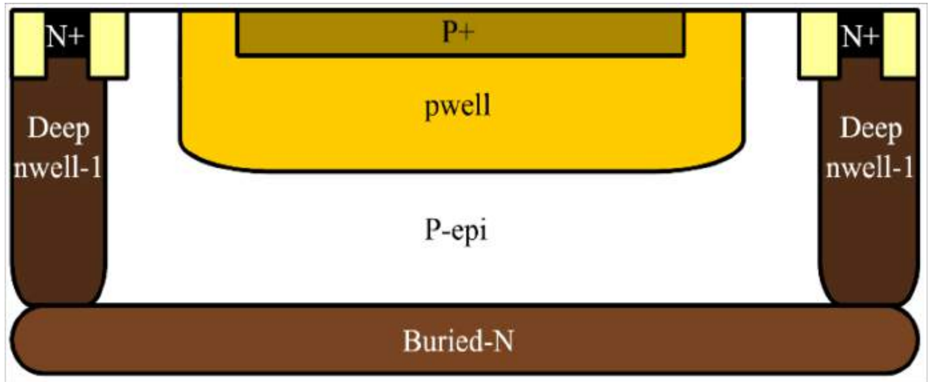
SwissSPAD2 System

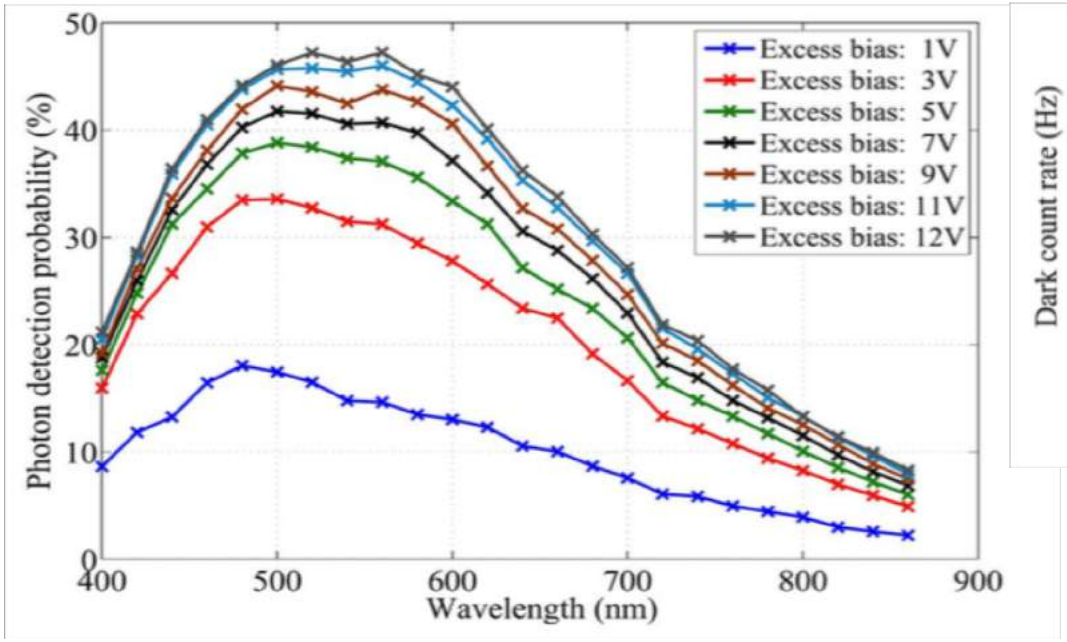


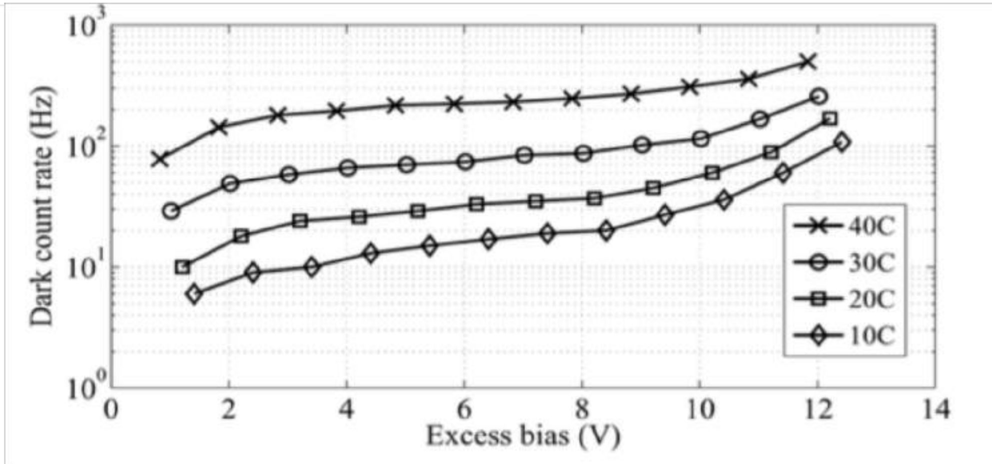
A. Ulku et al., IISW 2017

SwissSPAD2

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



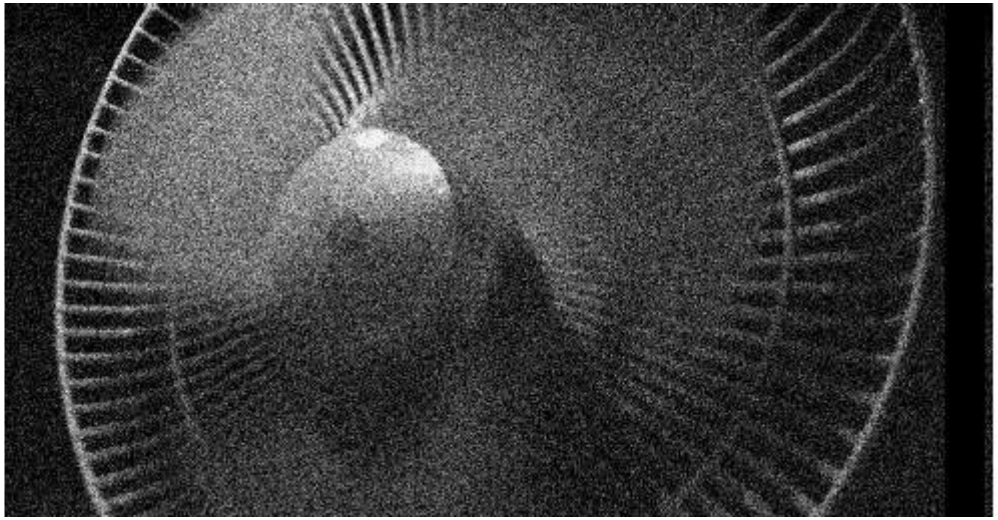




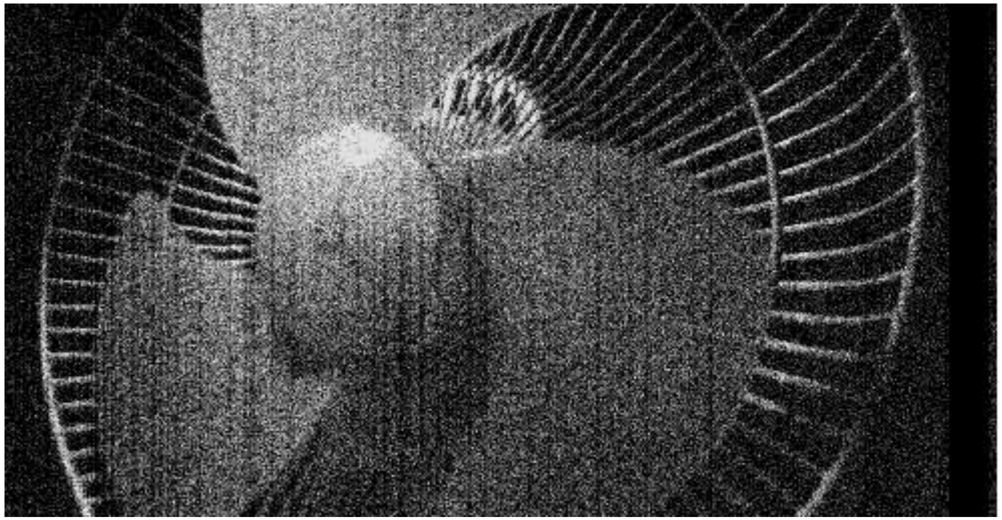
A. Ulku et al., *IISW* 2017

SwissSPAD-2 Speed Trials

10kfps, 3 bits



100kfps, 1 bit

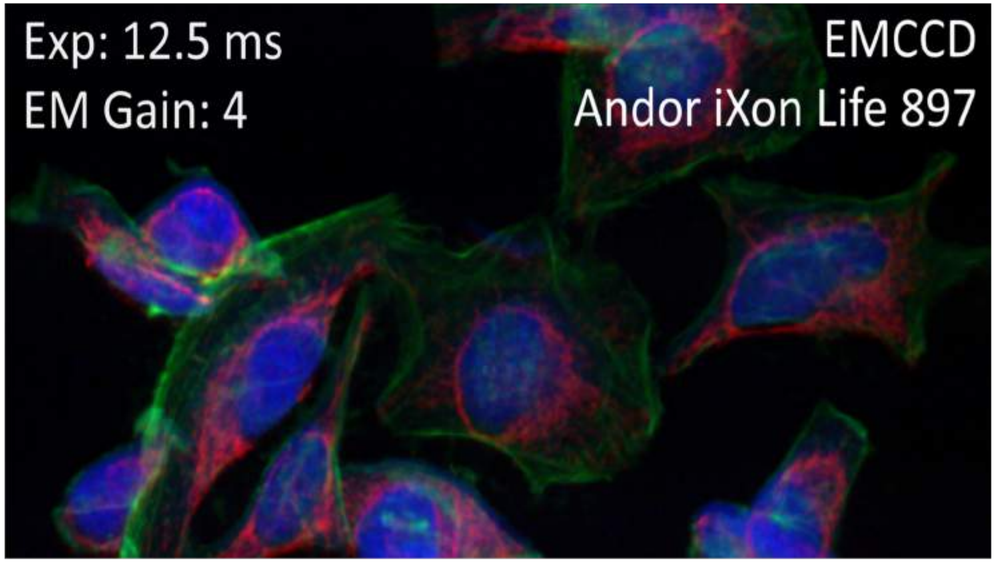


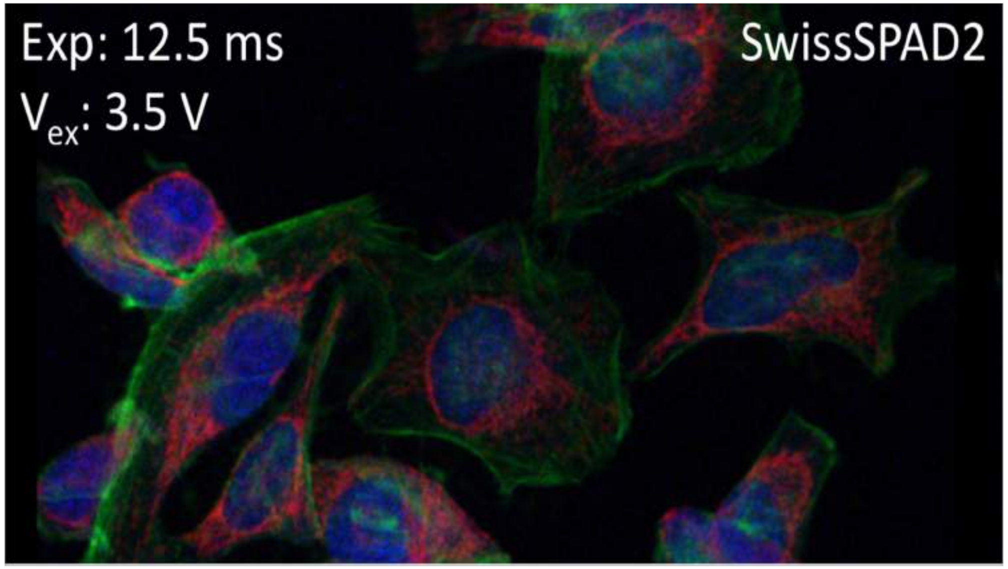
A. Ulku et al., talk at *IISW* 2017

Multi-dye Fluorescence Microscopy (HeLa Cells)

Read Noise: < 1 e^-
QE_{max}: > 95% @ 560 nm
(100% Fill Factor)

Read Noise: 0
PDP_{max}: > 42% @ 520 nm
(10.5% Fill Factor w/o microlenses)





Microscope: Olympus ix81 Inverted, Objective: 40×

Nucleus:
DAPI (358/461 nm)

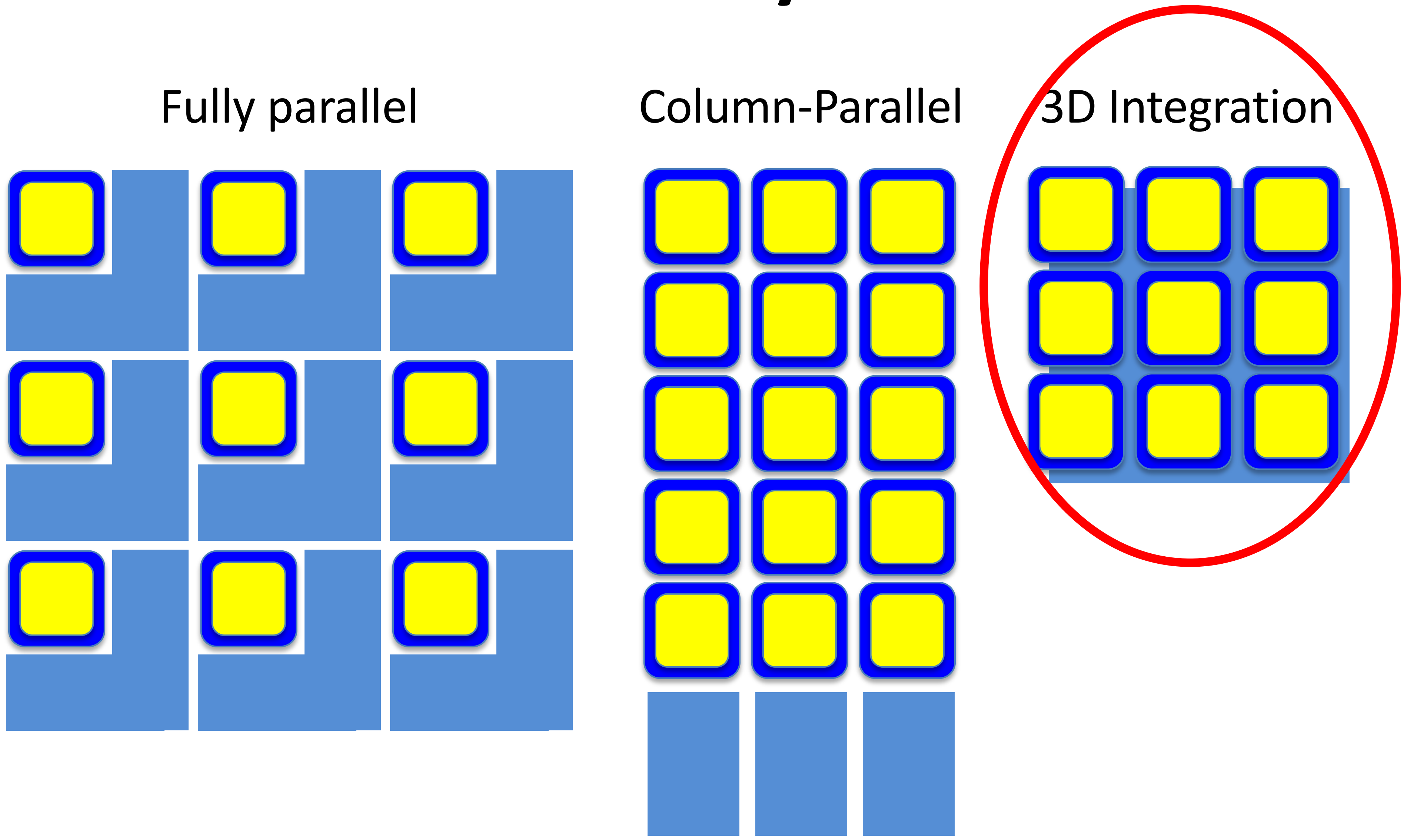
Actin:
Alexa 488 (490/525 nm)

Mitochondria:
Alexa 555 (555/580 nm)

A. Ulku, C. Bruschini, S. Weiss, X. Michalet, E. Charbon, SPIE PW 2018

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

2D Arrays



3D (IC) for 3D (Imaging)

3D Imaging Techniques

- Direct time-of-flight
  - Explicit measurement of the time
  - No ambiguity but precise chronometer per pixel

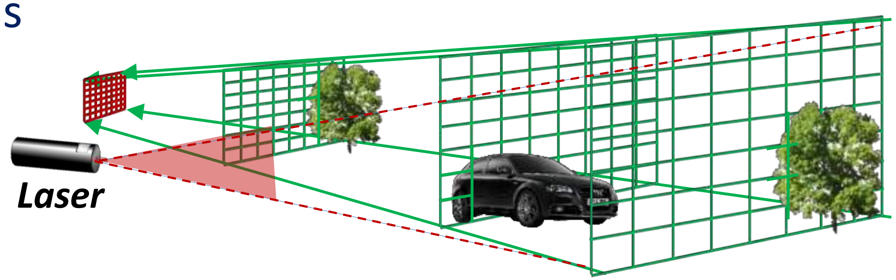
- Indirect time-of-flight
  - Implicit measurement through phase
  - Ambiguity but simple to implement

Flash vs. Scanning for Auto LiDAR

"Flash" illumination: elegant but impractical for Auto

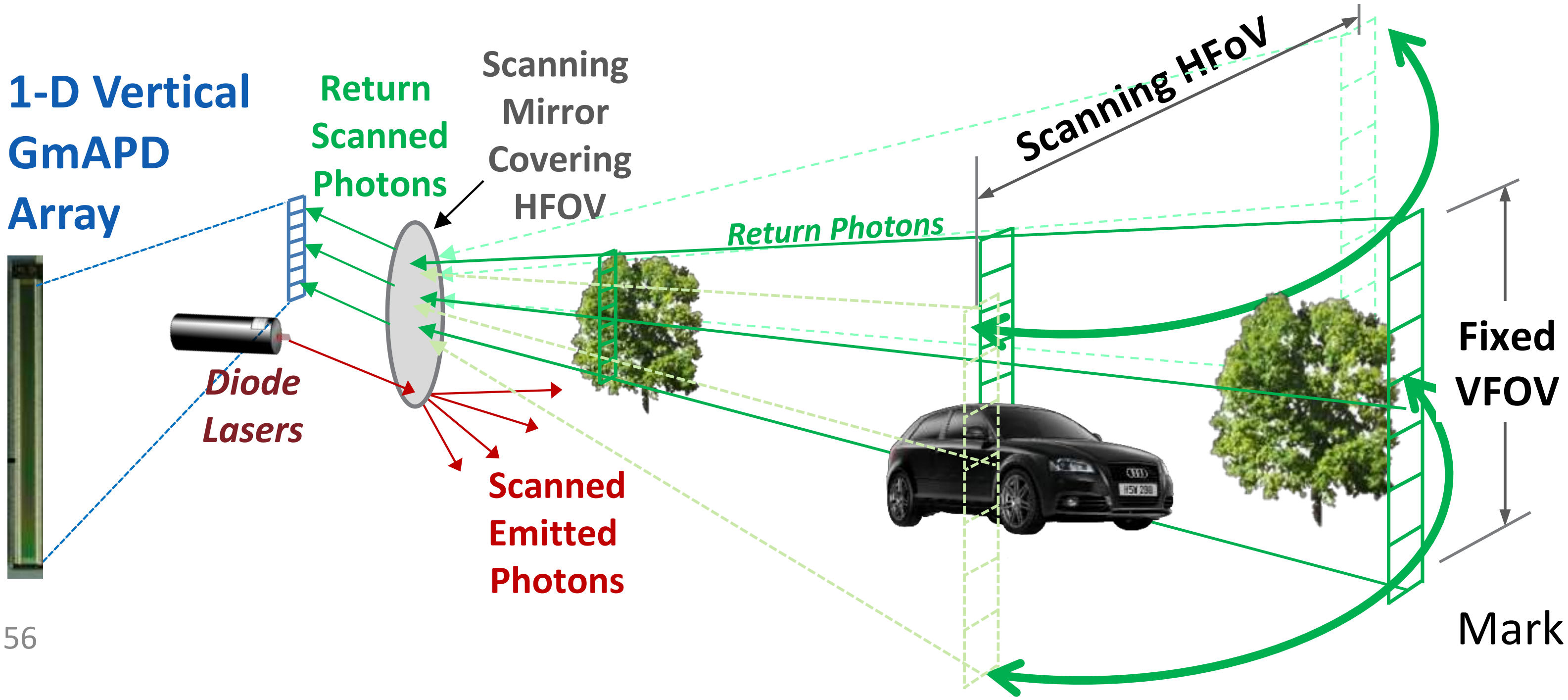
~100° FOV with 0.1° resolution needs 1000 pixels in one direction → ~Mpixel 2D array

Even given Mpixel array, illuminating all pixels takes prohibitive laser energy



Scanning provides best balance of laser/detector resources

Image vertical FOV with ~1000 pixel 1D array, scan to cover horizontal FOV



Mark Itzler, Argo AI

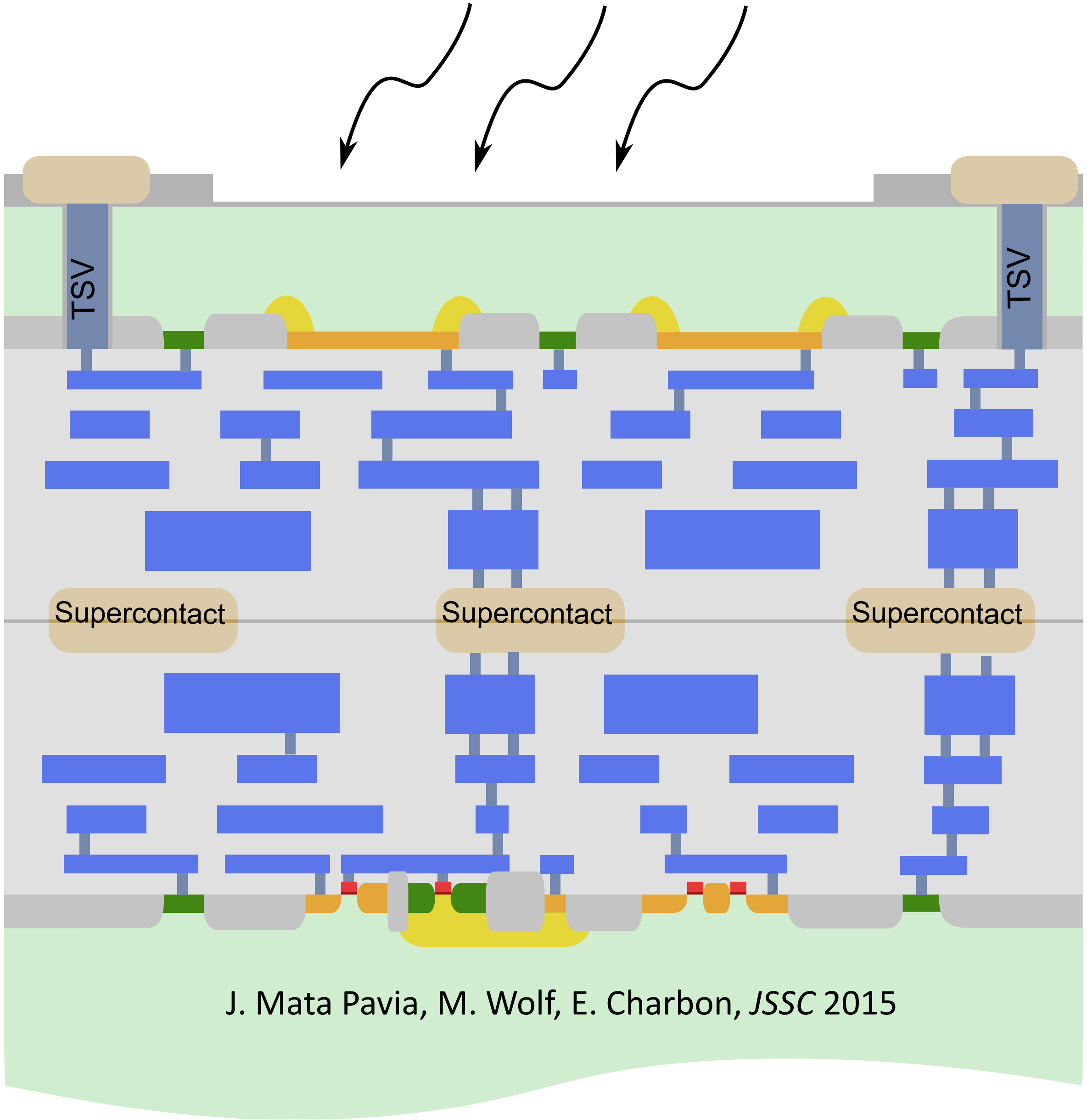
Our Strategy (ISSCC 2018)

- At large distances: single-point measurement
- At medium distances: small FOV (32x32)
- At short distances: maximum FOV (256x256)

- We achieved this with *automatic clustering* of SPADs with <u>variable laser scanning</u>

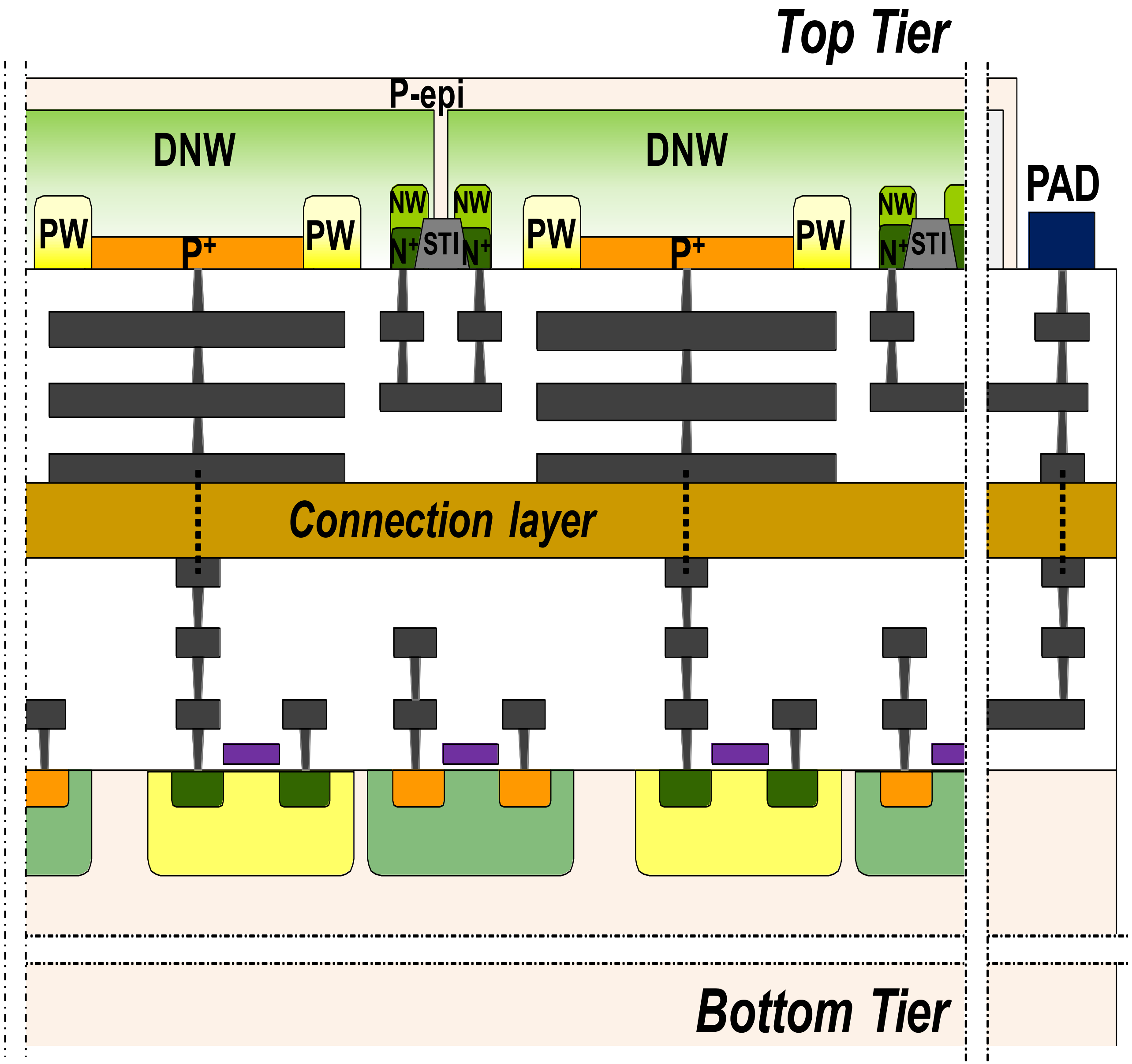
- Closest objects have priority
- Always eye safe, always adequate x-y resolution

Imager Technology: 3D-stacked BSI



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

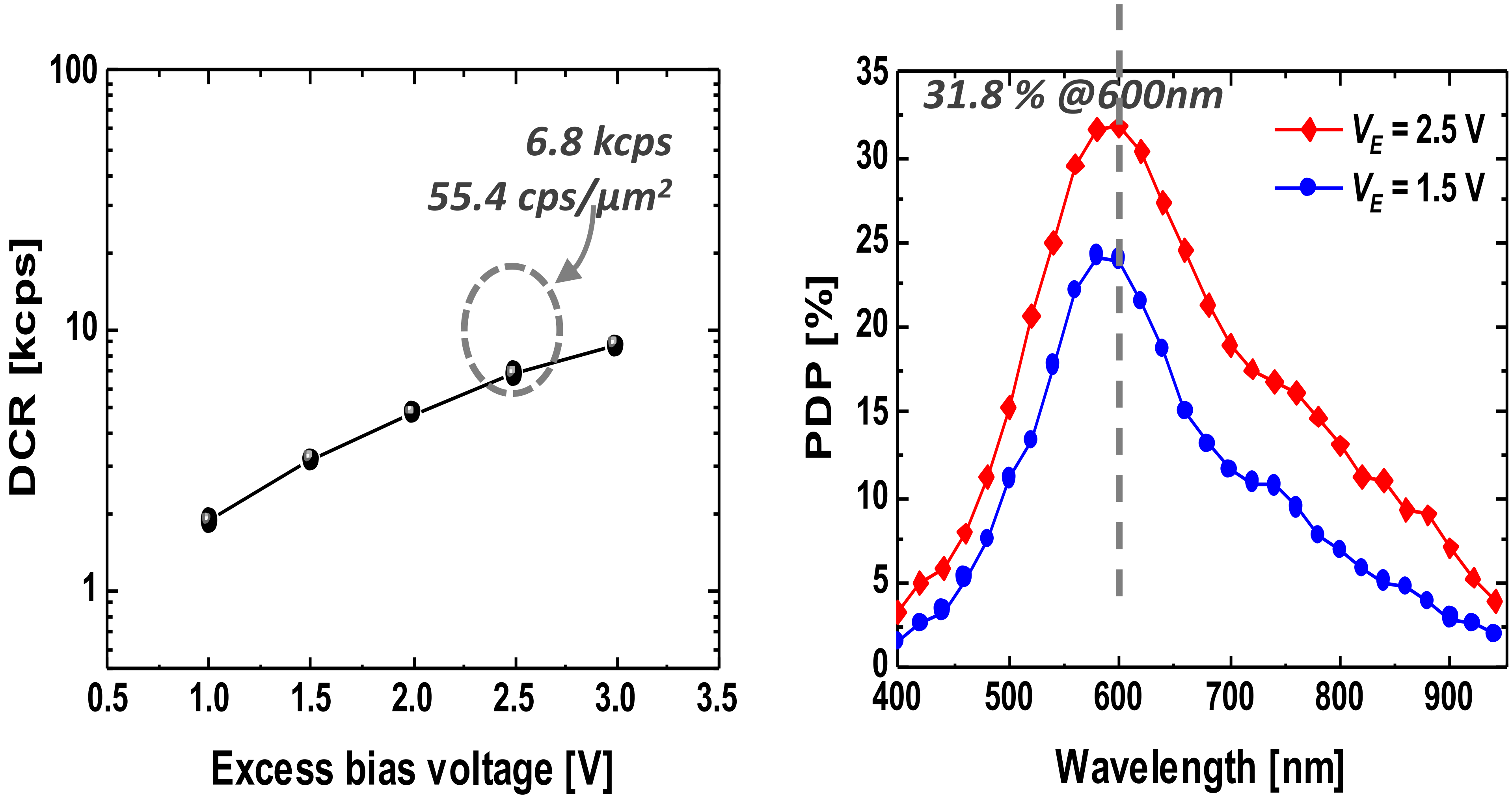
TSMC’s 3D-stacked BSI



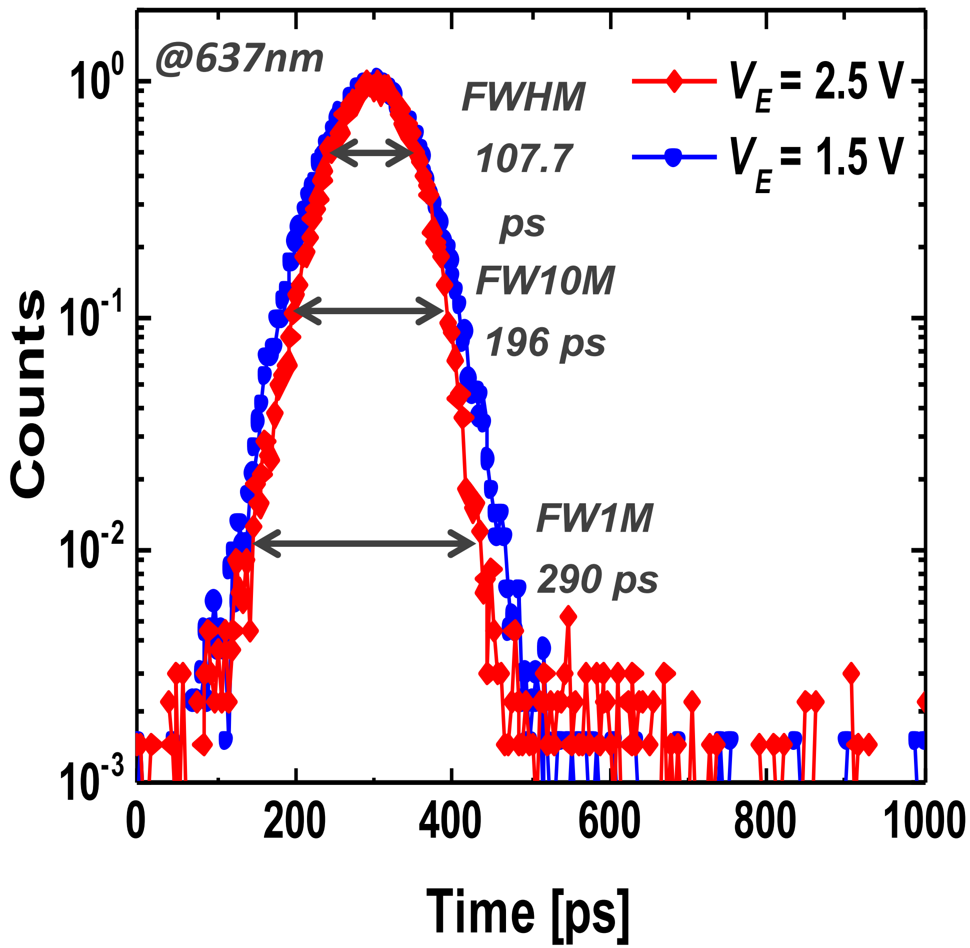
- **Top tier: 45nm CIS**
  (Bottom tier: 65nm CMOS)
  – Pixel pitch: 19.8 µm
  – Active: 12.5 µm diameter
  – Guard ring(GR): 2 µm
- **High quality backside thinning & 3D stacking technology**
  (w/ BSI process optimization)

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

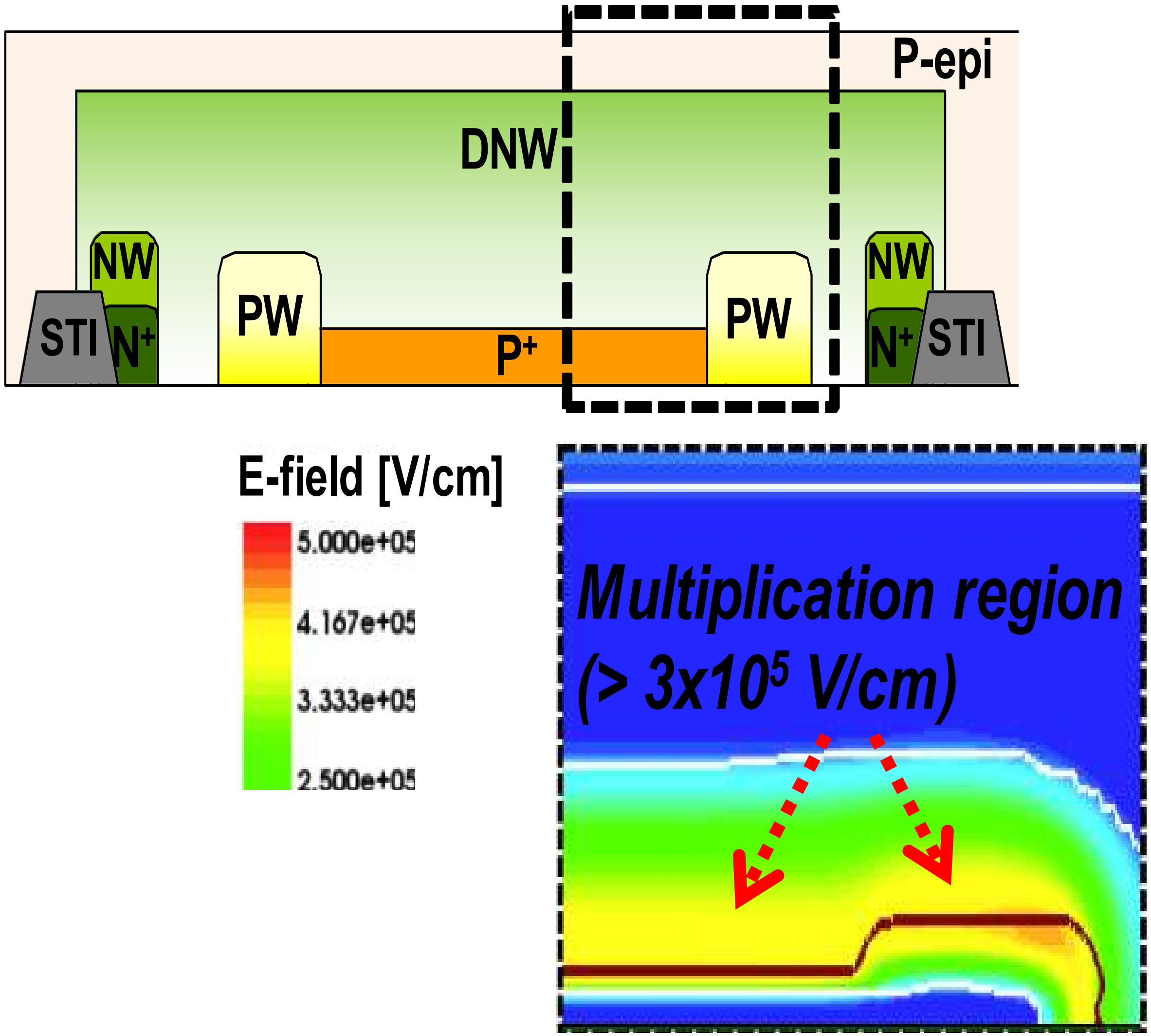
DCR and PDP


100
10
1
DCR [kcps]
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Excess bias voltage [V]
6.8 kcps
55.4 cps/μm²
35
30
25
20
15
10
5
0
PDP [%]
400
500
600
700
800
900
Wavelength [nm]
31.8 % @600nm
V_E = 2.5 V
V_E = 1.5 V

Timing Jitter



Electrical Microlenses

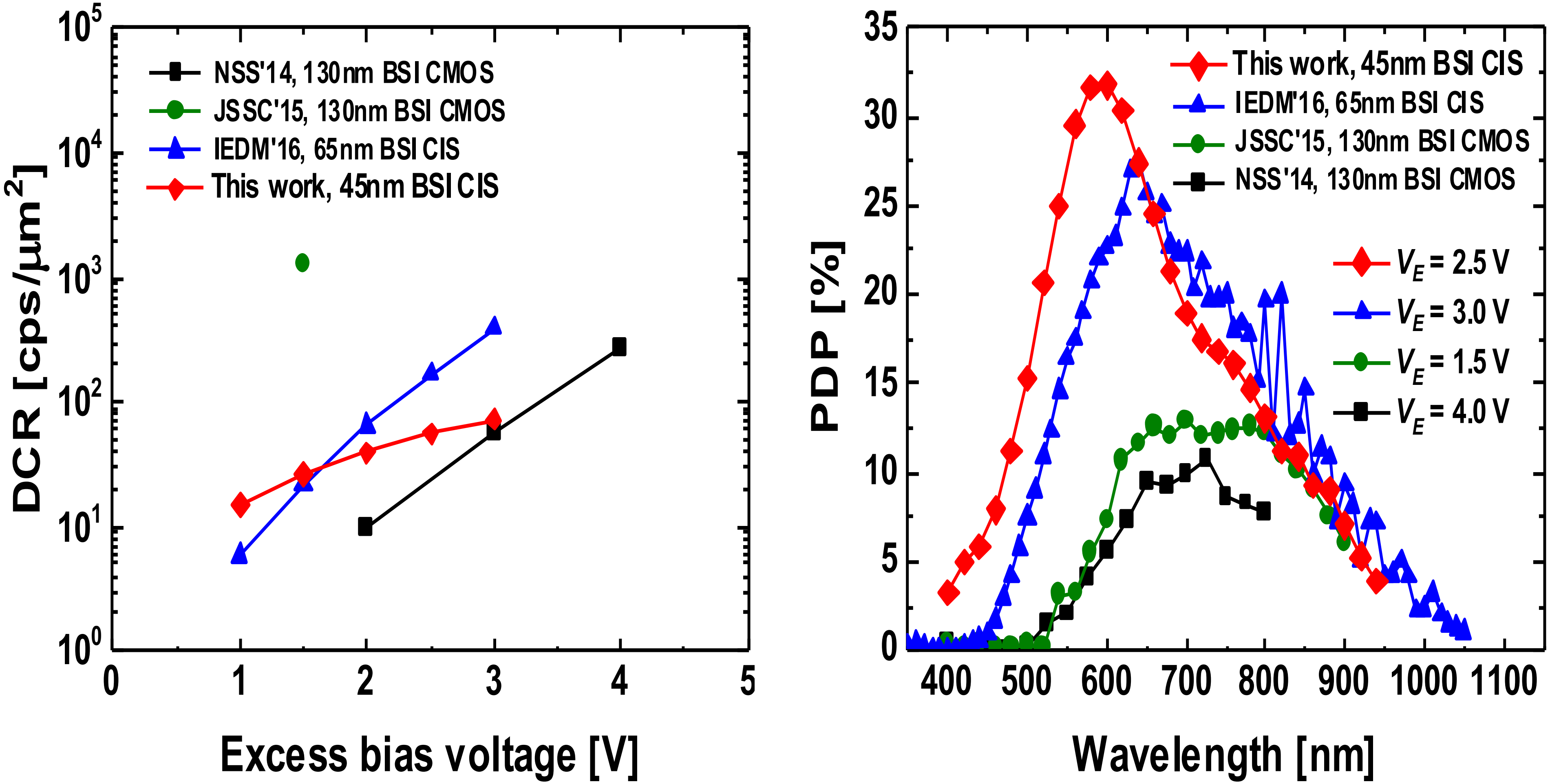


E-field profile

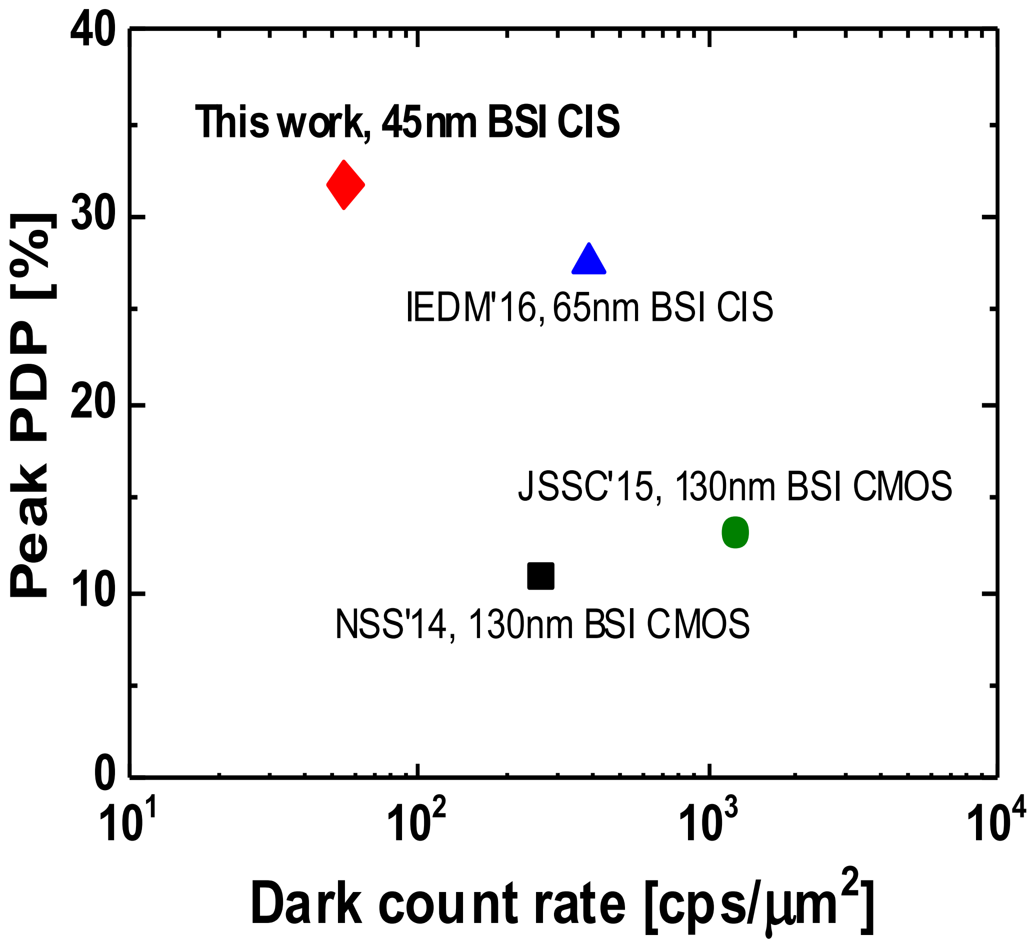
- **Extended multiplication region below GR**

  ➔ ***Larger FF***

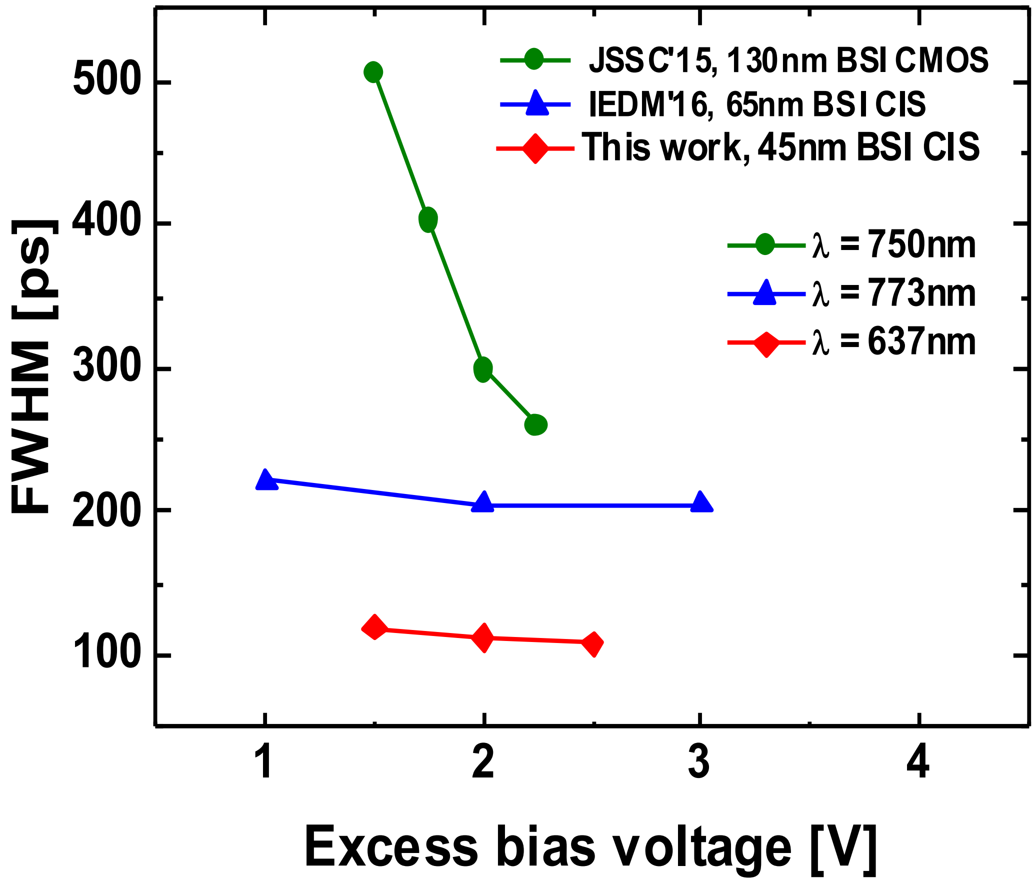
3D-Stacked BSI Comparison: DCR & PDP



3D-Stacked BSI Comparison: DCR & PDP



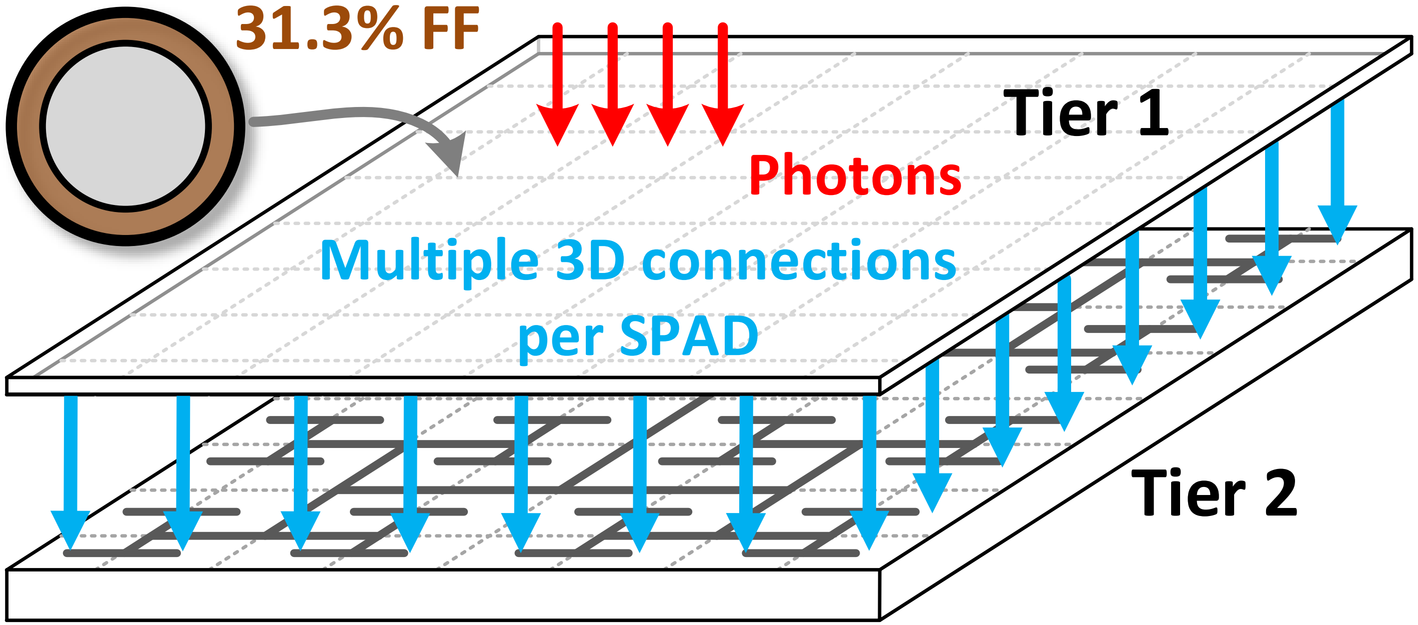
3D-Stacked BSI Comparison: Timing Jitter



3D-Stacked BSI State-of-the-art

	NSS'14	JSSC'15	IEDM'16	This work
Technology (Top/Bottom)	130nm CMOS 130nm CMOS	130nm CMOS 130nm CMOS	65nm CIS 40nm CMOS	**45nm CIS 65nm CMOS**
Junction | GR	P^+/NW | PW GR	NLDD/PW | NW GR	PW/DNW | Virtual GR	**P^+/DNW | PW GR**
Active area	28.3 μm^2	28 μm^2	27.6 μm^2	**122.7 μm^2**
Fill factor	n.a.	23.3 %	45 %	**up to 60.5 %**
$V_B + V_E$	12.3 V + 4 V	16.5 V + 1.5 V	12.0 V + 3 V	**28.5 V + 2.5 V**
DCR	7.5 kcps 265.3 cps/μm^2	35 kcps 1250 cps/μm^2	10.8 kcps 391.4 cps/μm^2	**6.8 kcps 55.4 cps/μm^2**
PDP peak (@λ)	11 % (@725nm)	13 % (@700nm)	27.5 % (@640nm)	**31.8 % (@600nm)**
PDP @450nm	0.3 %	0.3 %	0.9 %	**6.9 %**
FWHM (@λ)	n.a.	505 ps (@750nm)	205 ps (@773nm)	**107.7 ps (@637nm)**

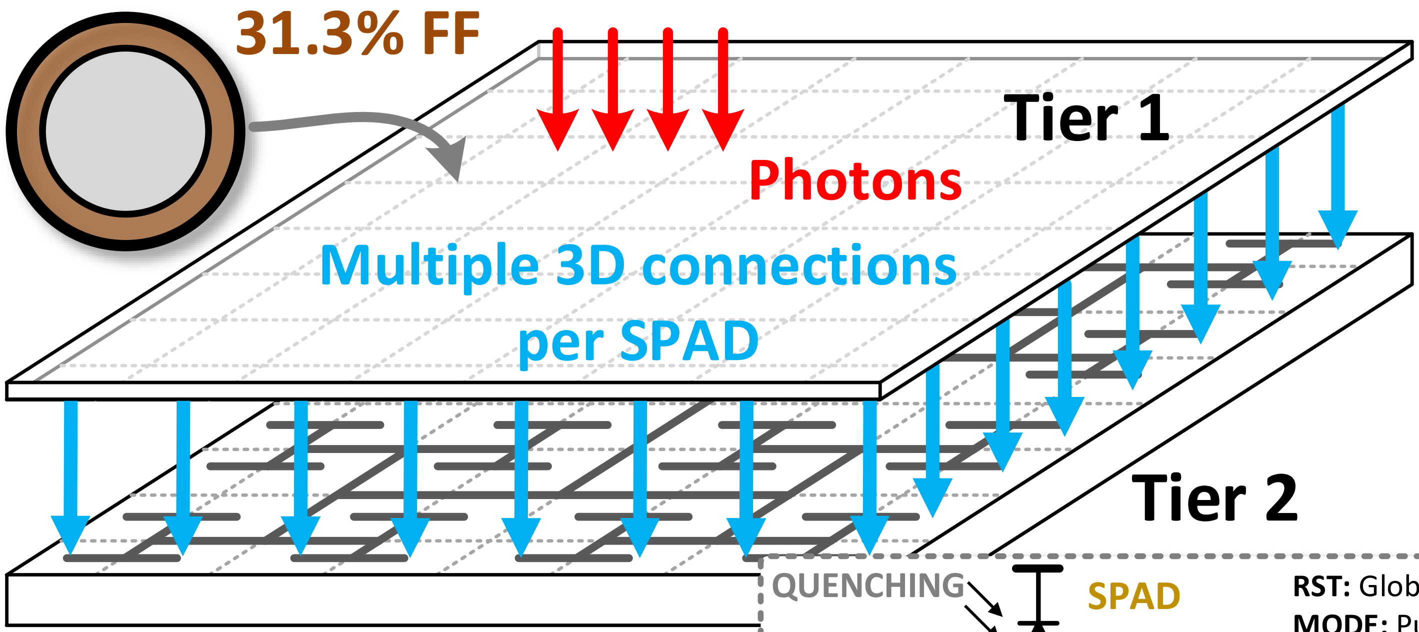
Case Study: LiDAR Sensor



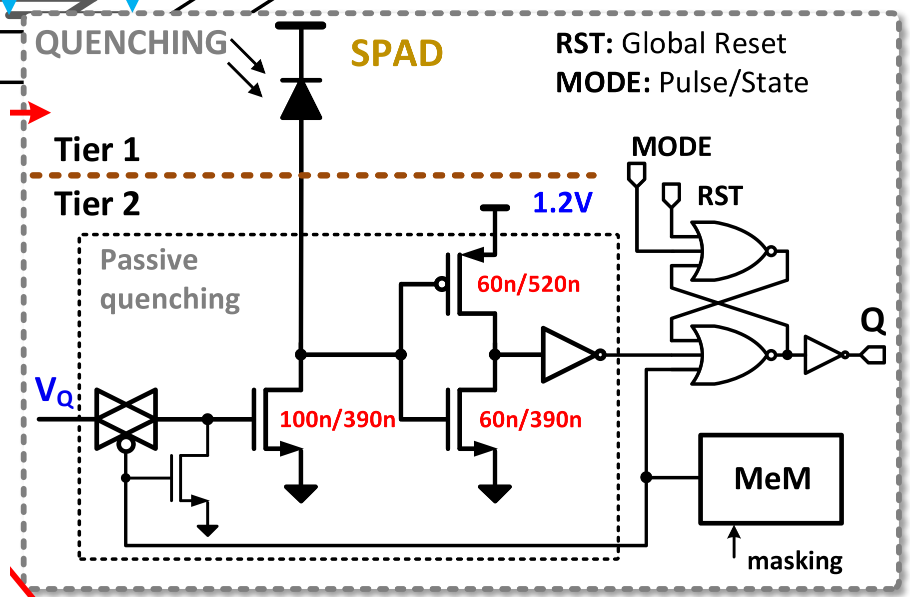
M.J. Lee, A.R. Ximenes, P. Padmanabhan, Y. Yamashita, D.N. Yaung, E. Charbon, IEDM 2017

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

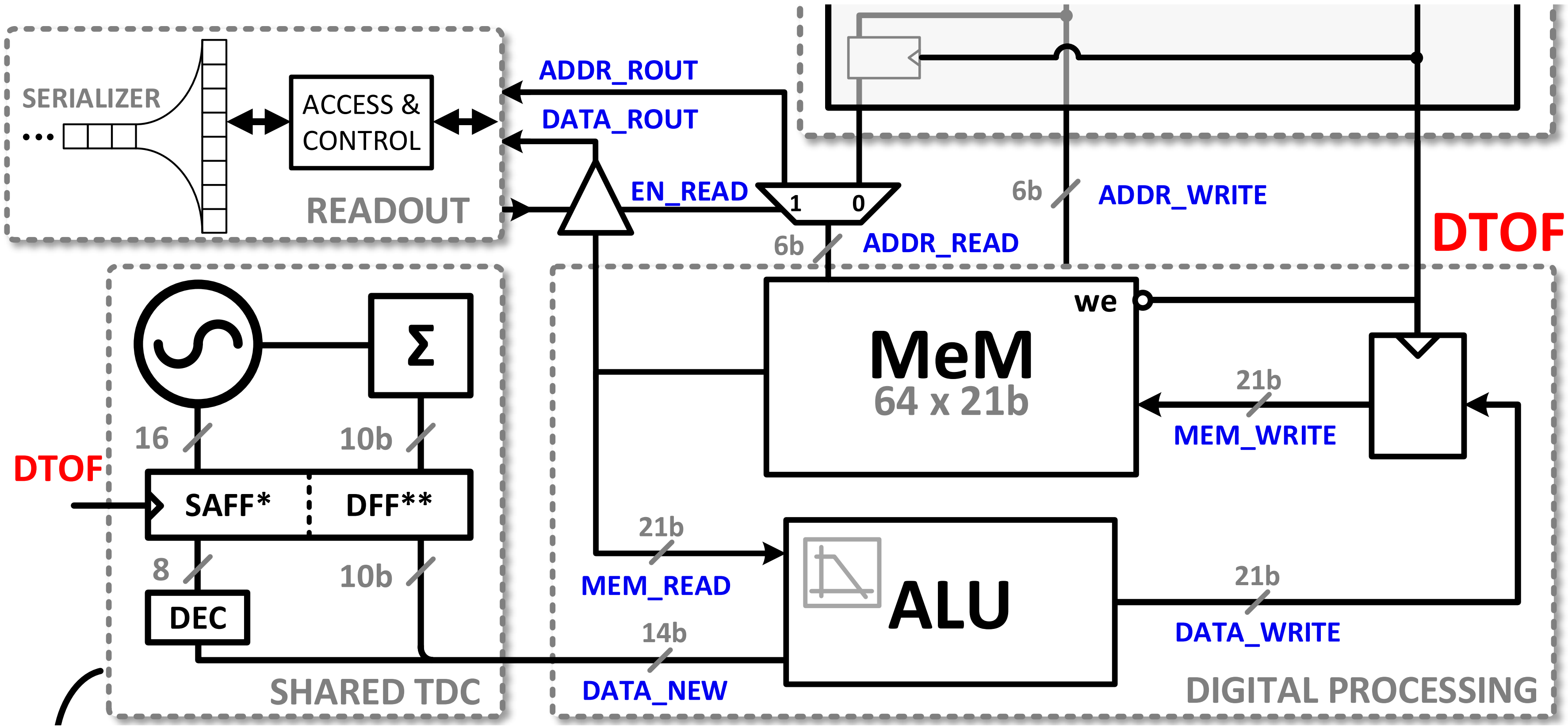
Case Study: LiDAR Sensor



- Masking mechanism
- Interface
- Memory

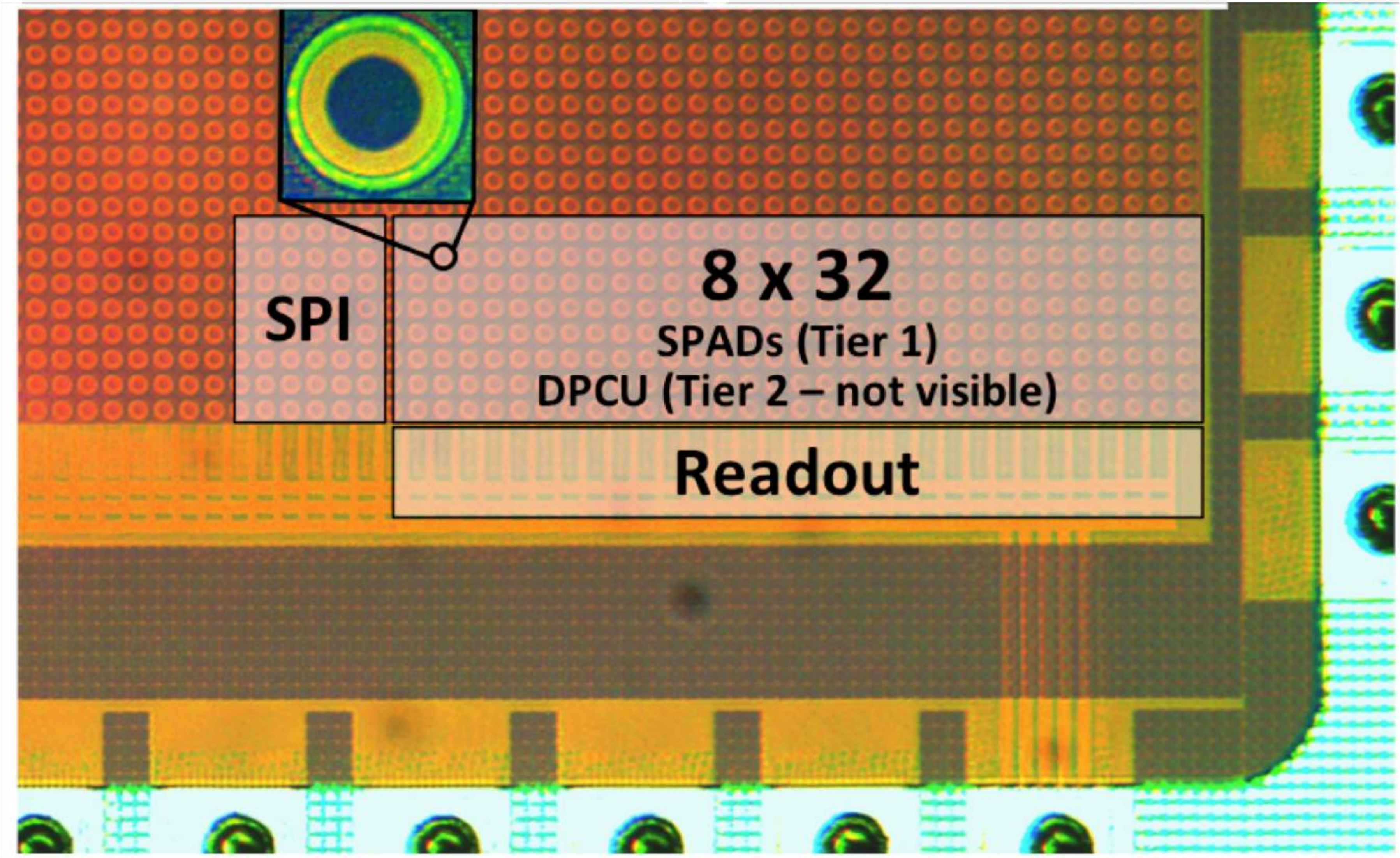


Case Study: LiDAR Sensor

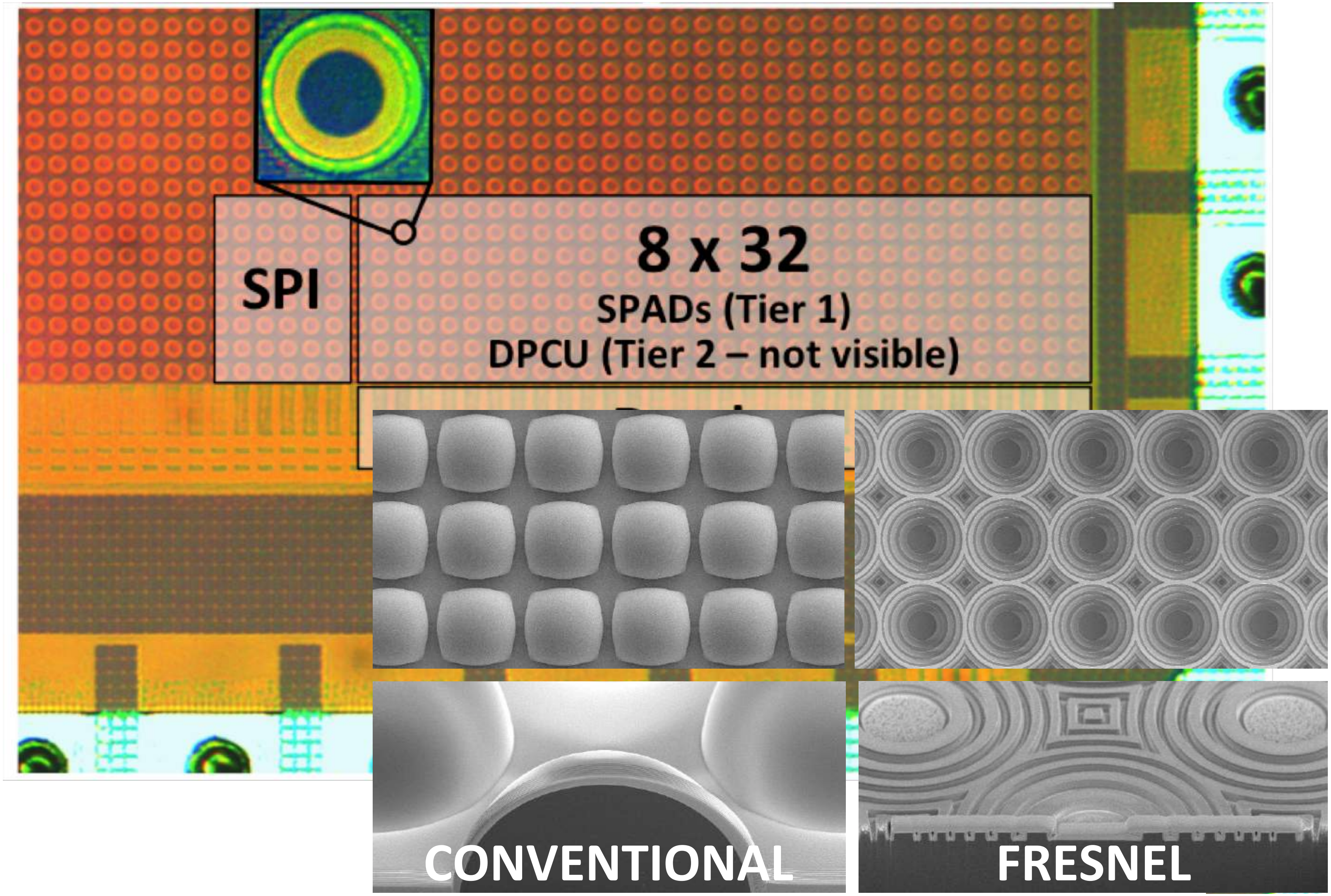


A.R. Ximenes, P. Padmanabhan, M.J. Lee, Y. Yamashita, D.N. Yaung, E. Charbon, ISSCC 2018

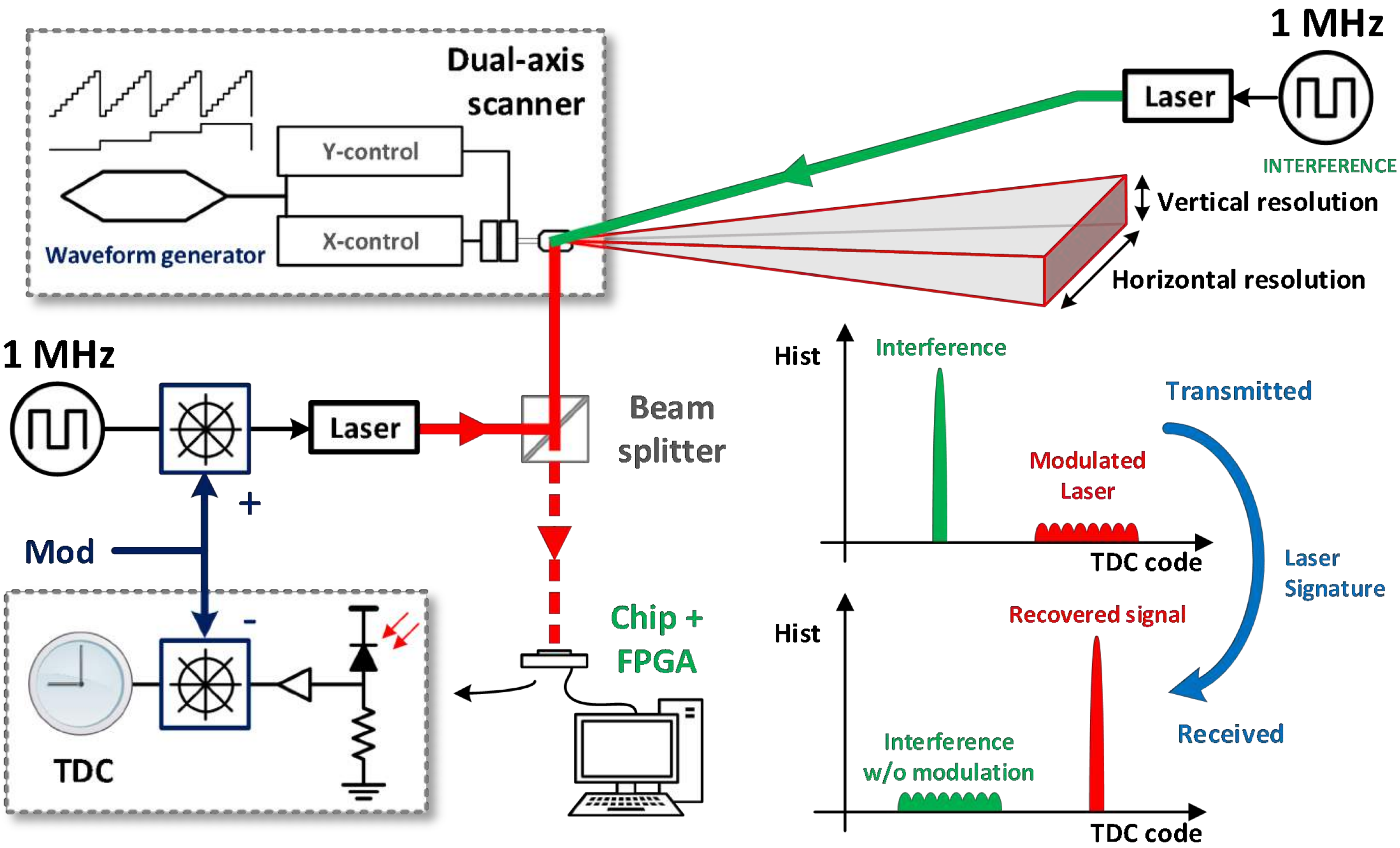
3D-Stacked Chip Micrograph



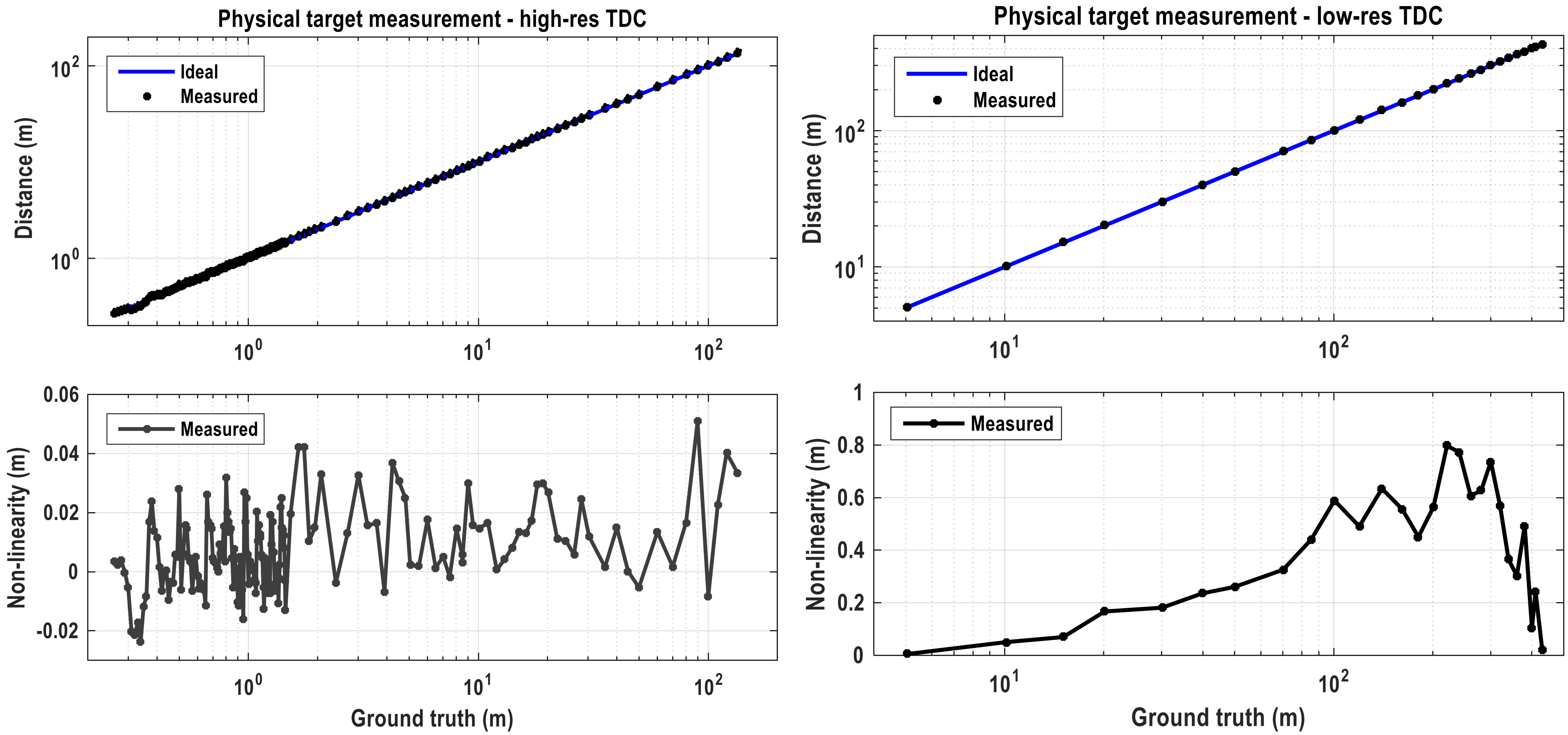
3D-Stacked Chip Micrograph



The LiDAR System

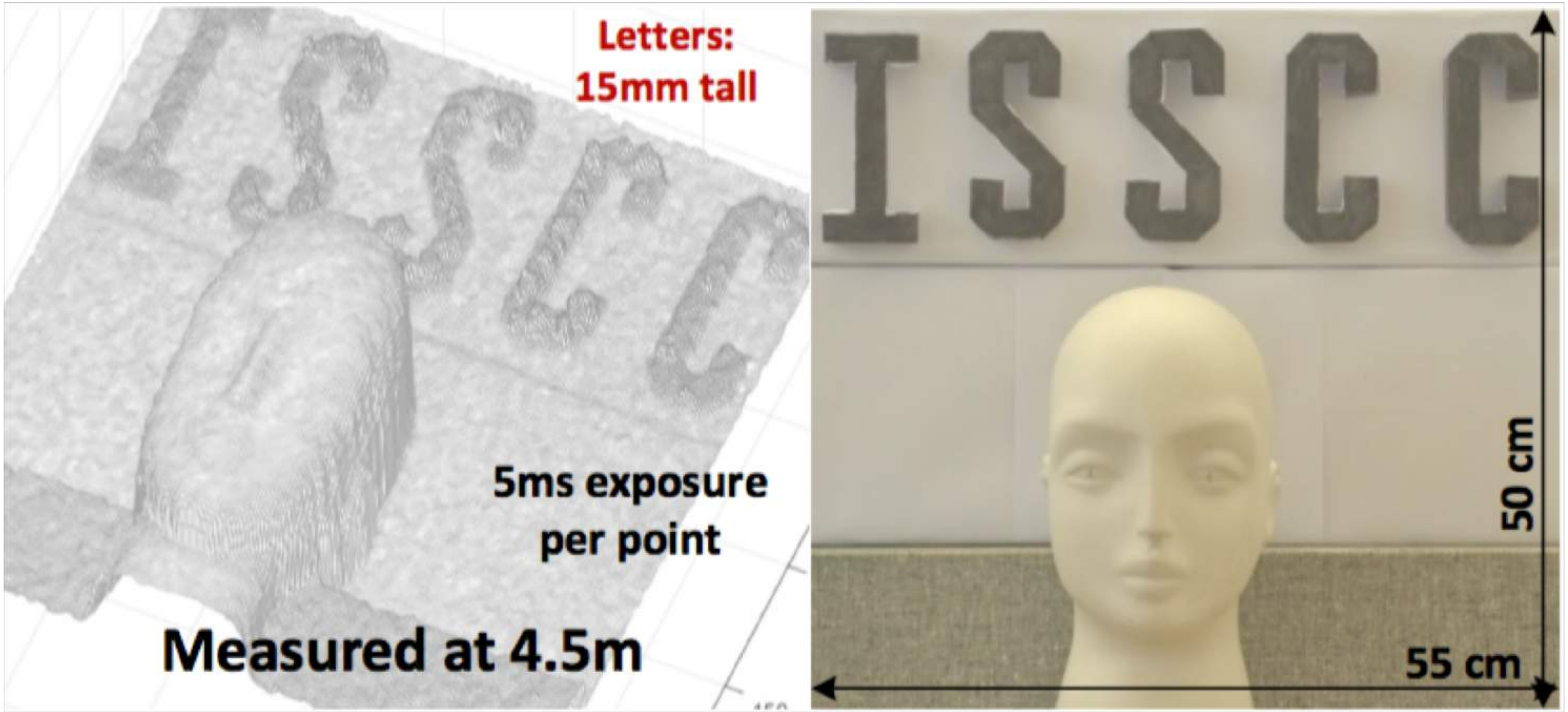


Distance Measurements

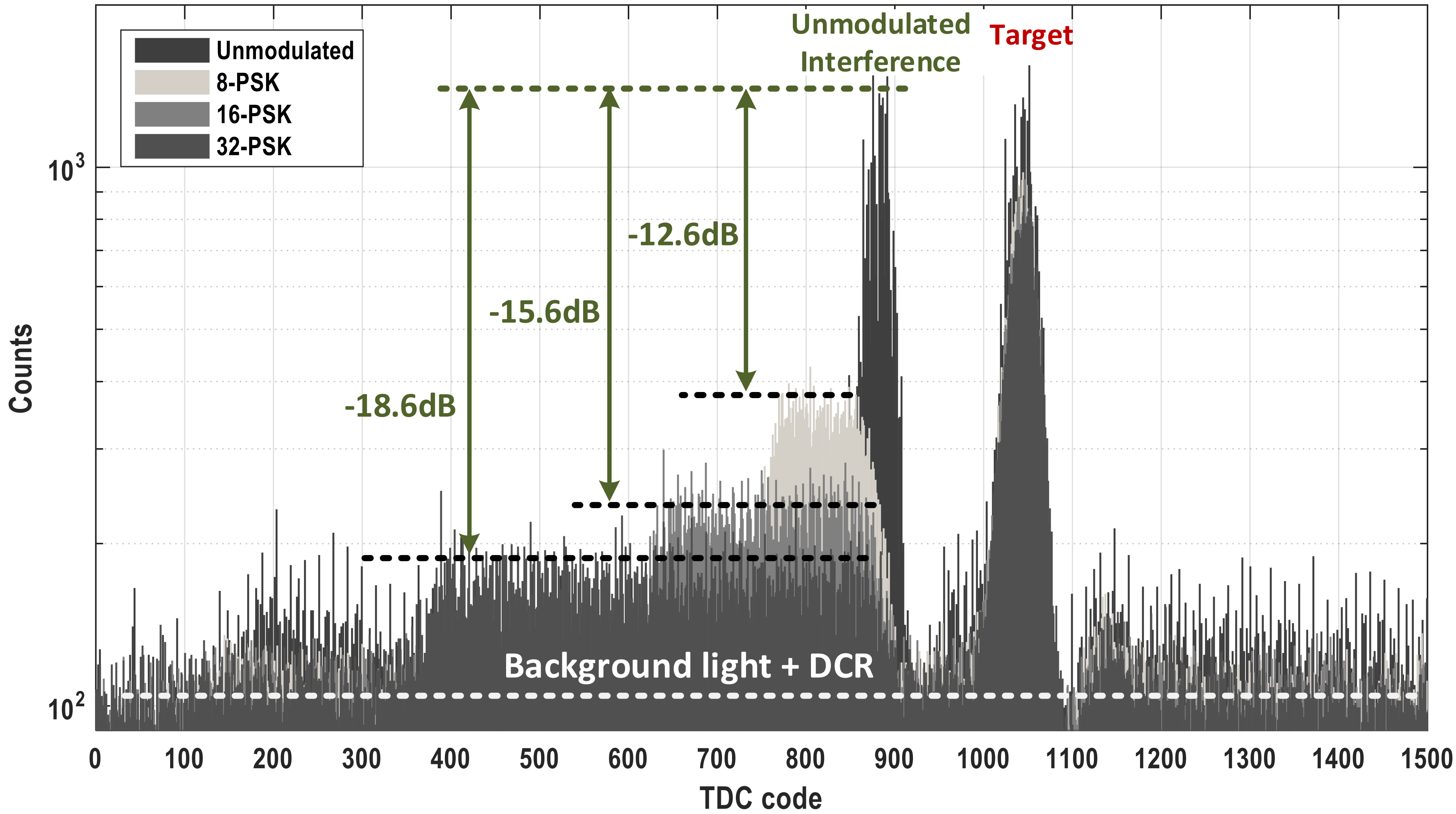


A.R. Ximenes, P. Padmanabhan, M.J. Lee, Y. Yamashita, D.N. Yaung, E. Charbon, ISSCC 2018

256x256 3D Image Reconstruction

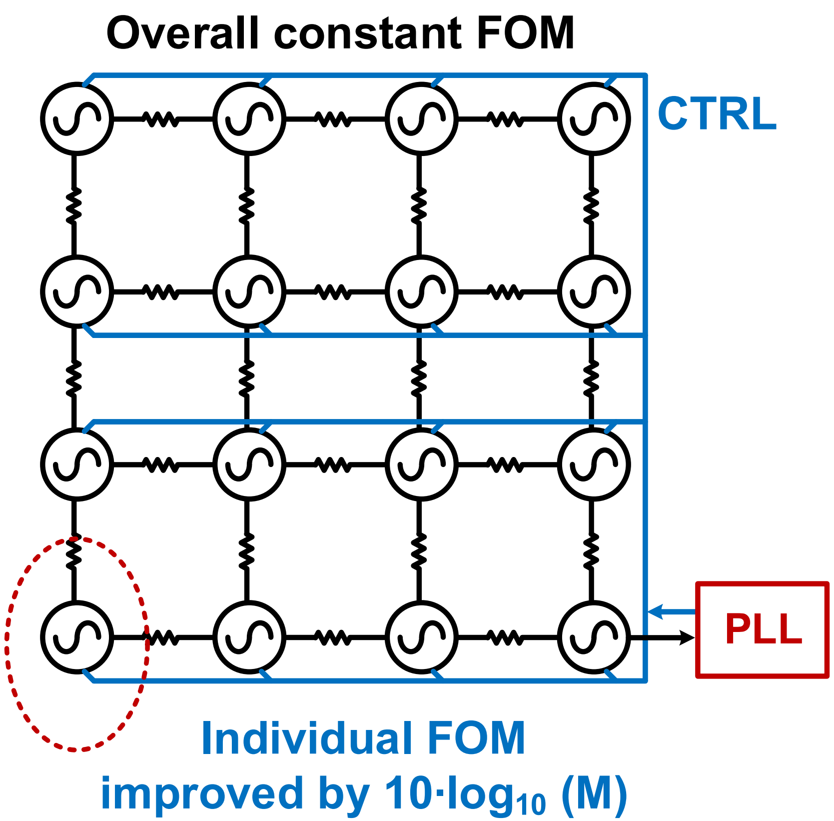


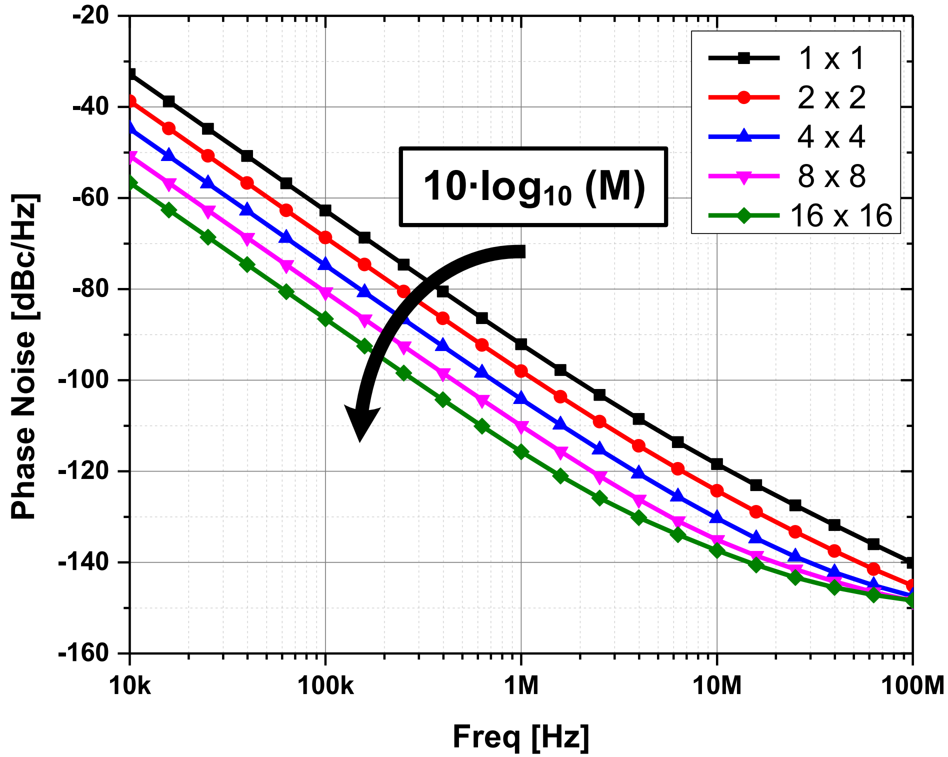
Interference Suppression



Large Array Synchronization

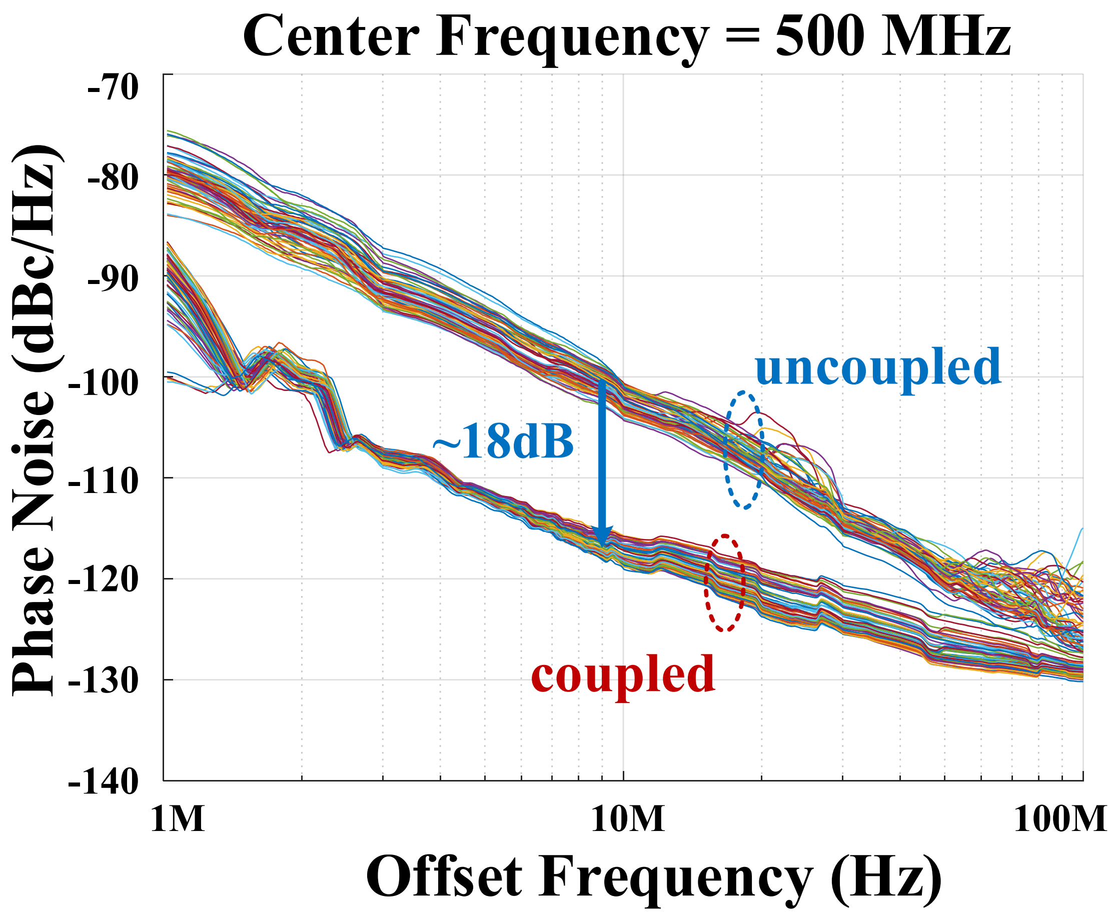
- Use injection locking for coupling VCOs
- The PLL only forces the desired frequency on the VCOs

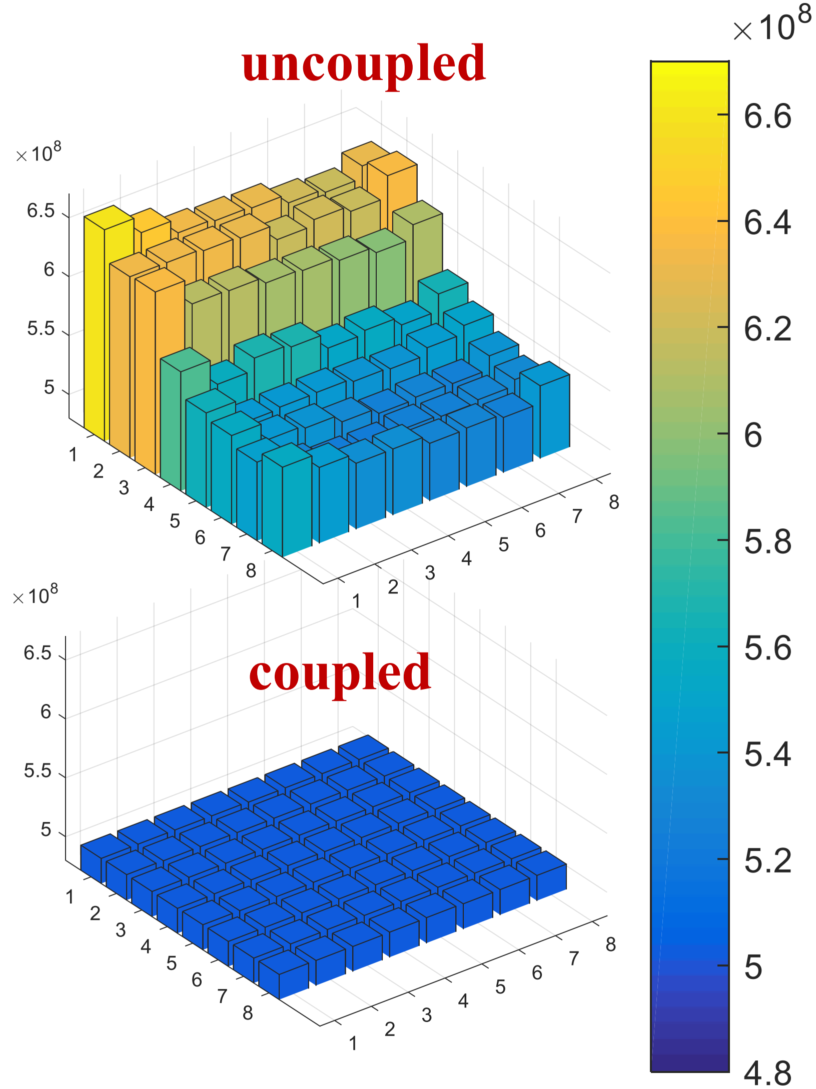




A.R. Ximenes, P. Padmanabhan, et al., IISW 2018

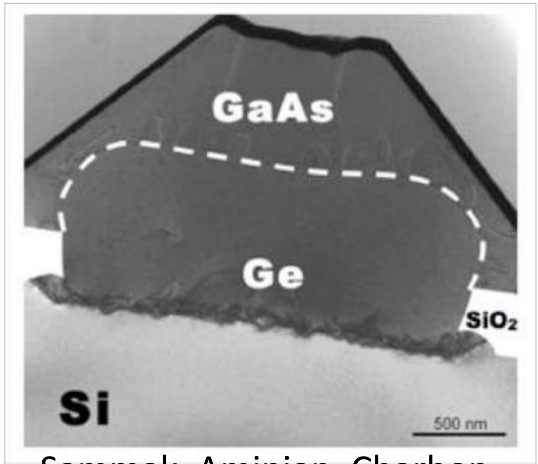
Mutual Coupling Measurements





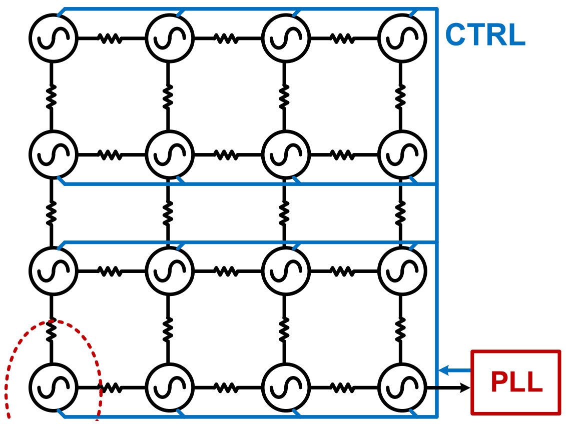
Perspectives for 2020

- Sub-65nm CMOS
- Large, scalable designs (Lego™ approach)
- Backside illumination (BSI) 3D IC
- New Materials (InP, GaAs, Ge, polymers)
- Small pixels, low noise, µlenses

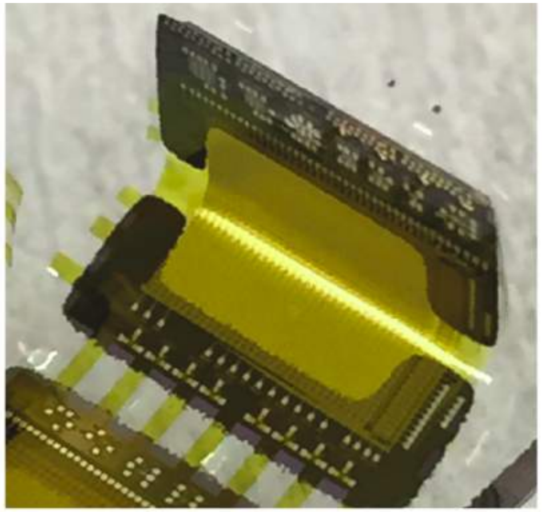


Sammak, Aminian, Charbon, Nanver, IEDM11

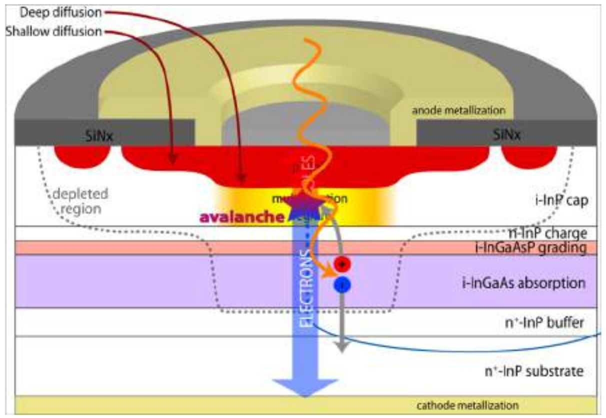
Overall constant FOM



Ximenes, Padmanabhan, Charbon, IISW, 2017

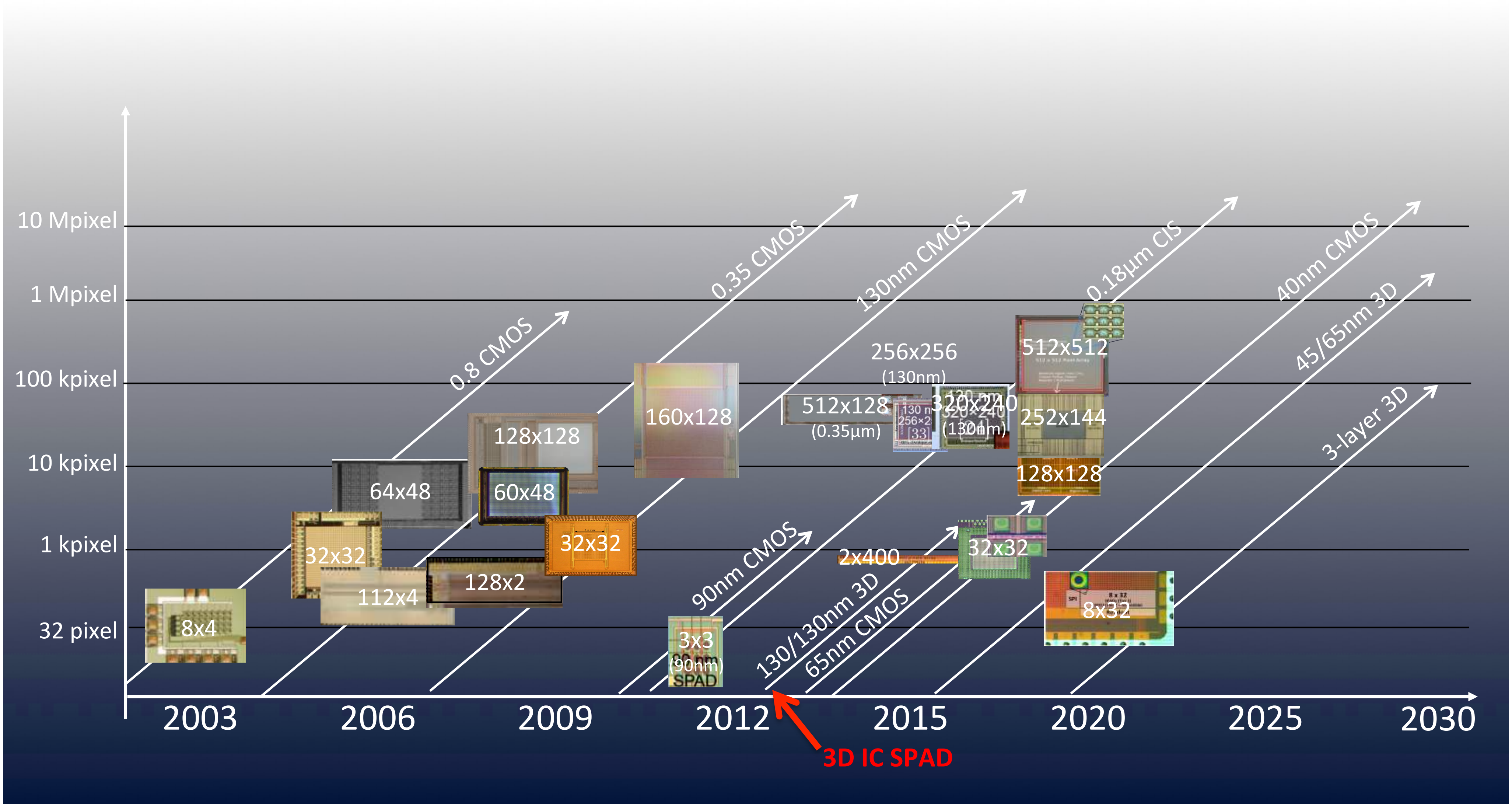


Sun, Ishihara, Charbon, IISW, 2017



Tosi et al, 2012

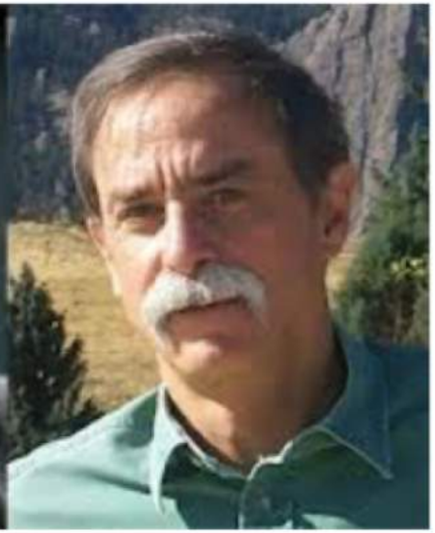
Moore's Law for SPADs



SPADs in Quantum Computing

Quantum Computing

Serge Haroche



David Wineland

2012 Physics Nobel Prize

Both Laureates work in the field of quantum optics studying the fundamental interaction between light and matter, a field which has seen considerable progress since the mid-1980s. Their ground-breaking methods have enabled this field of research to take the very first steps towards building a new type of super fast computer based on quantum physics. Perhaps the quantum computer will change our everyday lives in this century in the same radical way as the classical computer did in the last century.

–Announcement 2012 Nobel Prize

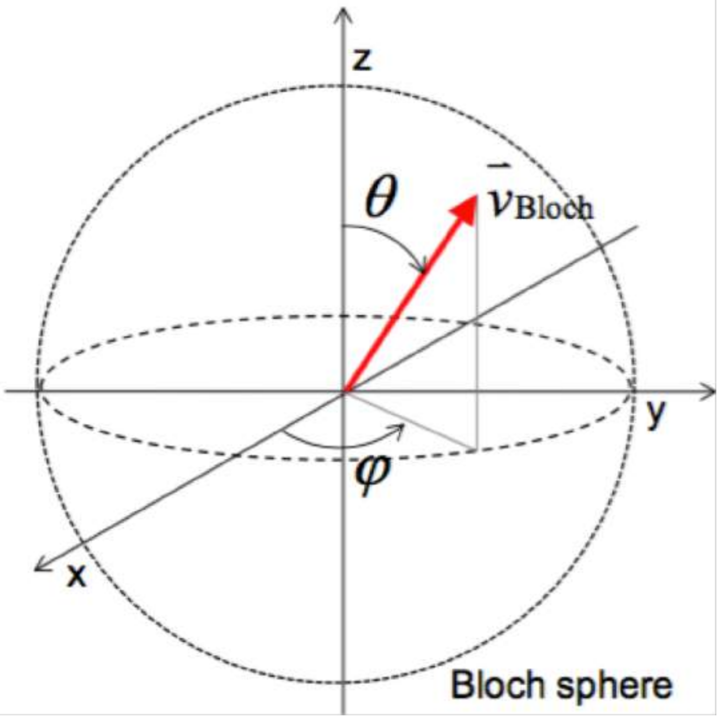
From bits to qubits

- A quantum bit or qubit is a quantum system in which the Boolean states 0 and 1 are represented by a pair of mutually orthogonal quantum states labeled as $|0\rangle, |1\rangle$
- Quantum properties: **superposition** and **entanglement**

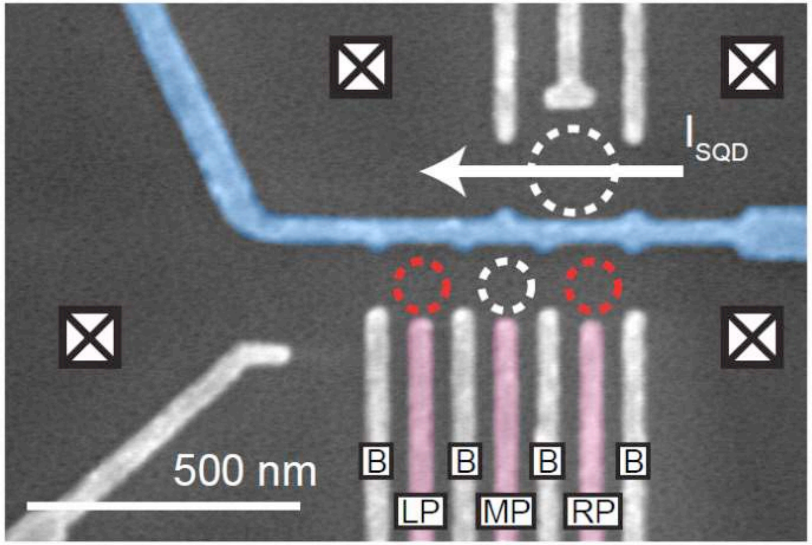
- $\alpha_0, \alpha_1 \in C$
- $|\alpha_0|^2 + |\alpha_1|^2 = 1$

$$|\psi\rangle = e^{i\delta}\left(\cos(\theta/2)|0\rangle + e^{i\varphi}\sin(\theta/2)|1\rangle\right)$$

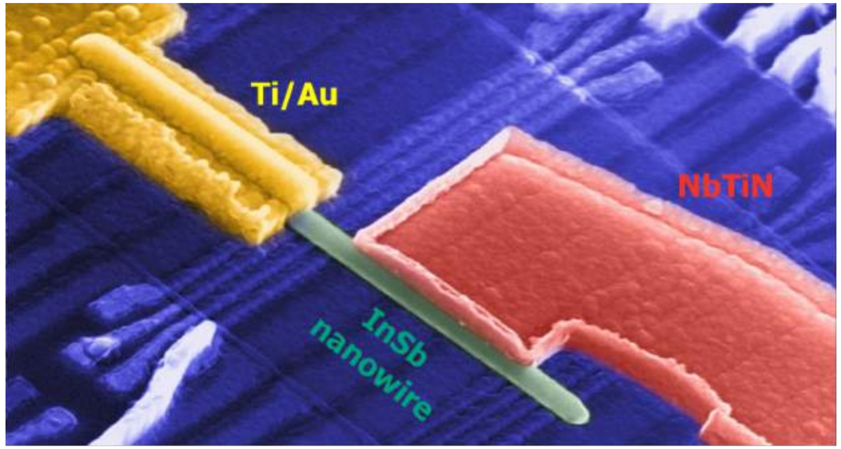
θ is polar angle
φ is azimuthal angle



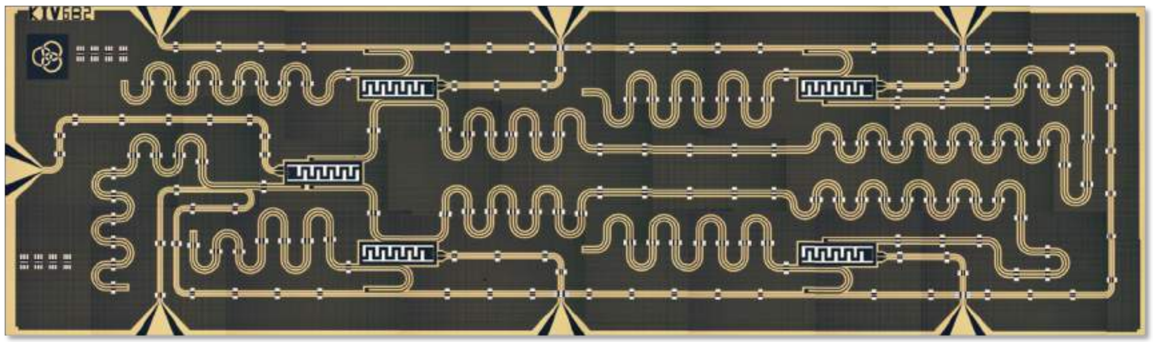
Qbits on a Chip



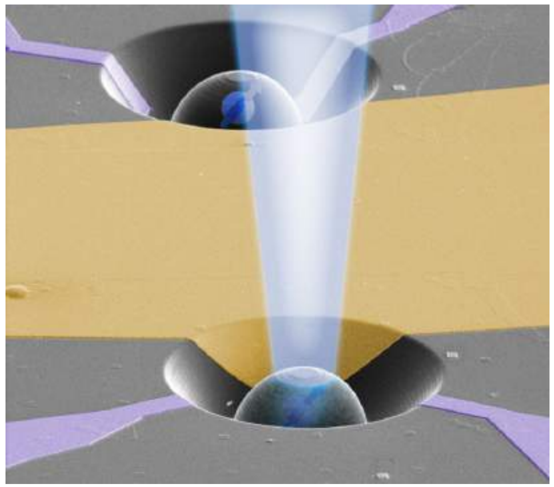
Semiconductor quantum dots



Semiconductor-superconductor hybrids



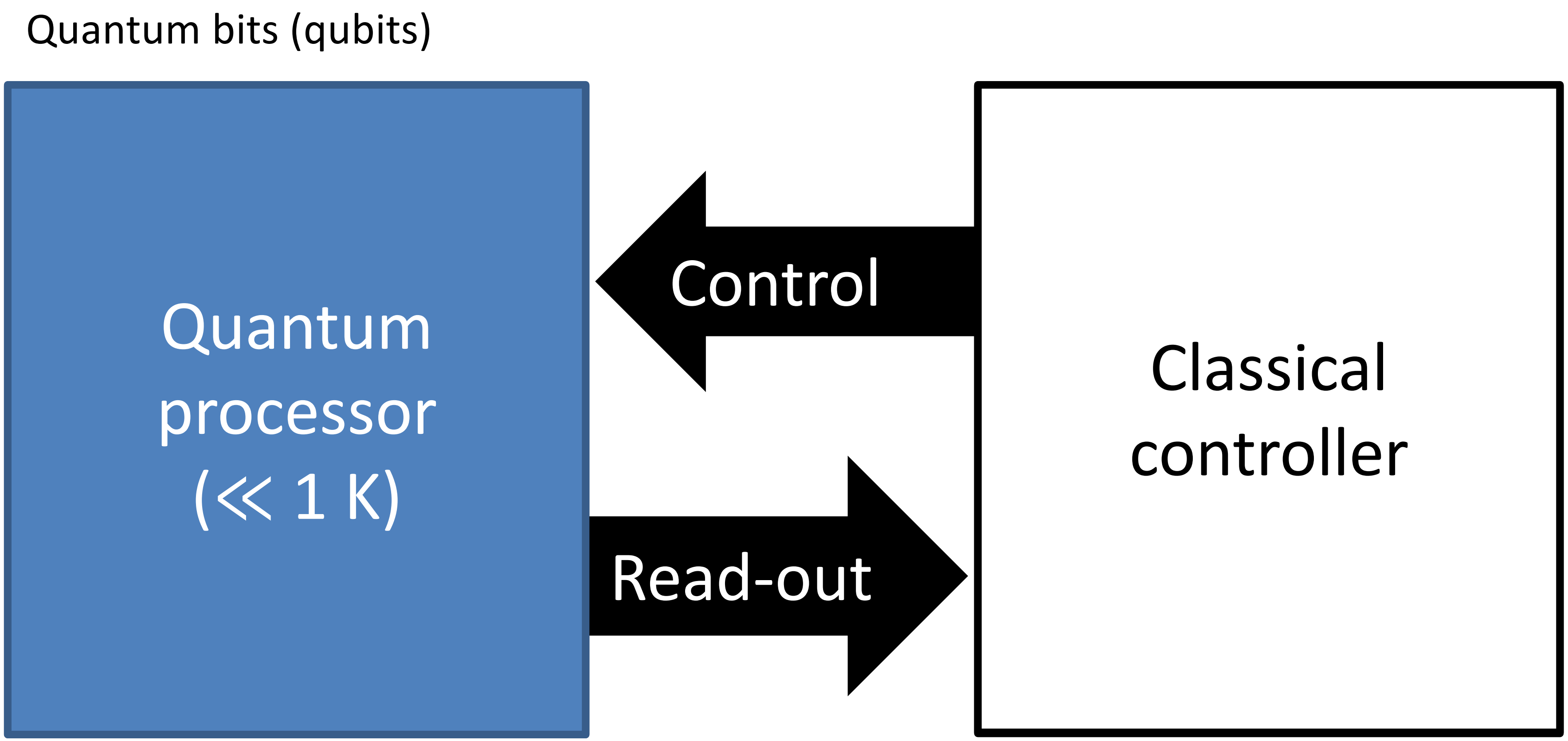
Superconducting circuits



Impurities in diamond or silicon

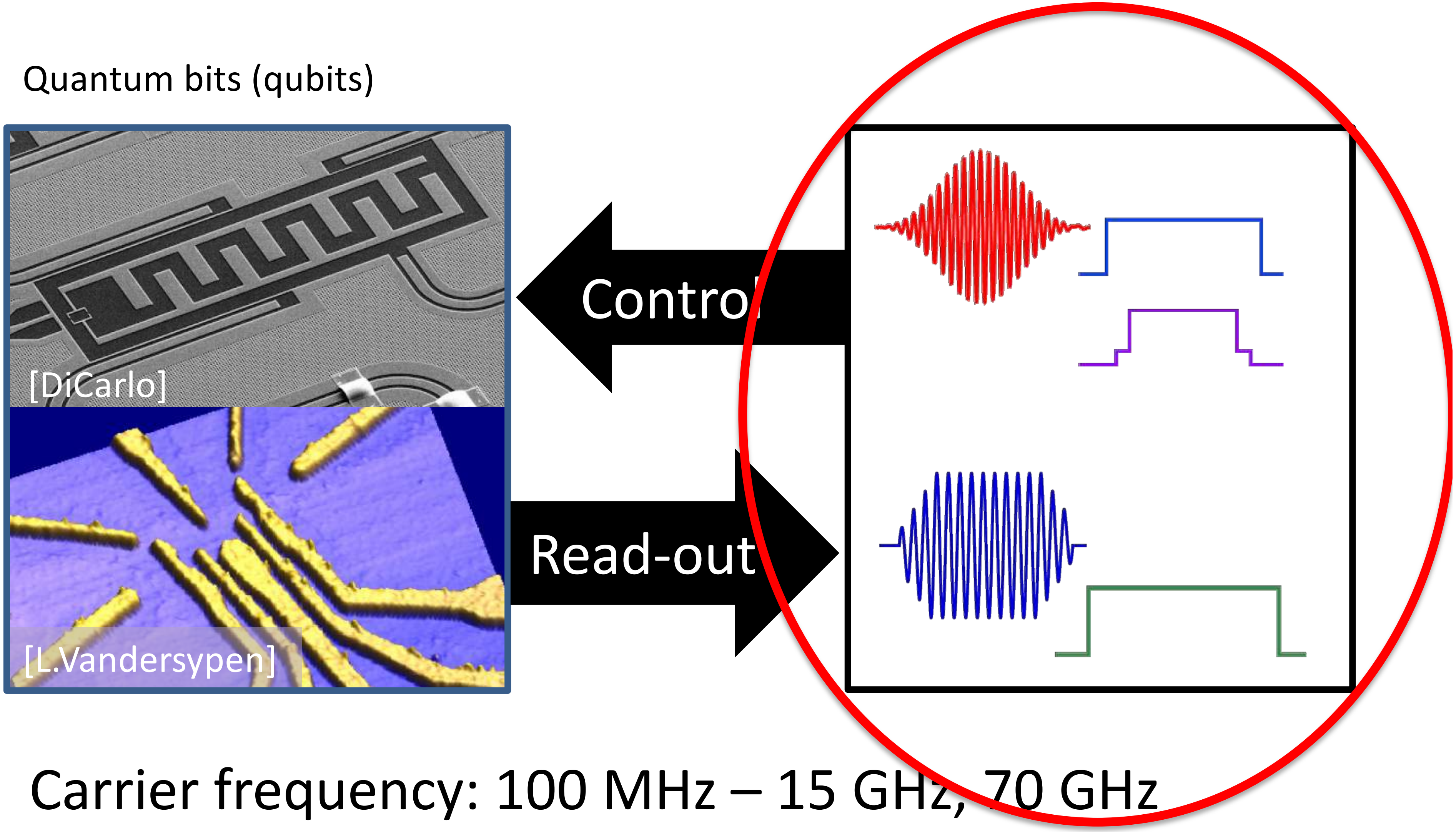
Source: L. Vandersypen, 2017

Quantum Computer Architecture



- Carrier frequency: 100 MHz – 15 GHz, 70 GHz
- Pulses: 10 – 100 ns

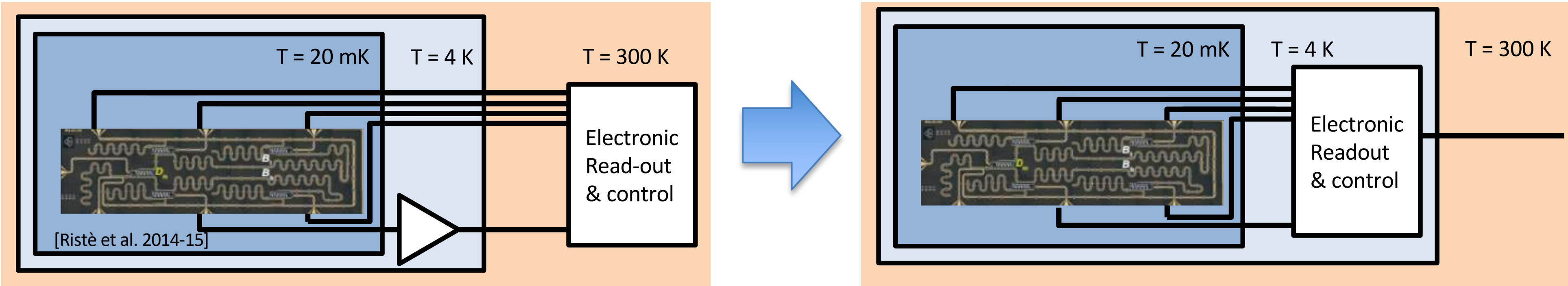
Quantum Computer Architecture



- Carrier frequency: 100 MHz – 15 GHz, 70 GHz
- Pulses: 10 – 100 ns

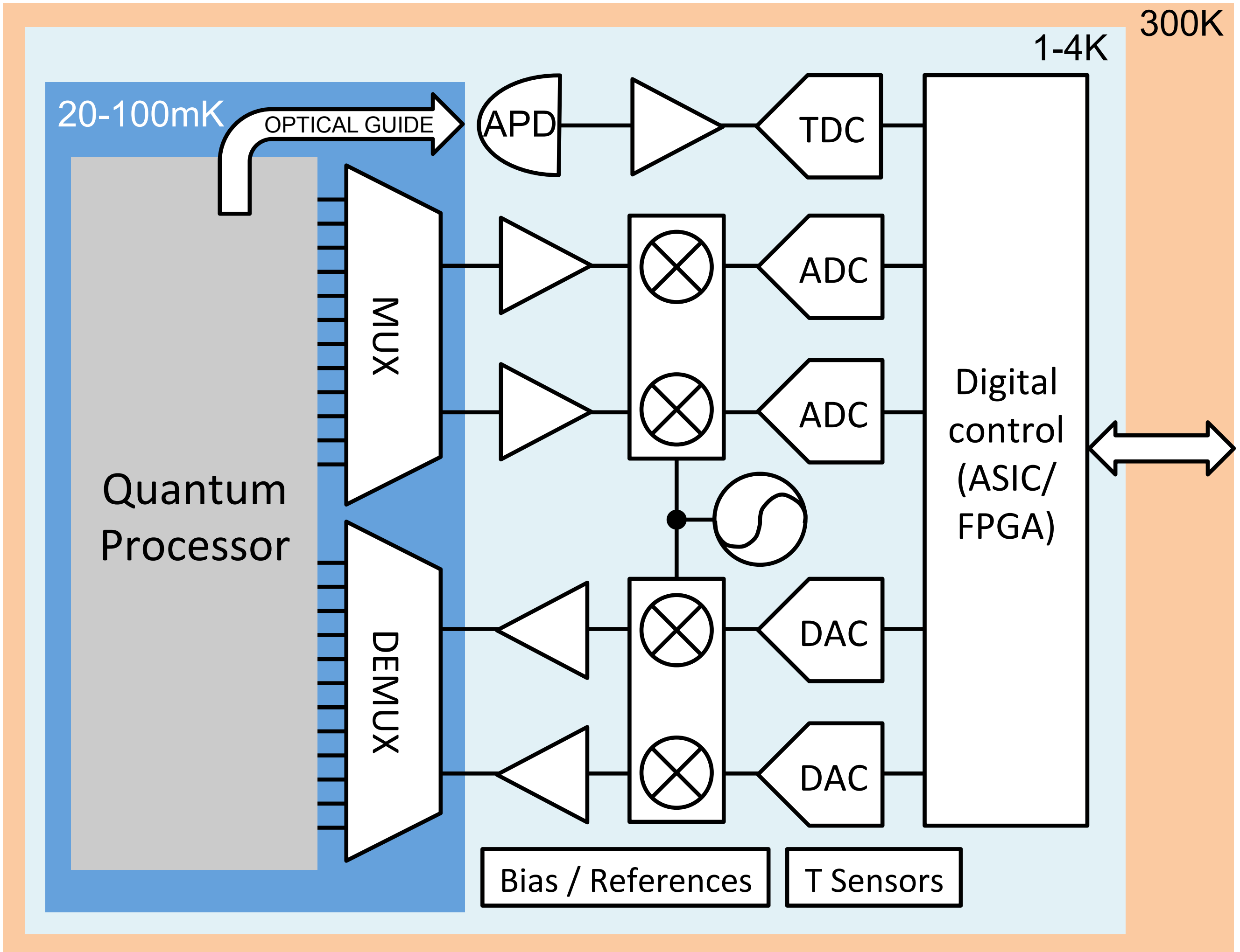
Possible Solutions

- **Proposed solution**
  - Electronics at 4 K
  - Only connections to 4 K to 20 mK are needed



- **Ultimate solution**
  - Qubits at 4 K
  - Monolithic integration

Electronic Readout & Control

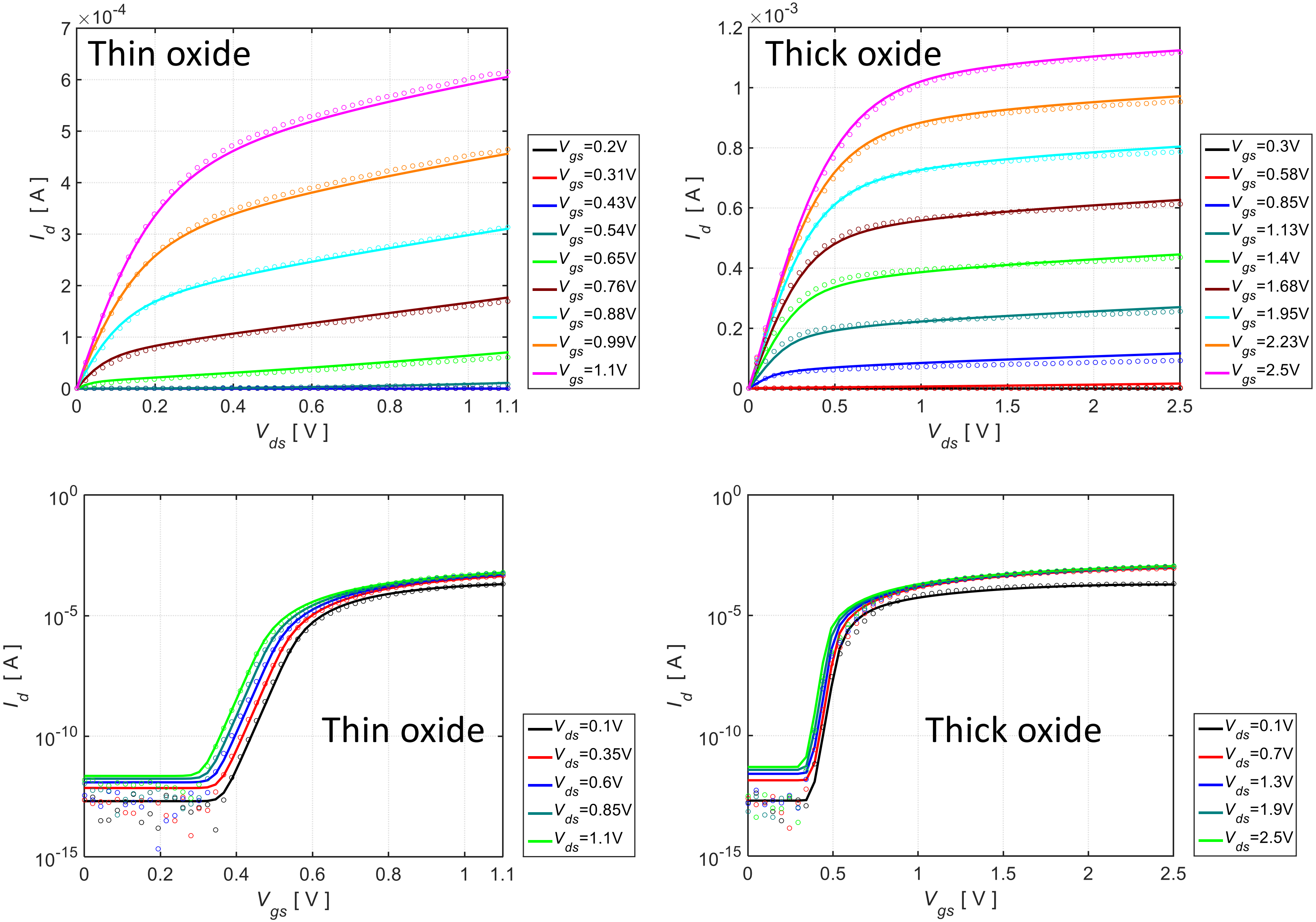


E. Charbon et al., *IEDM* 2016

Cryogenic Electronics

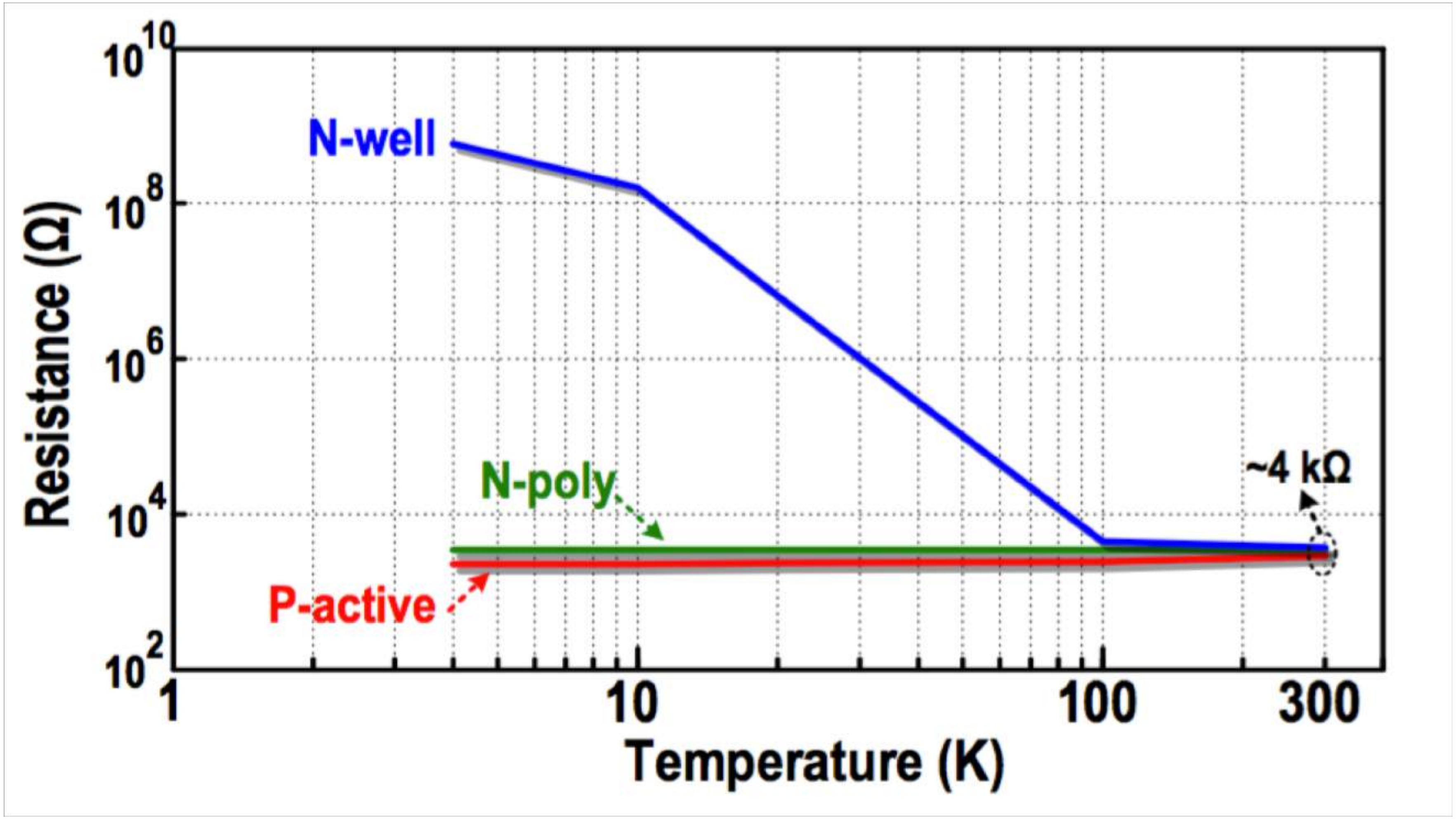
Cryo-CMOS Technologies

40nm MOS at 4K



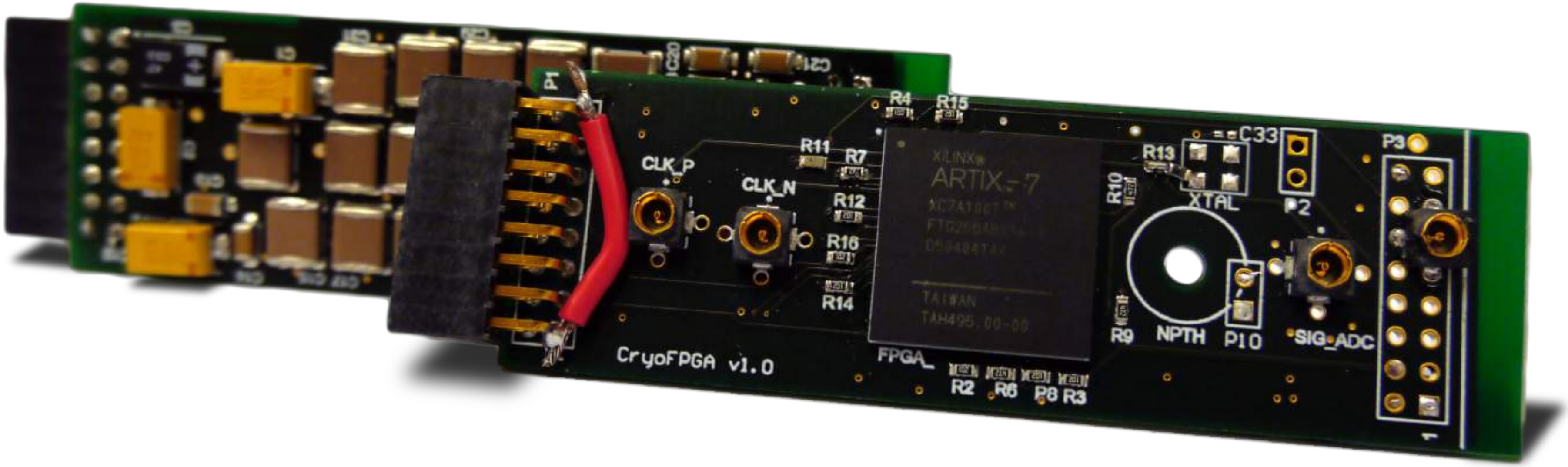
R.M. Incandela et al., *ESSDERC* 2017, Journal of EDS 2018

Substrate resistivity



B. Patra et al., *JSSC* 2018

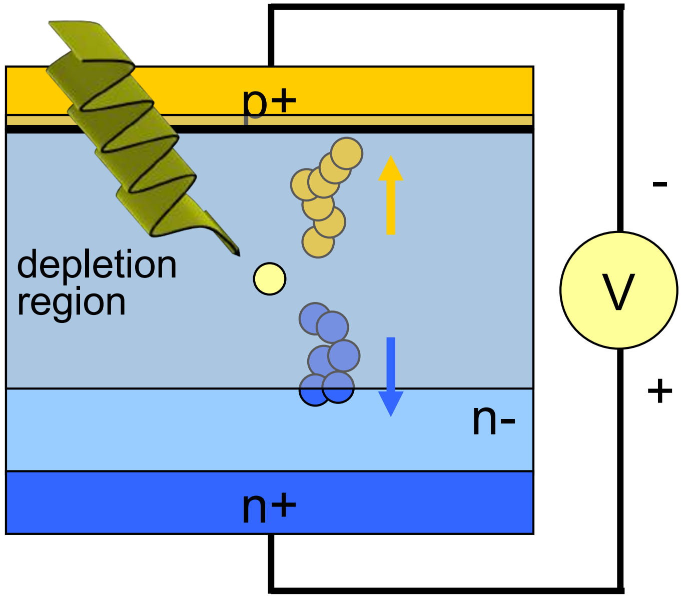
Cryo-FPGAs



Harald Homulle

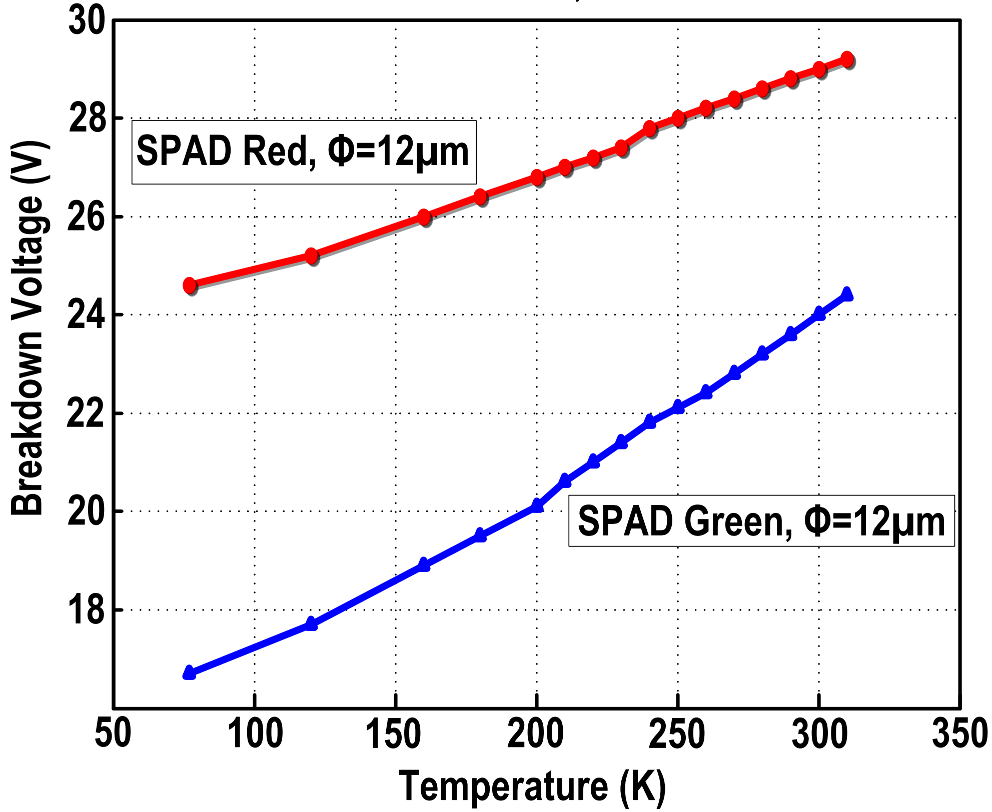
- Artix-7 full operation down to 4K
- Other FPGAs only limited to 30K

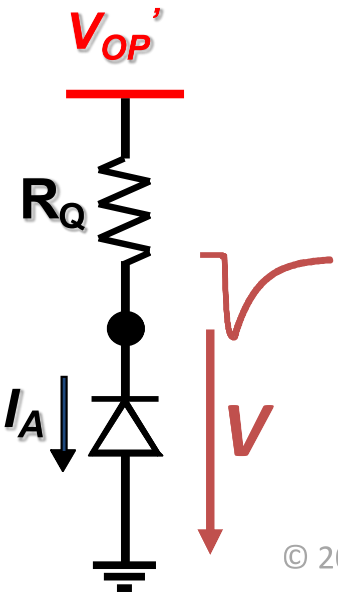
Cryo-SPADs



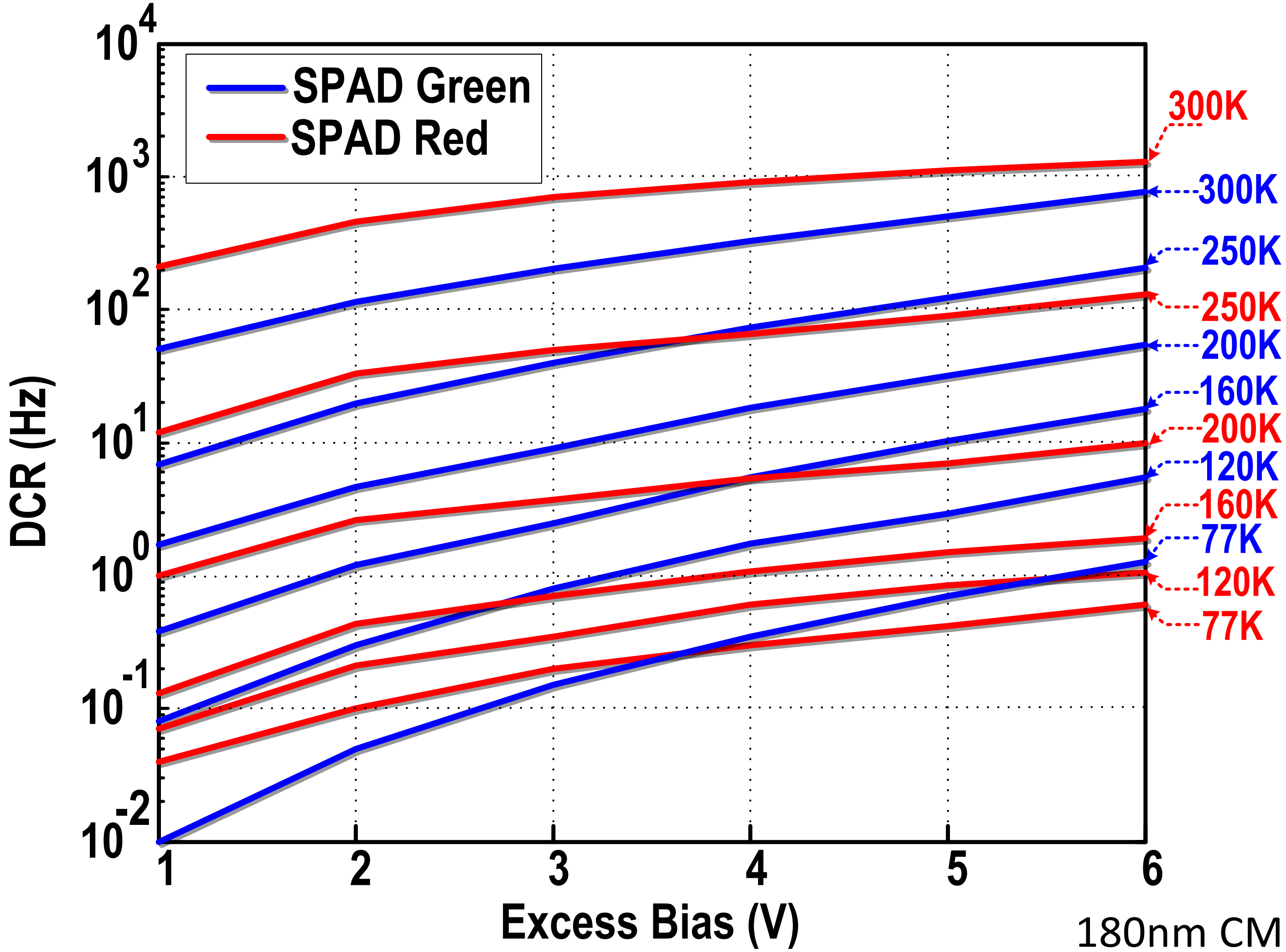
Operation in proportional and Geiger mode (SPAD)

E. Charbon et al., *ISSCC* 2017





Cryo-SPADs

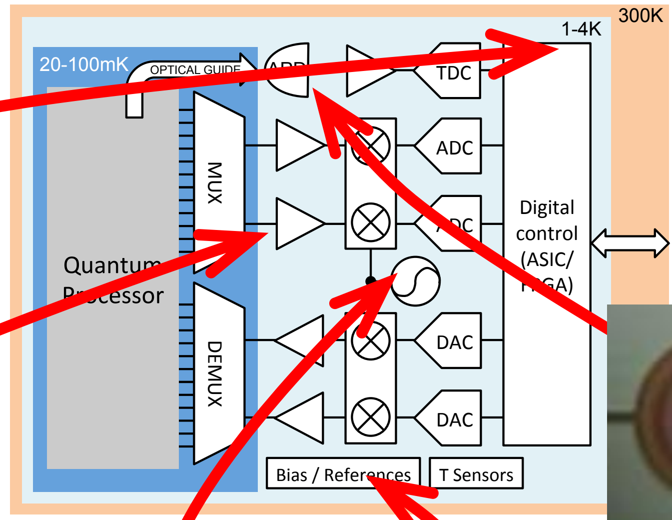


180nm CMOS bulk

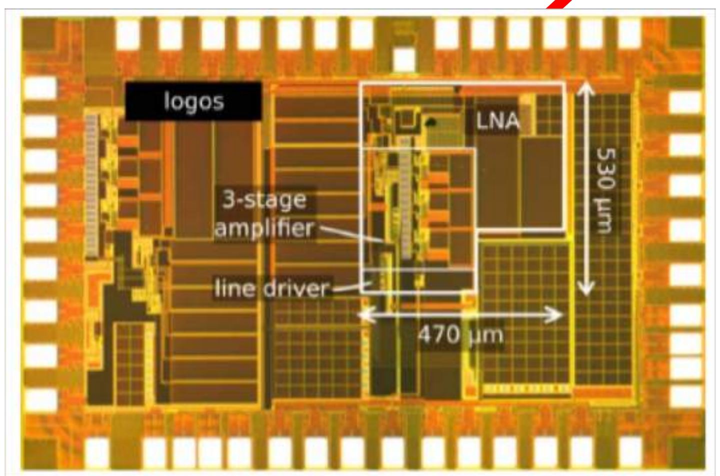
B. Patra et al., *JSSC* 2018

Building up

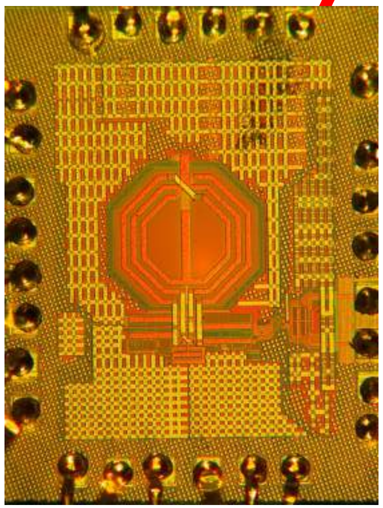
IEEE IEDM 2016



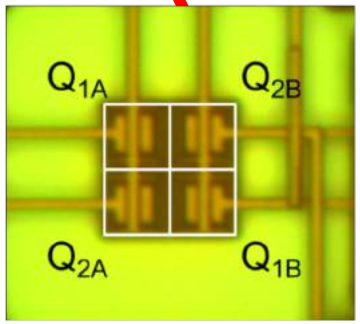
IEEE IEDM 2016
IEEE JSS



IEEE ISSCC 2017
IEEE JSSC 2018



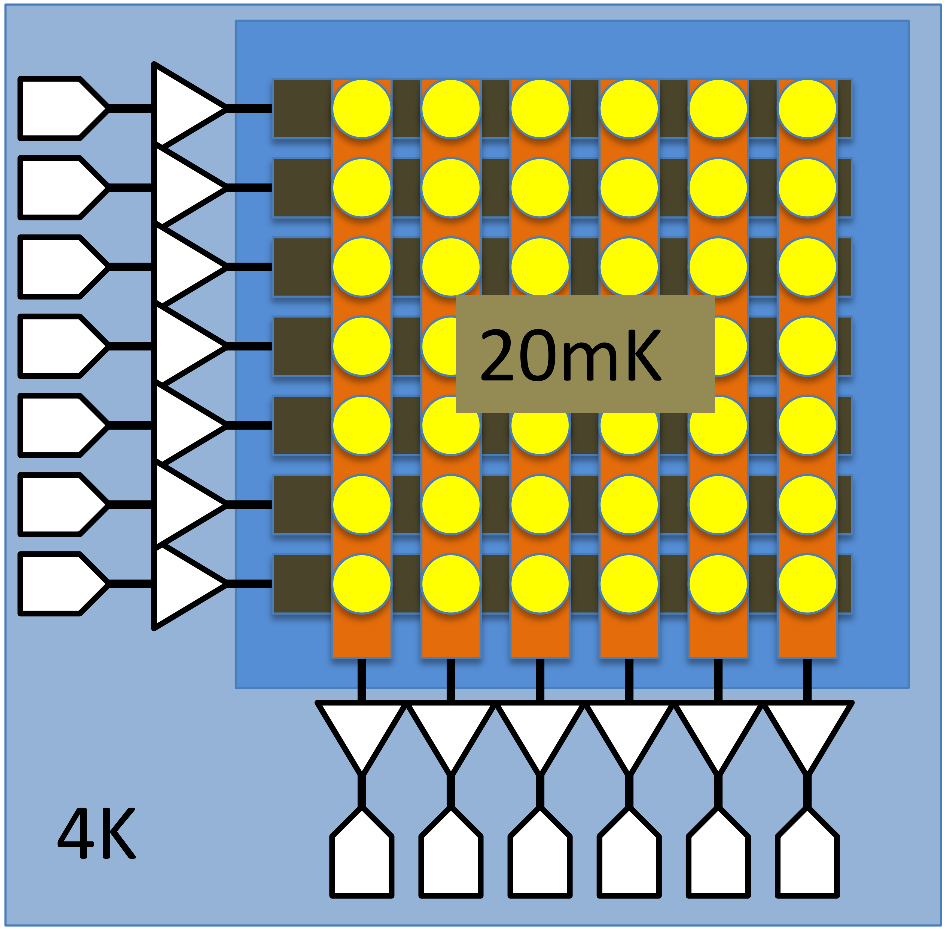
IEEE ISSCC 2017
IEEE JSSC 2018



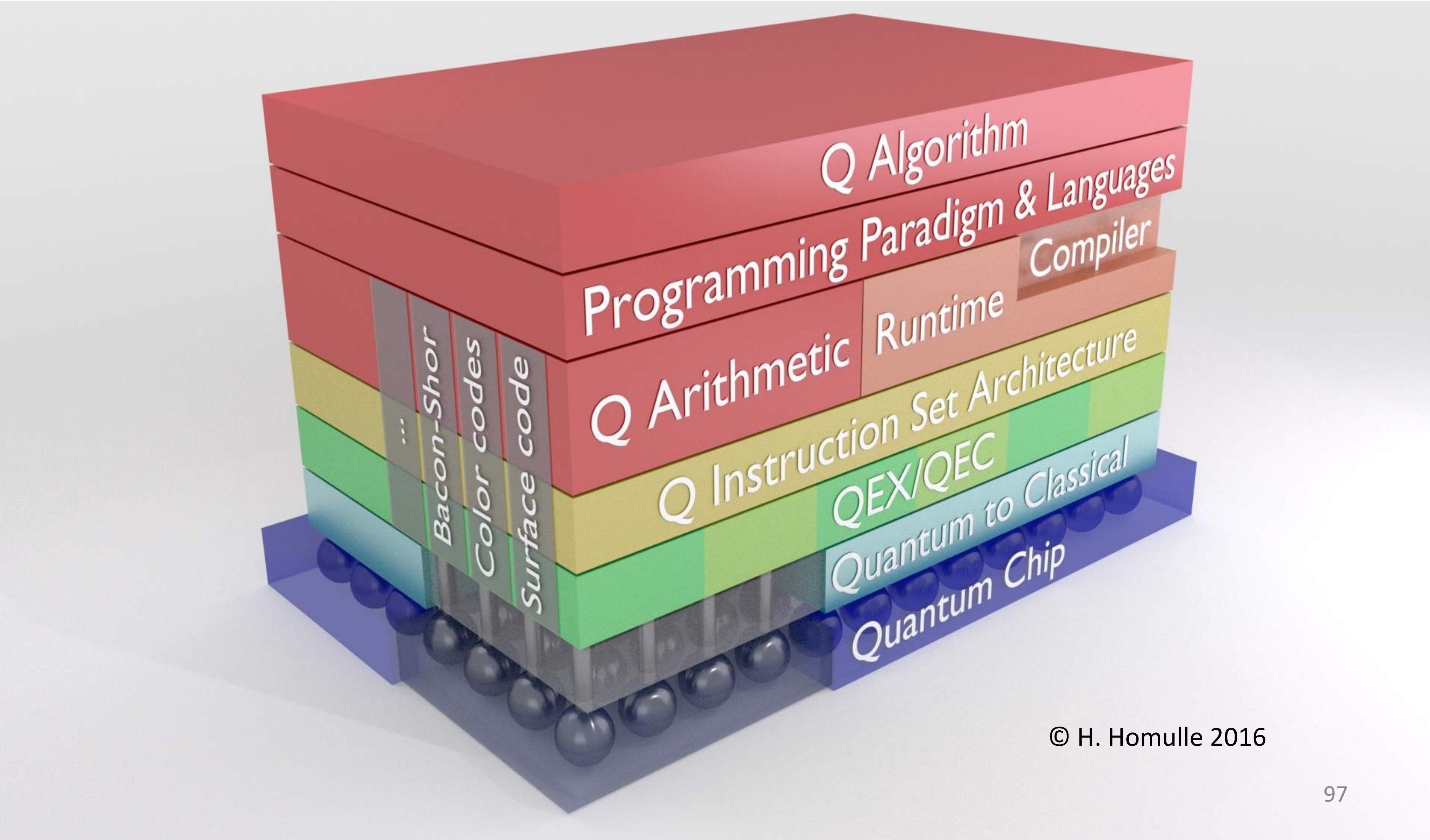
IEEE Sensors 2016

2D readout and control

- Use ***imaging sensor*** readout as inspiration
- Reduce number of transistors (ideally to zero)
- Use tunneling barriers as selectors
- (limited) use of 3D stacking



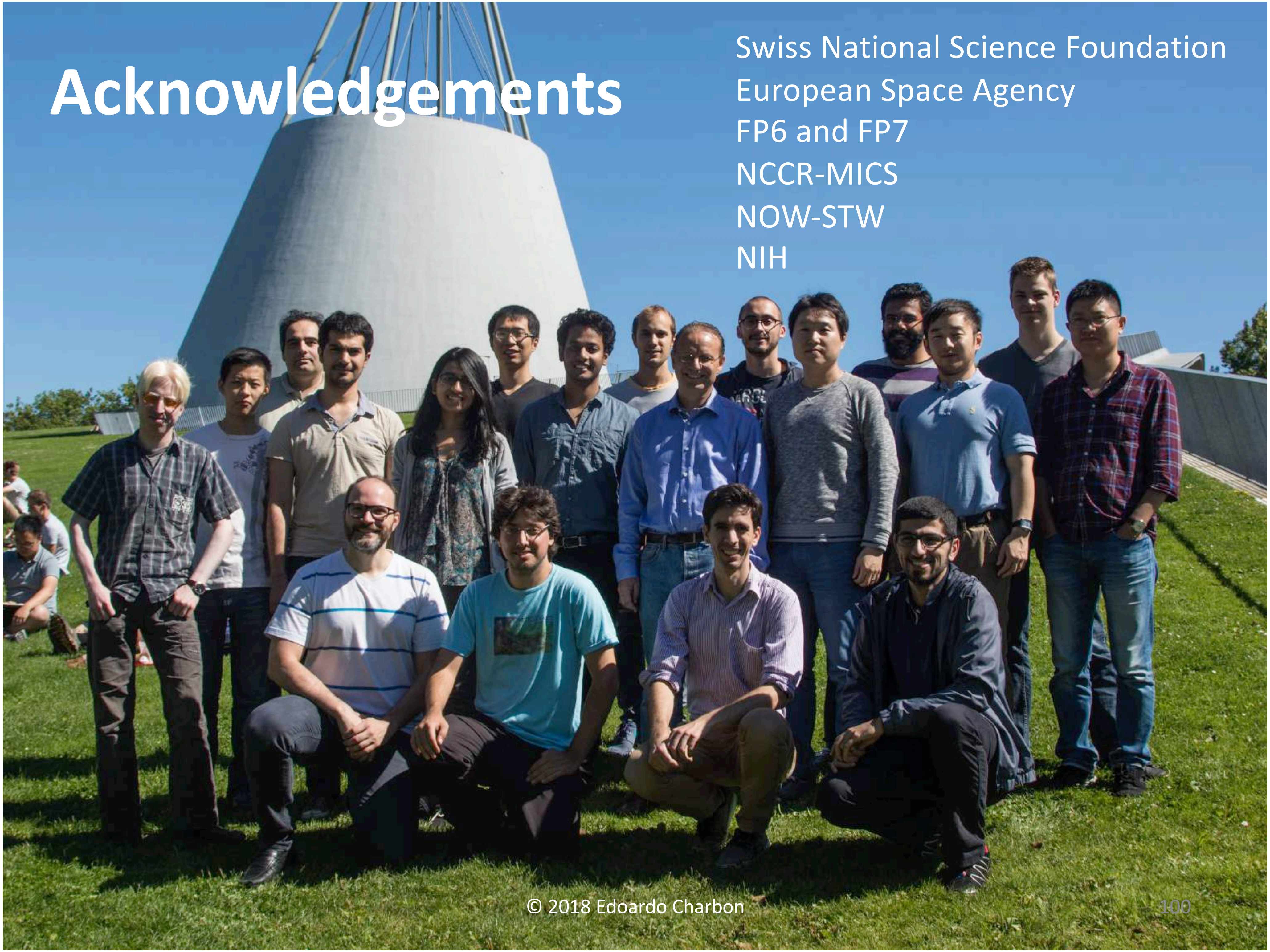
Putting things in context



Conclusions

Take-home Messages

- SPADs are quantum devices and that they can be used for quantum applications
- Modularity is an important ingredient to large photonic systems and even the technology of a cellphone camera will do
- One can actually make a product (and money) out of SPADs
- Quantum Computing will need cryo-SPADs and 3D ICs



Acknowledgements

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http://aqua.epfl.ch

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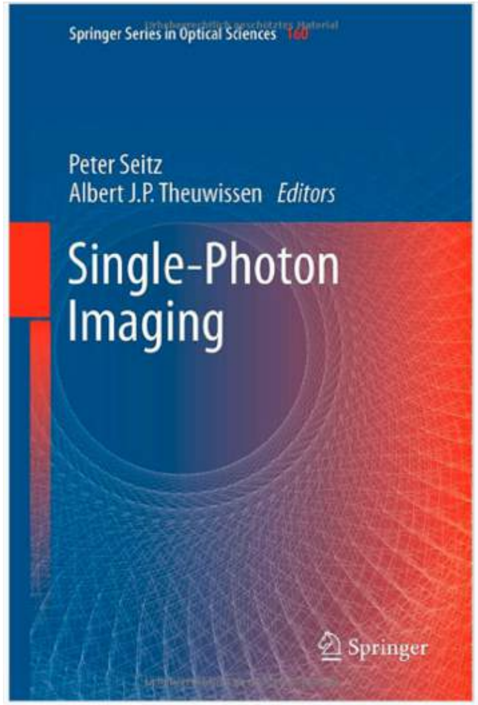

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