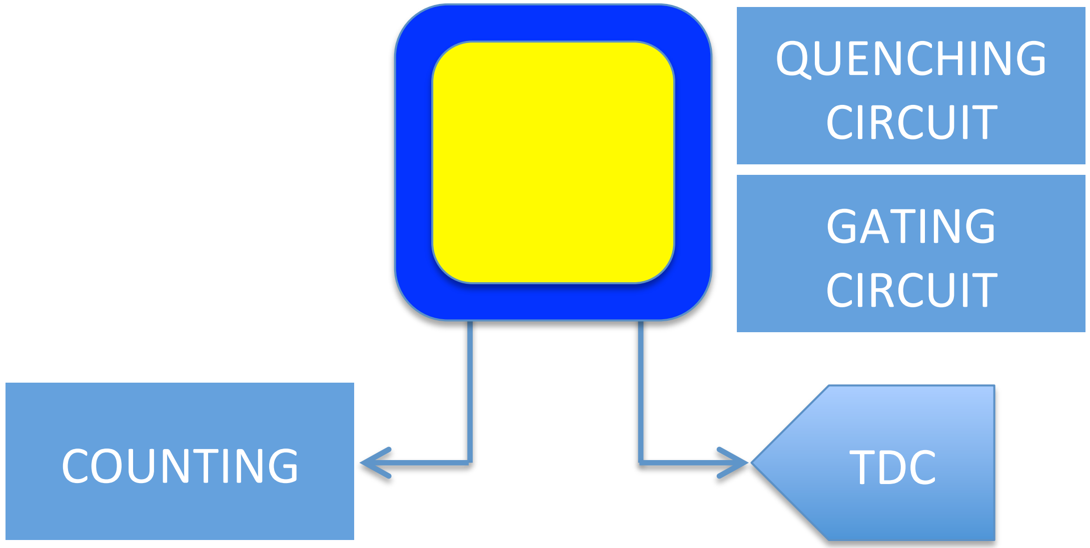
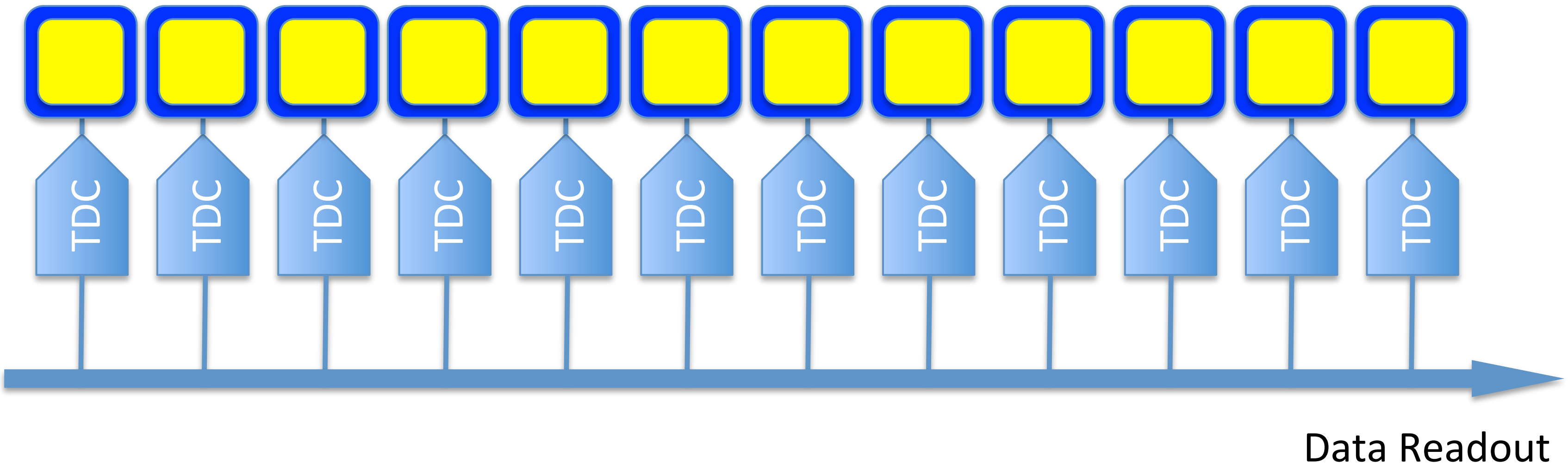
First, Let Us Define the Pixel



1D Arrays

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



1D Arrays

- No sharing of resources
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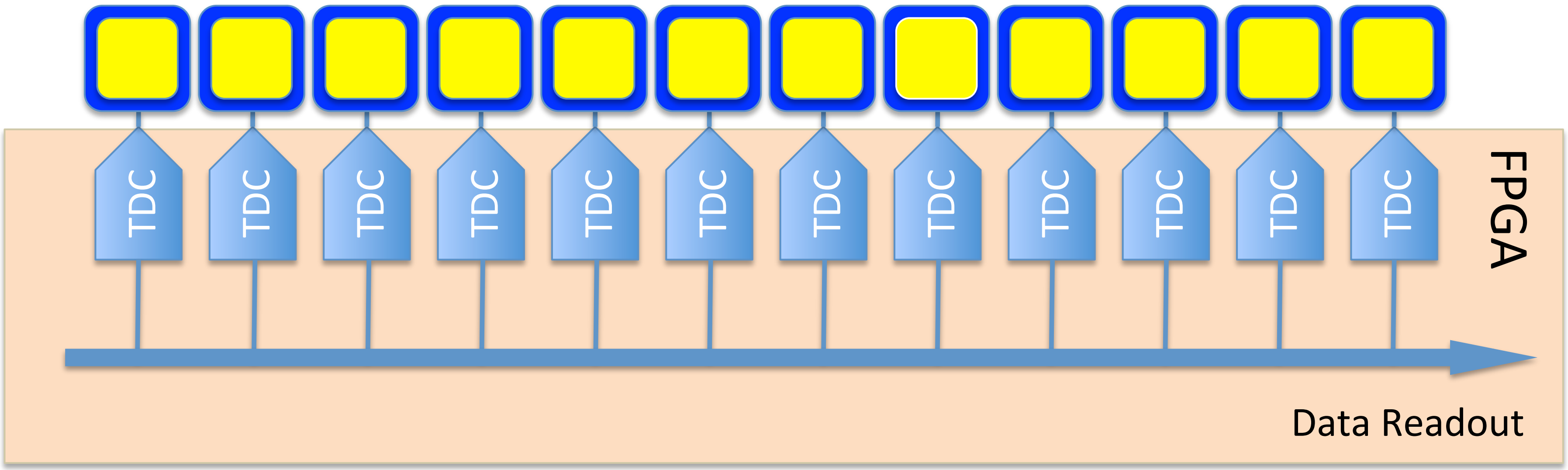
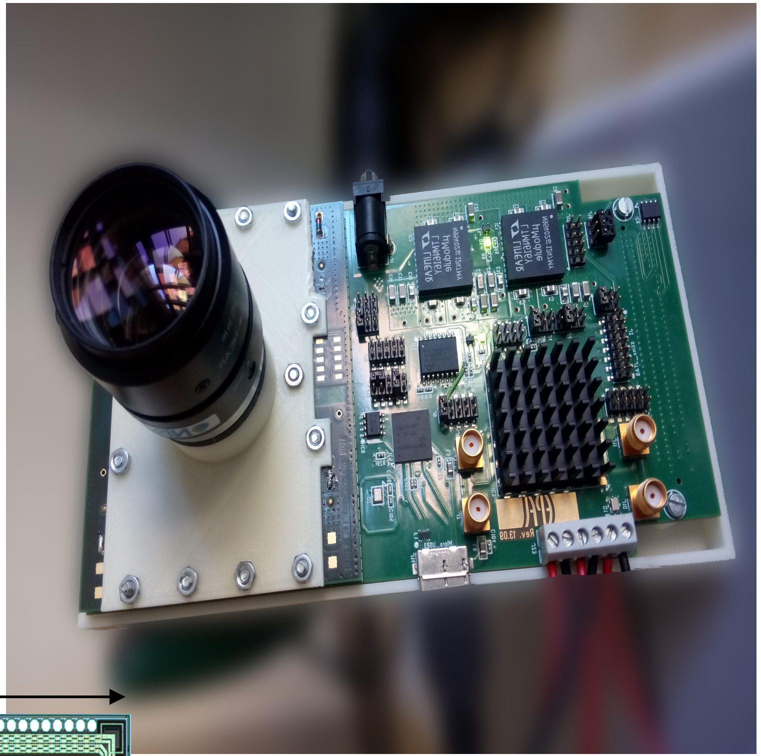
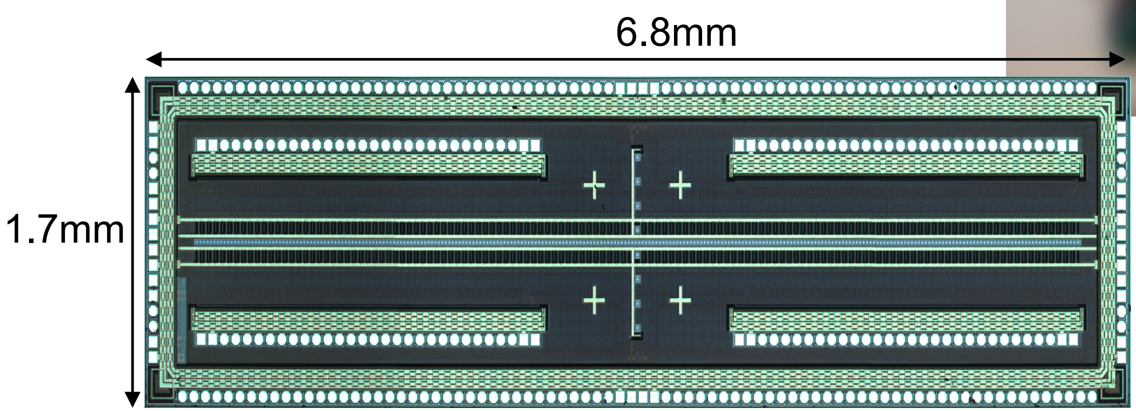


LinoSPAD: Time-resolved Camera

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



8cm x 16cm

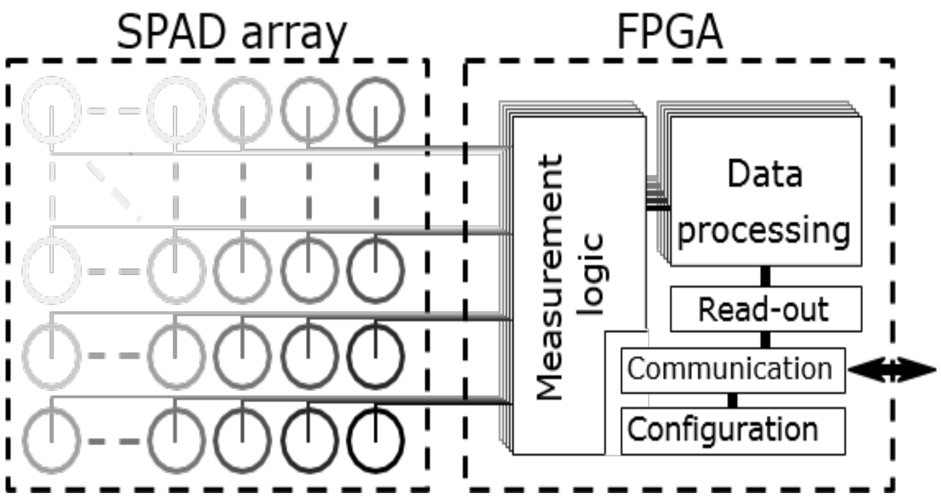


S. Burri, C. Bruschini, E. Charbon, *SPIE Photonics West* 2018, San Francisco

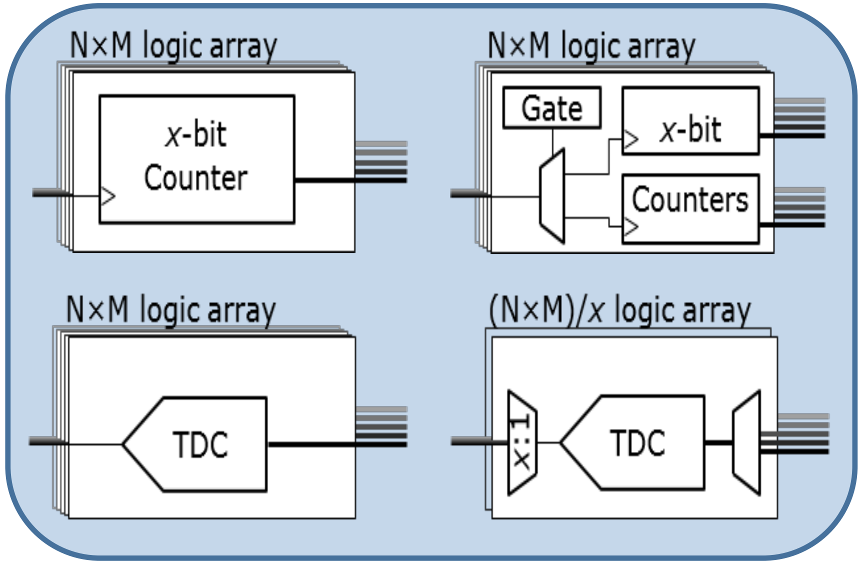
S. Burri et al., *MDPI Instruments* 2017

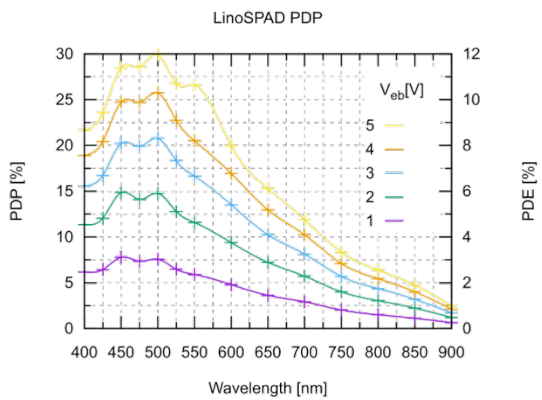
LinoSPAD Modularity

Combine options for pixel logic and processing

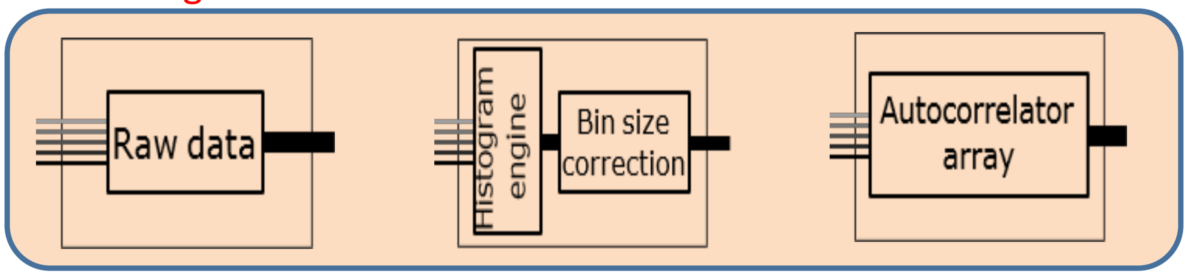


Measurement blocks





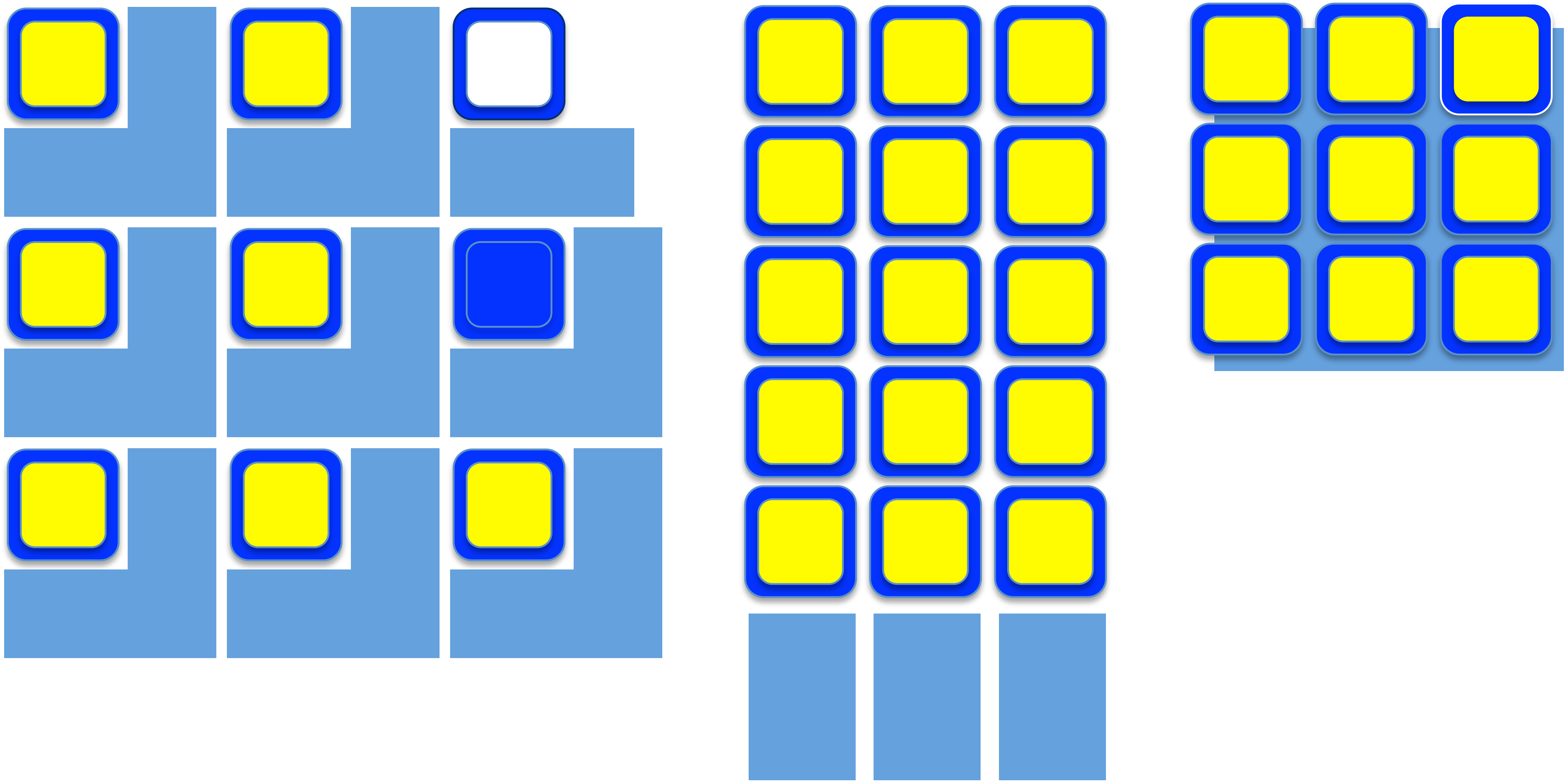
Processing blocks



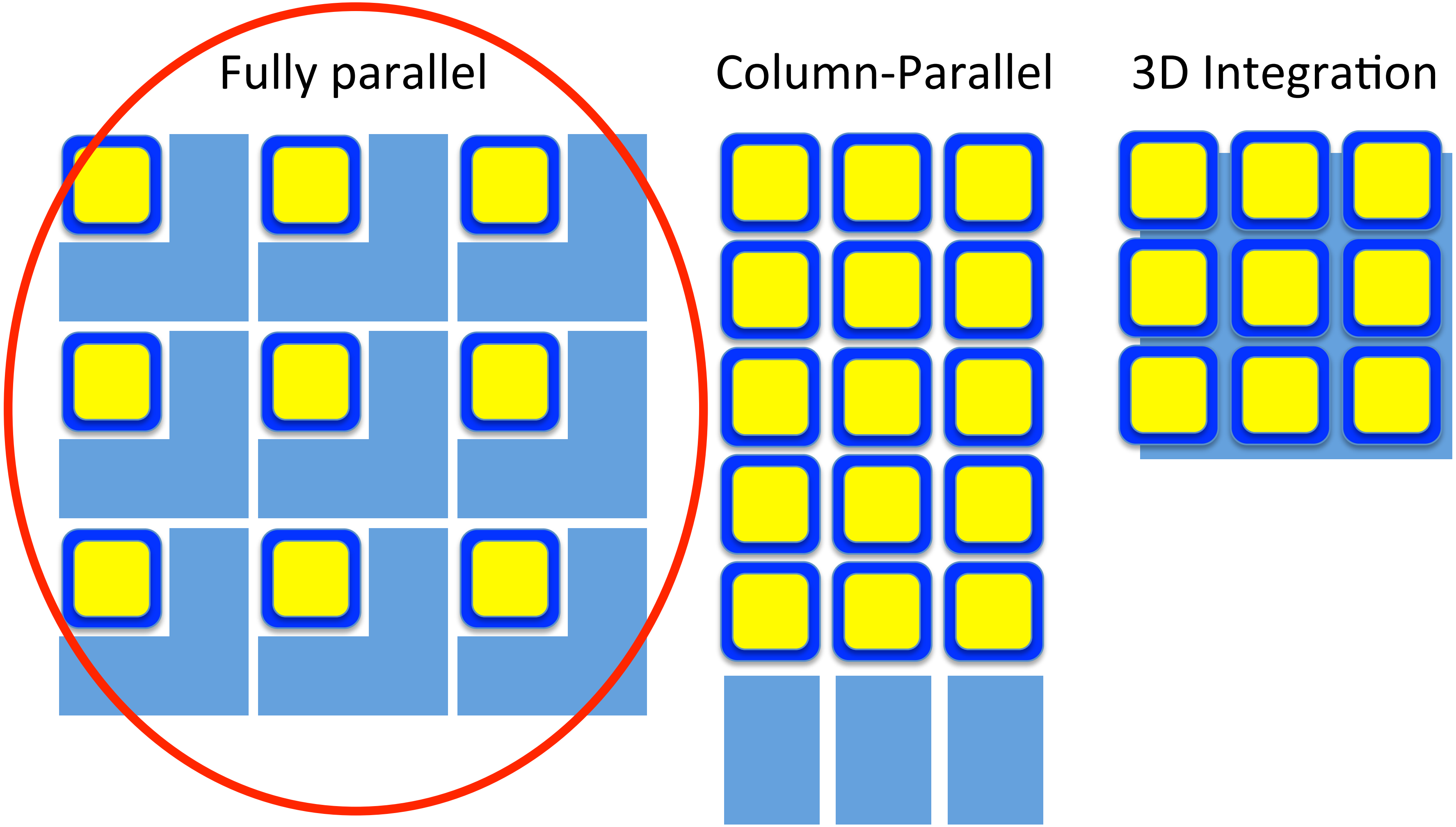
Illustrations: H. Homulle

2D Arrays

Fully parallel — Column-Parallel — 3D Integration



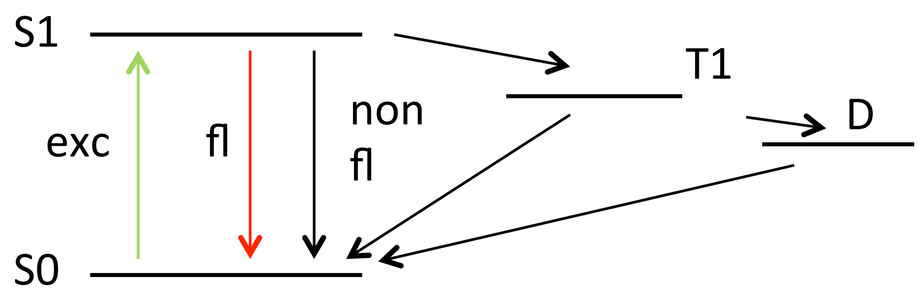
2D Arrays

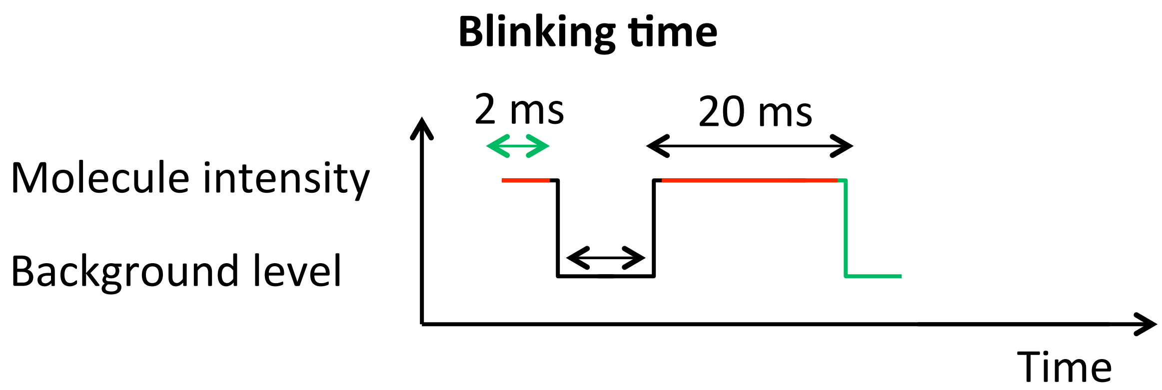


The GSDIM Super-resolution Project

Localization Super-resolution

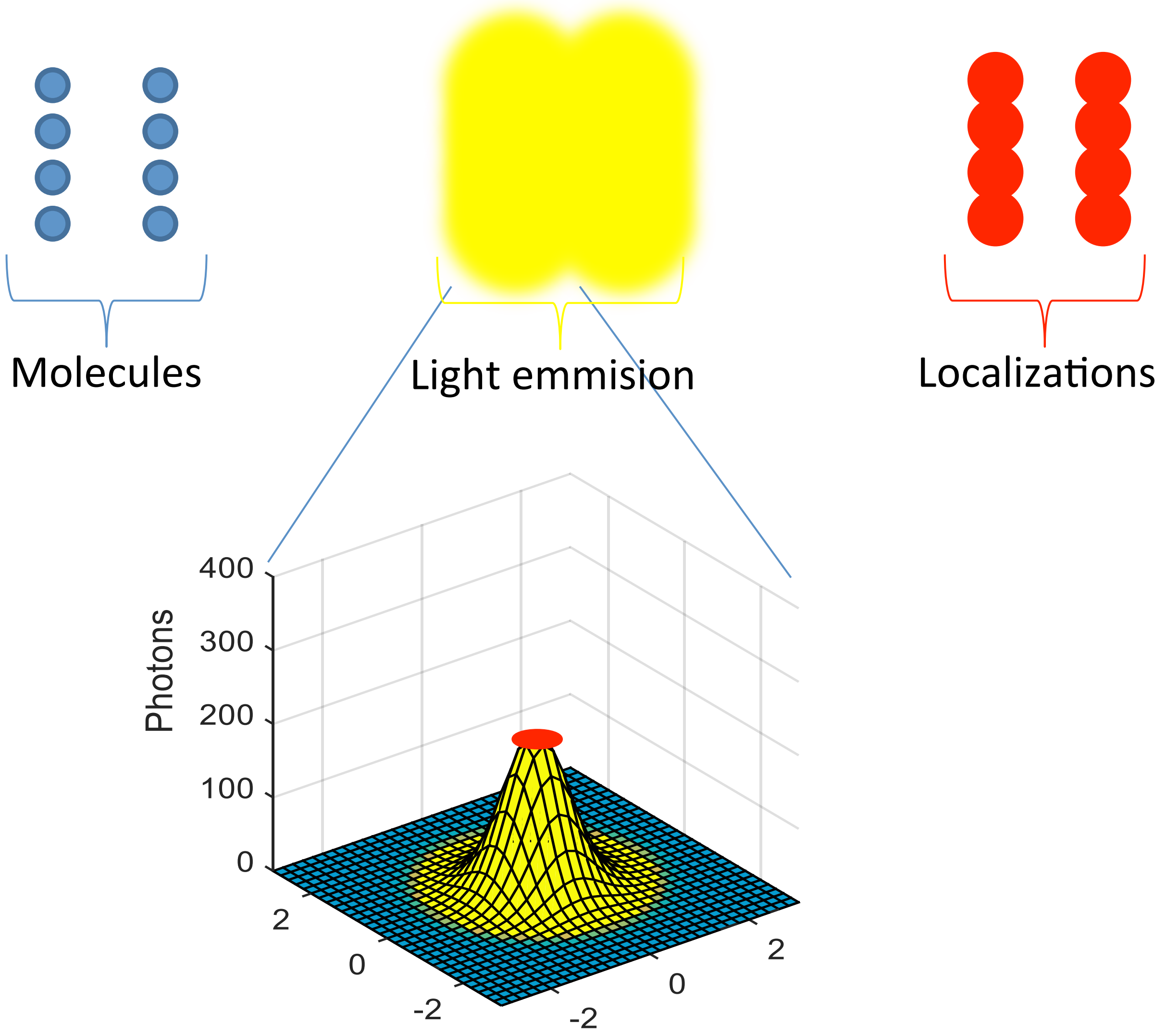
- PALM
- STORM
- dSTORM/GSDIM*



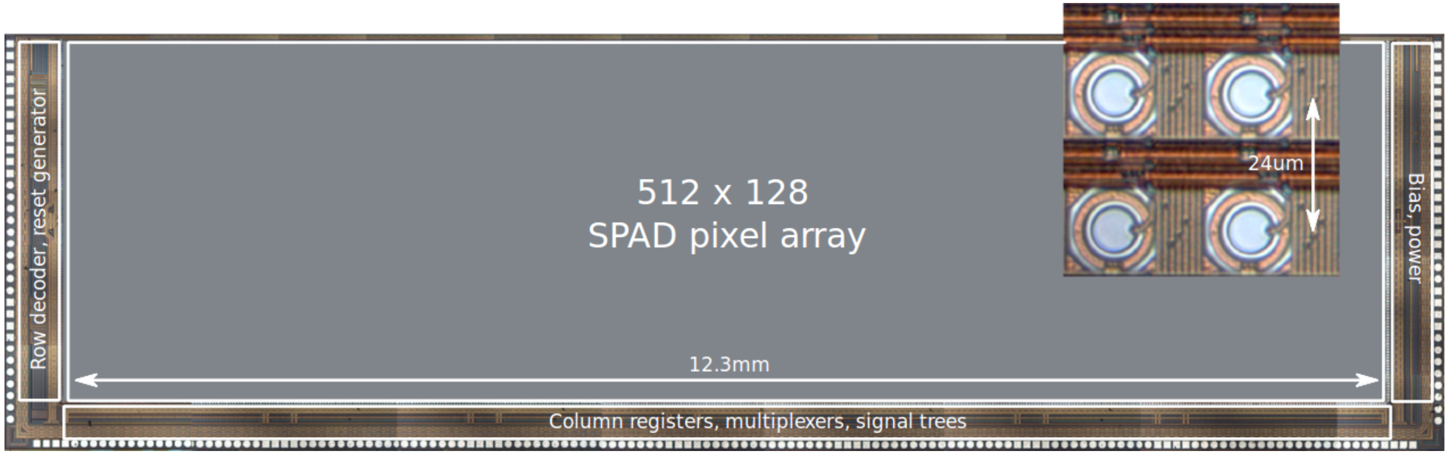


*) GSDIM = Ground-state depletion and single-molecule return

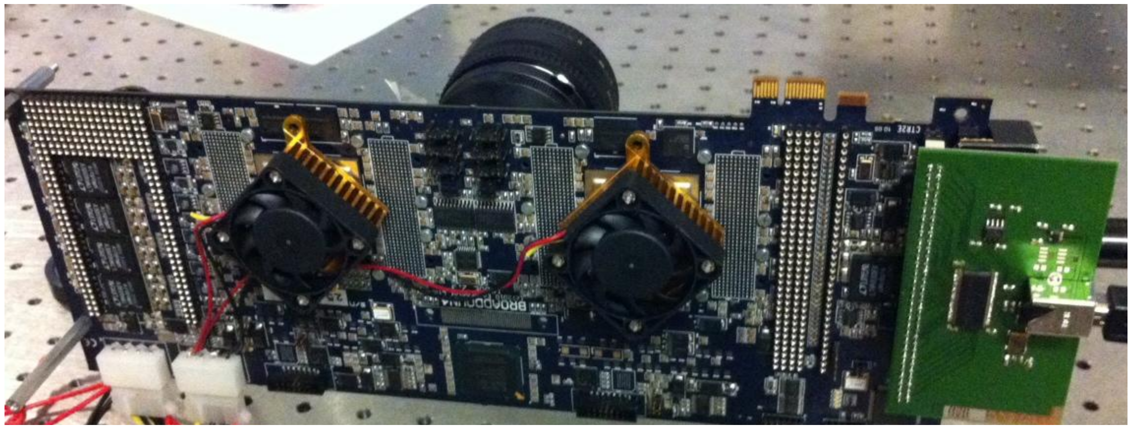
Localization Super-resolution



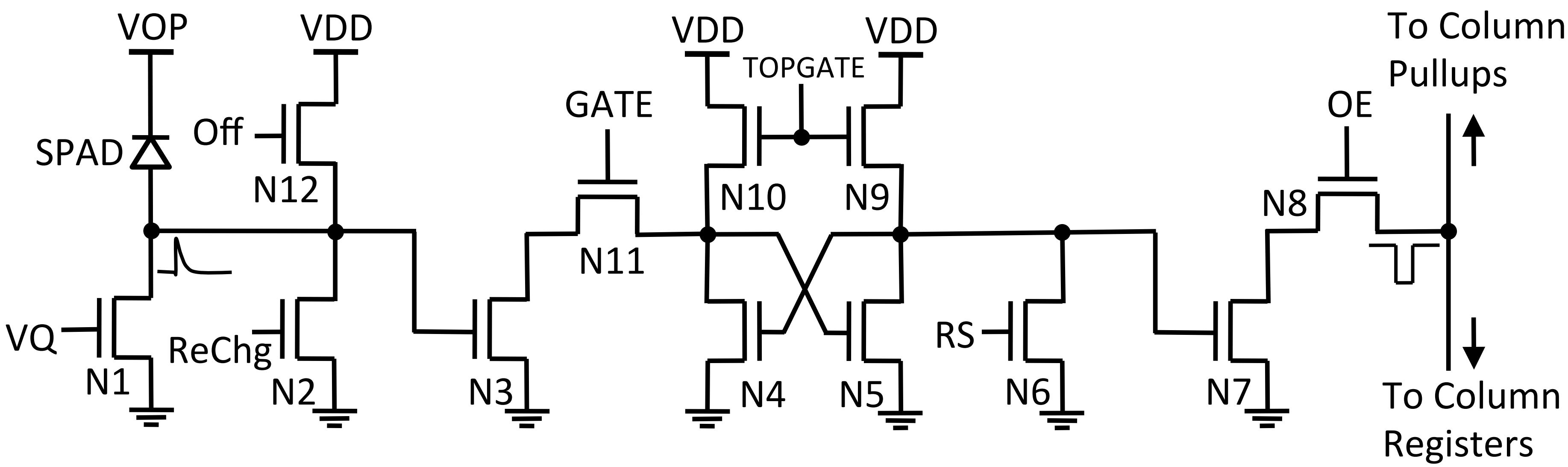
SwissSPAD



Burri et al., Optics Express 2014

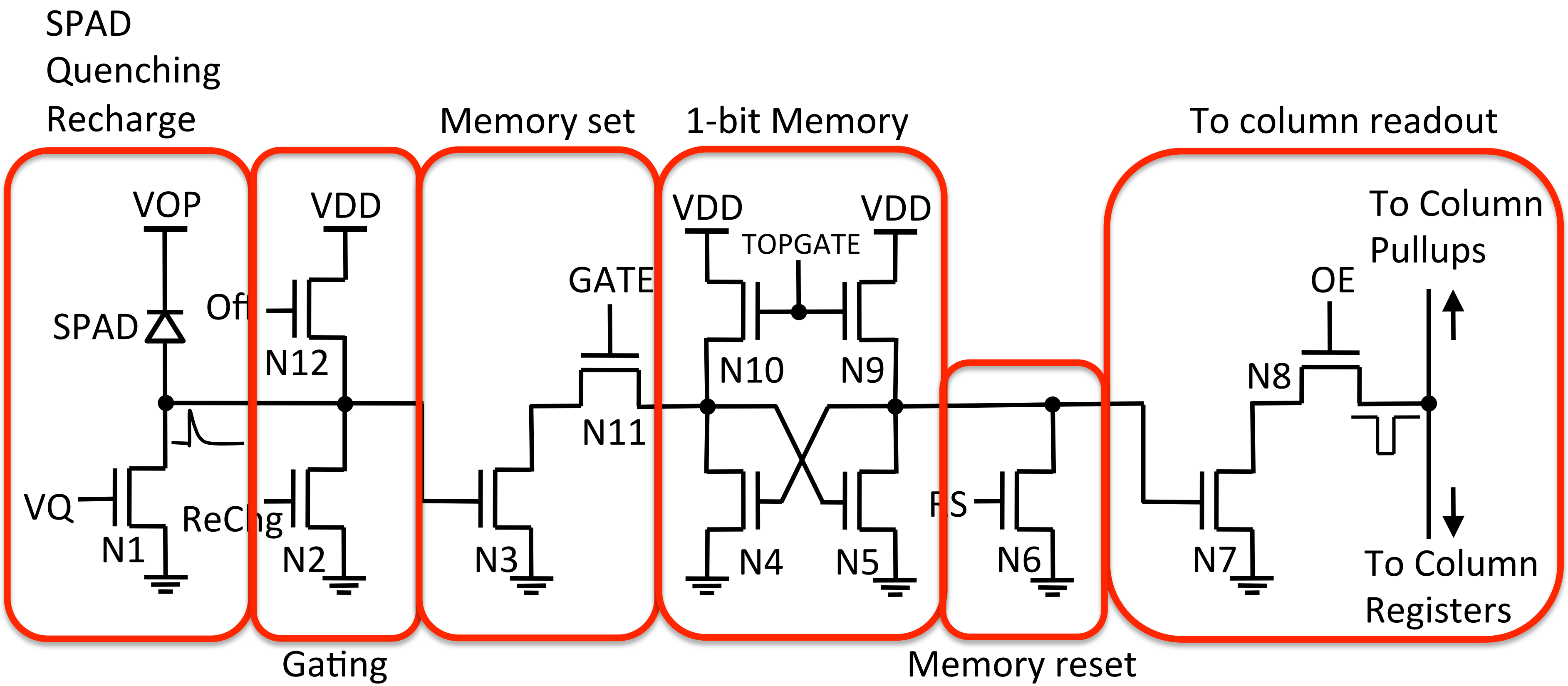


Pixel Architecture



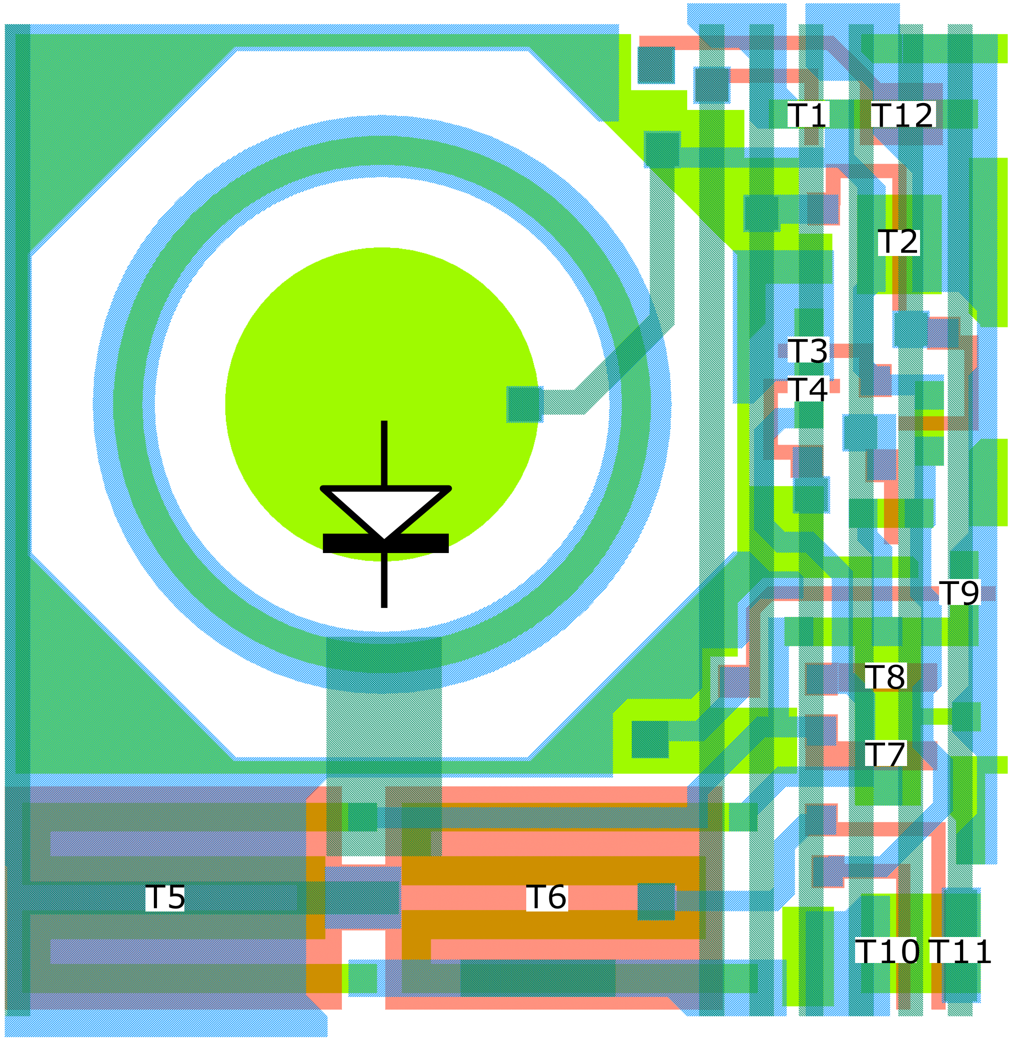
Burri et al., Optics Express 2014

Pixel Architecture

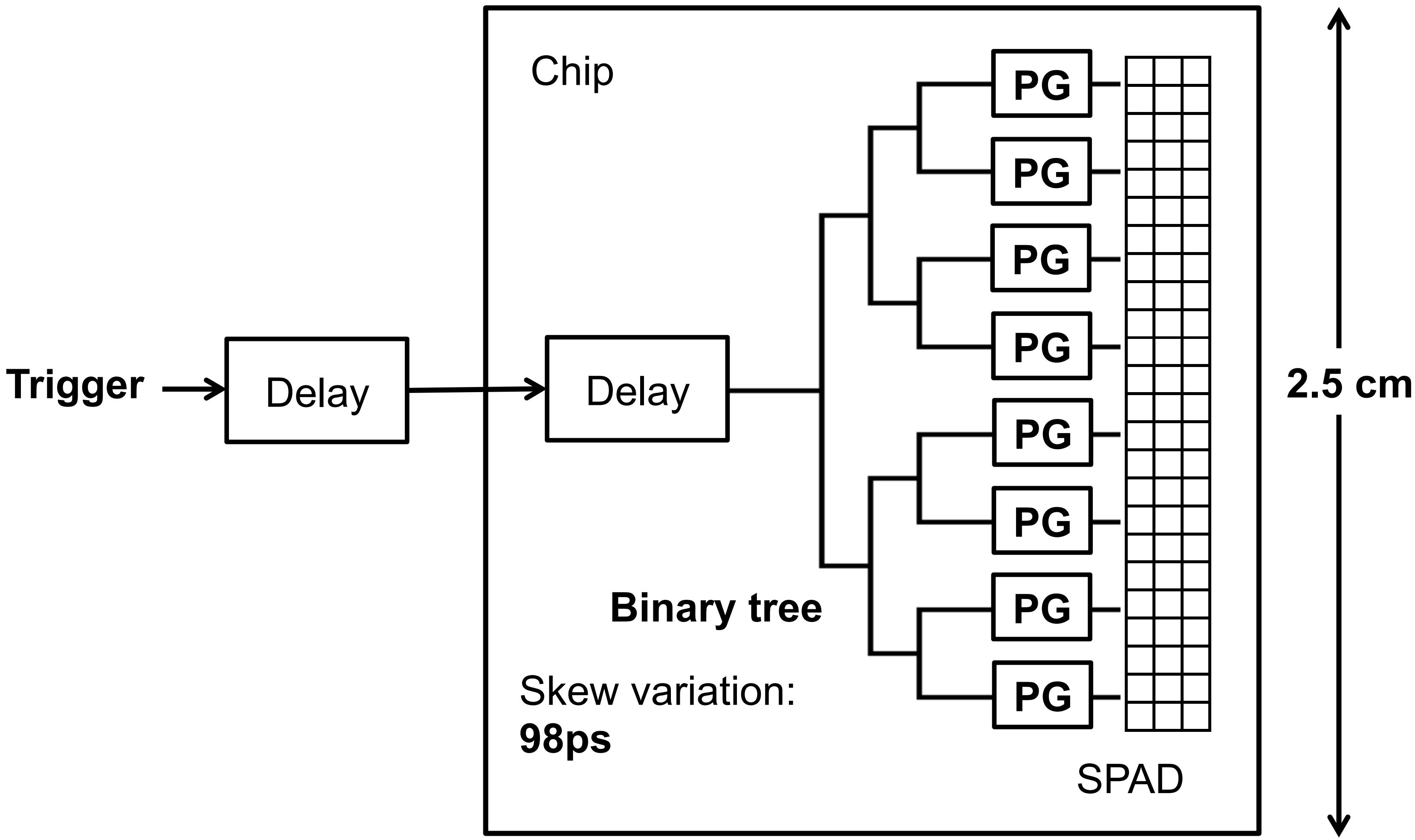


Burri et al., Optics Express 2014

Pixel Layout



Gating Synchronization: B-Trees

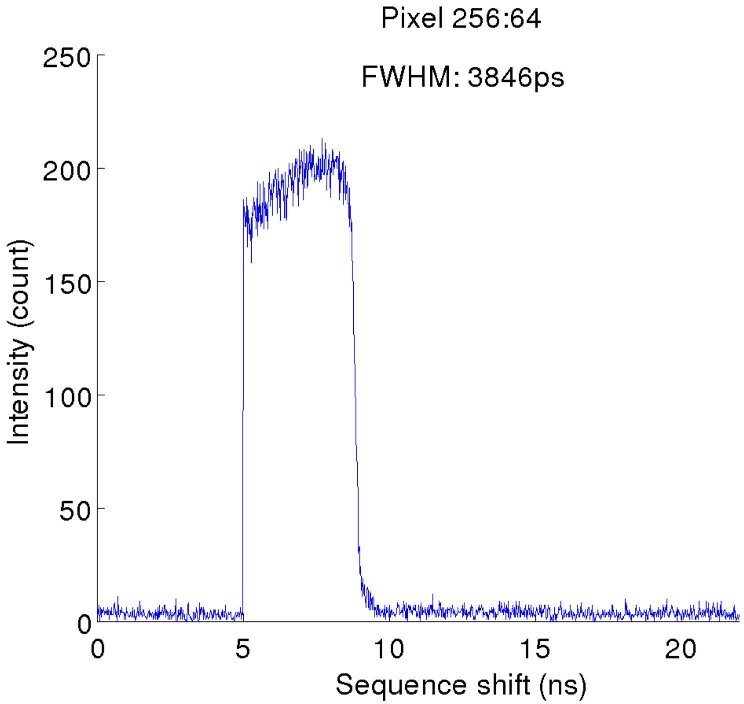


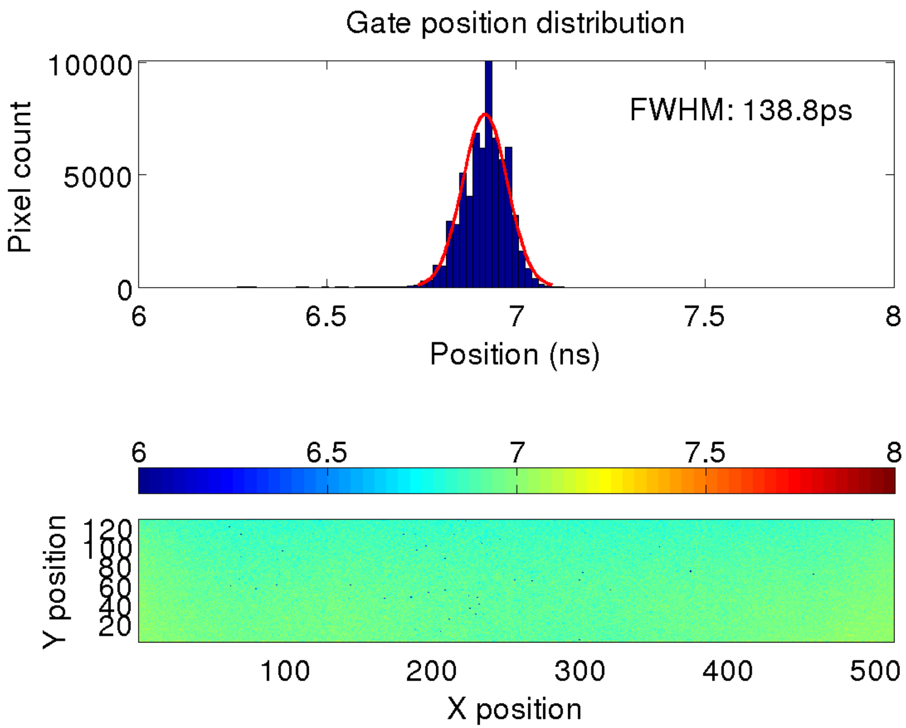
PG: Pulse Generator

Courtesy: Yuki Maruyama

Gate Accuracy and Uniformity

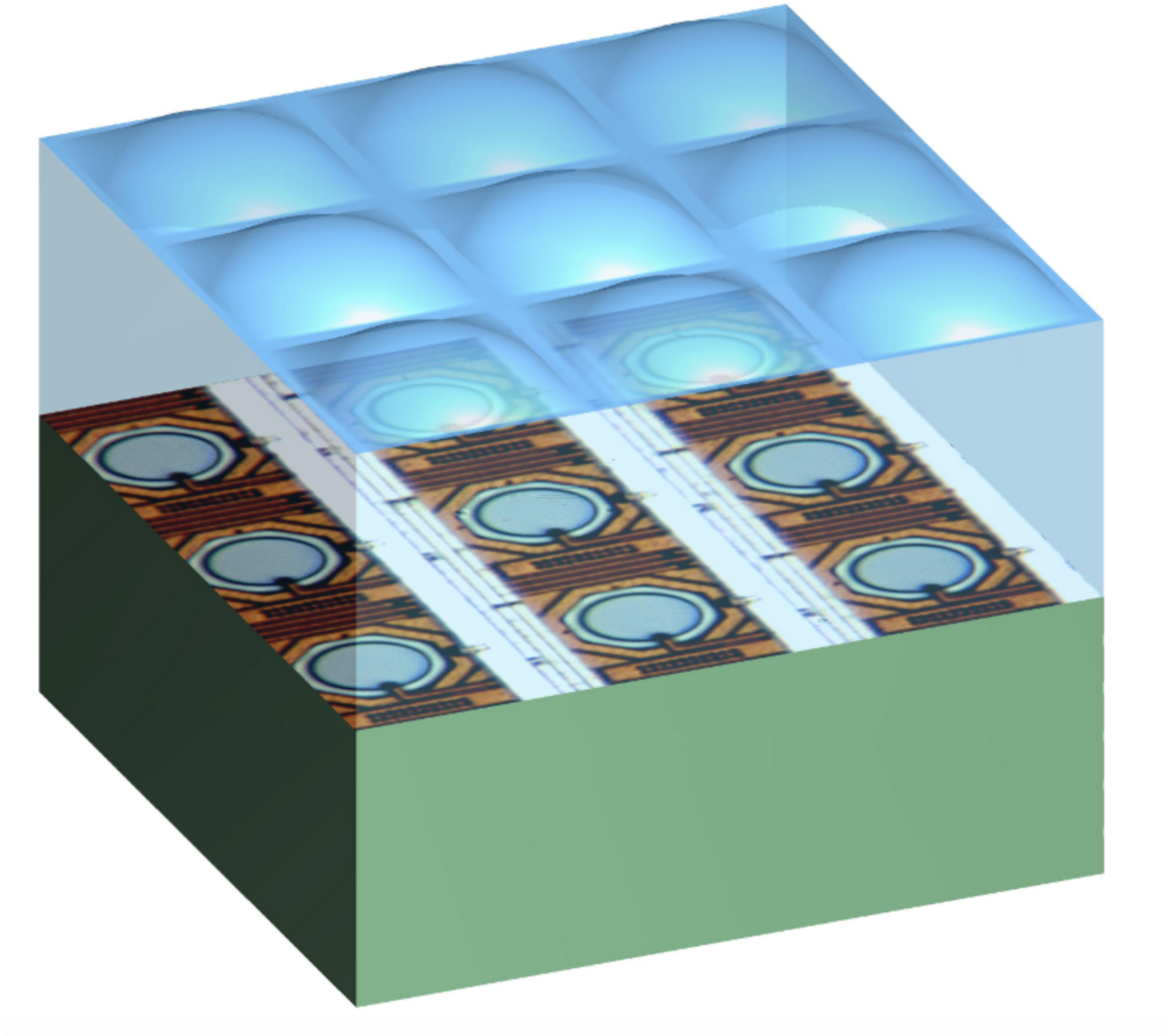
- 4ns gating (138ps FWHM)
- 156kfps frame rate



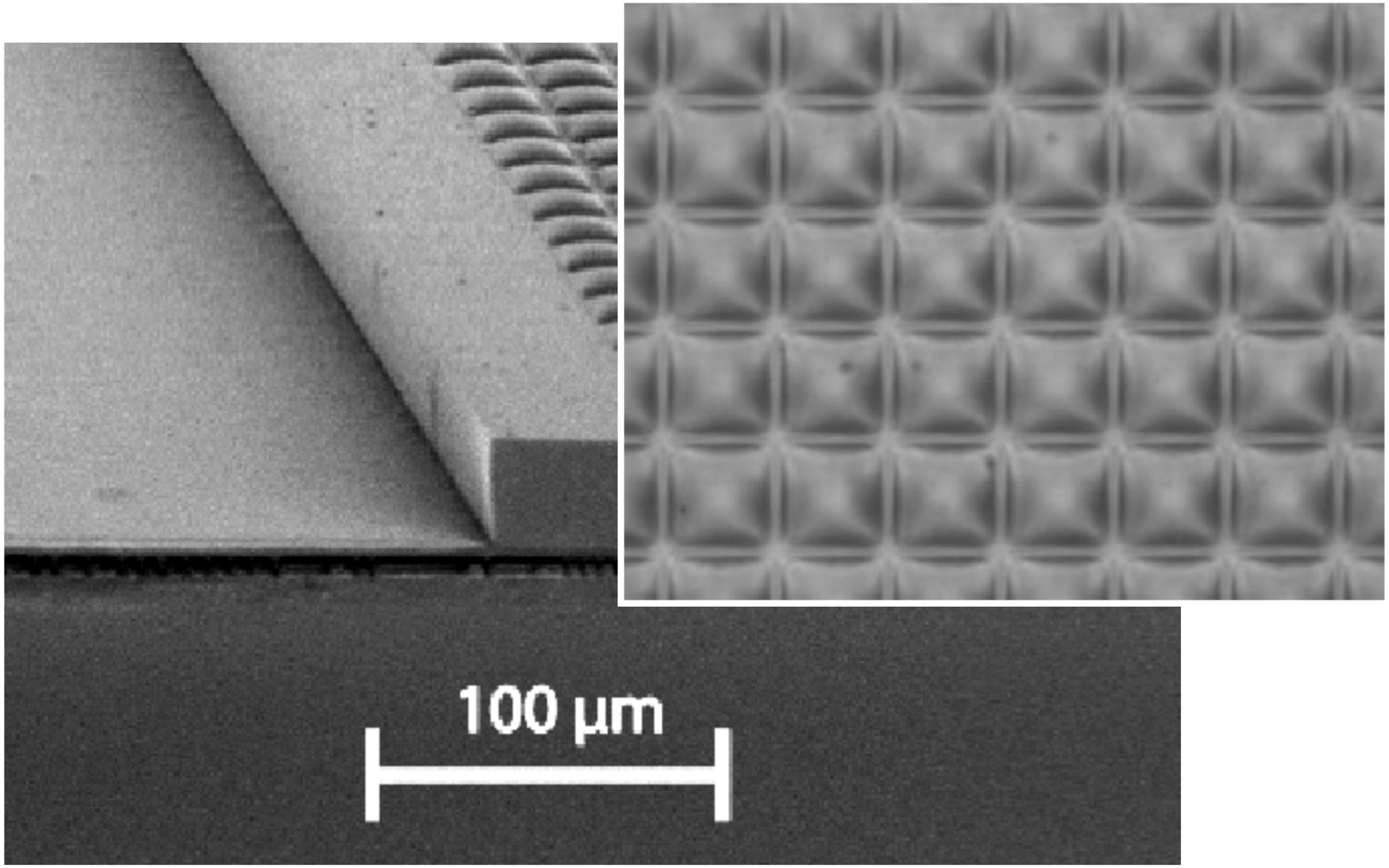


Burri et al., Optics Express 2014

Fill Factor Recovery: Microlenses

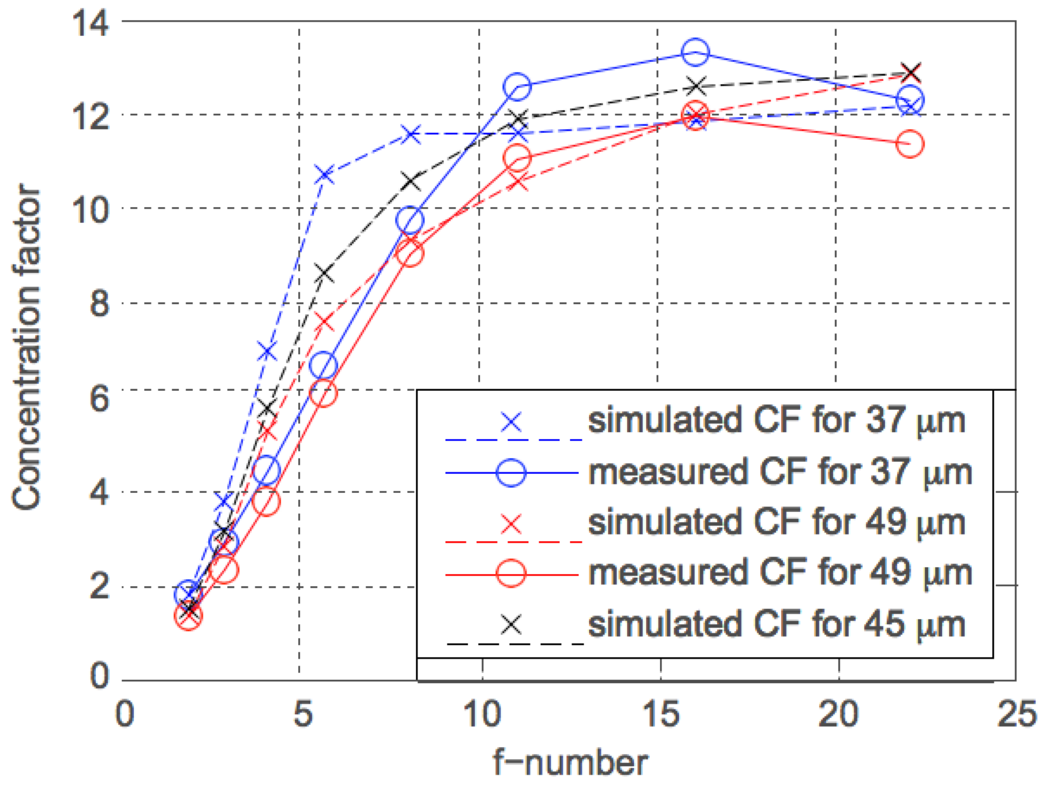


Fill Factor Recovery: Microlenses



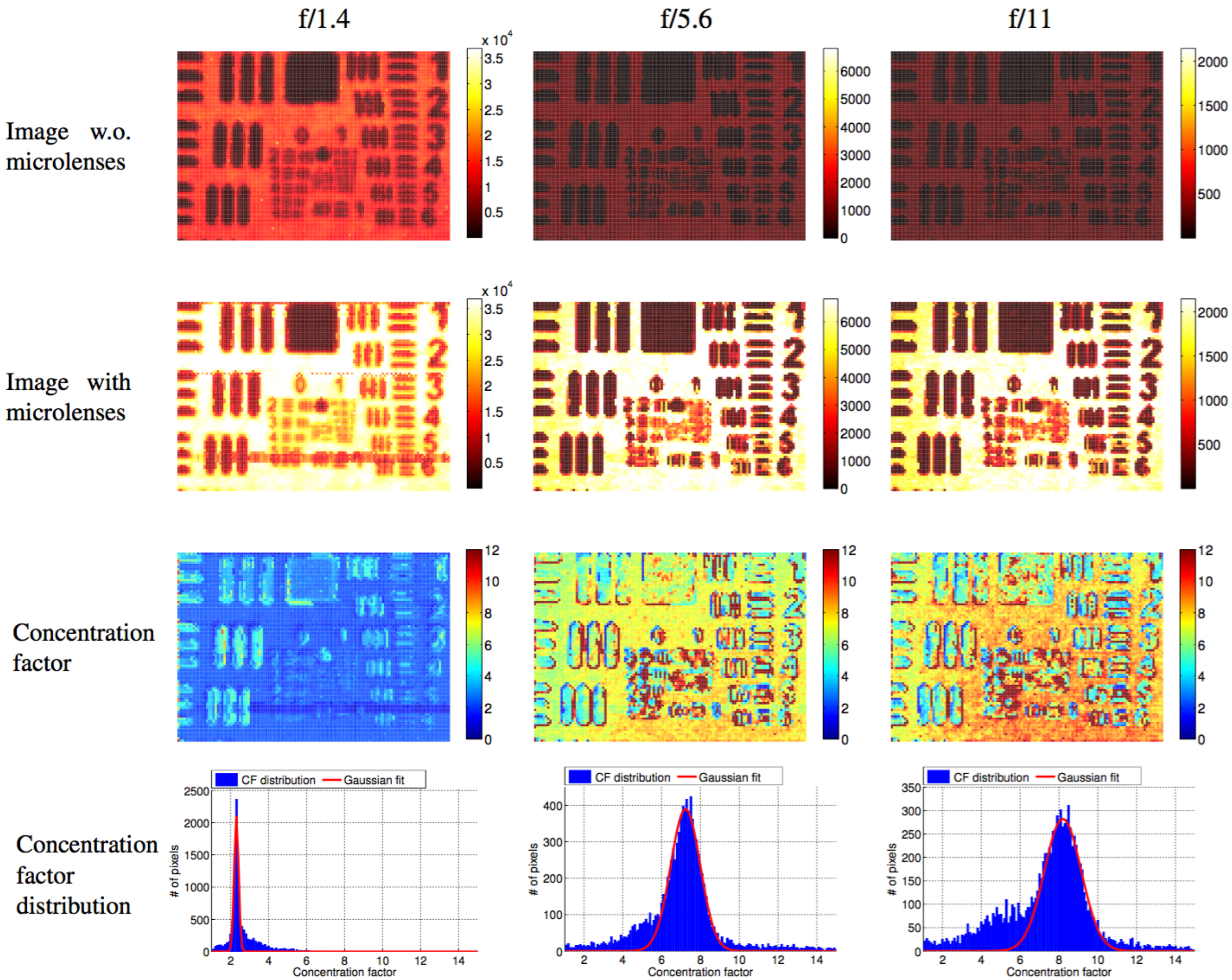
J. Mata Pavia et al., Optics Express 2014

Fill Factor Recovery: Microlenses



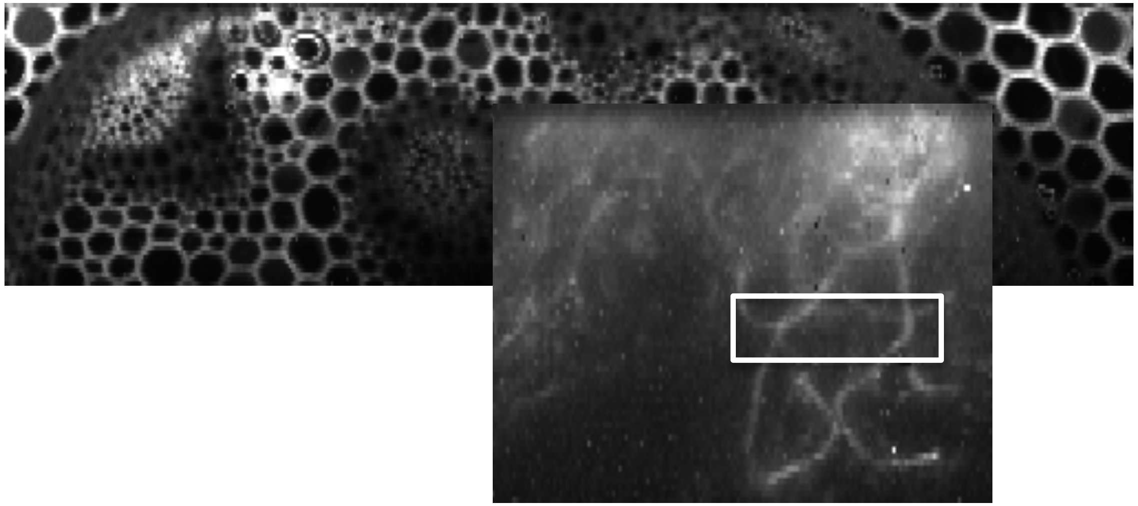
J. Mata Pavia et al., Optics Express 2014

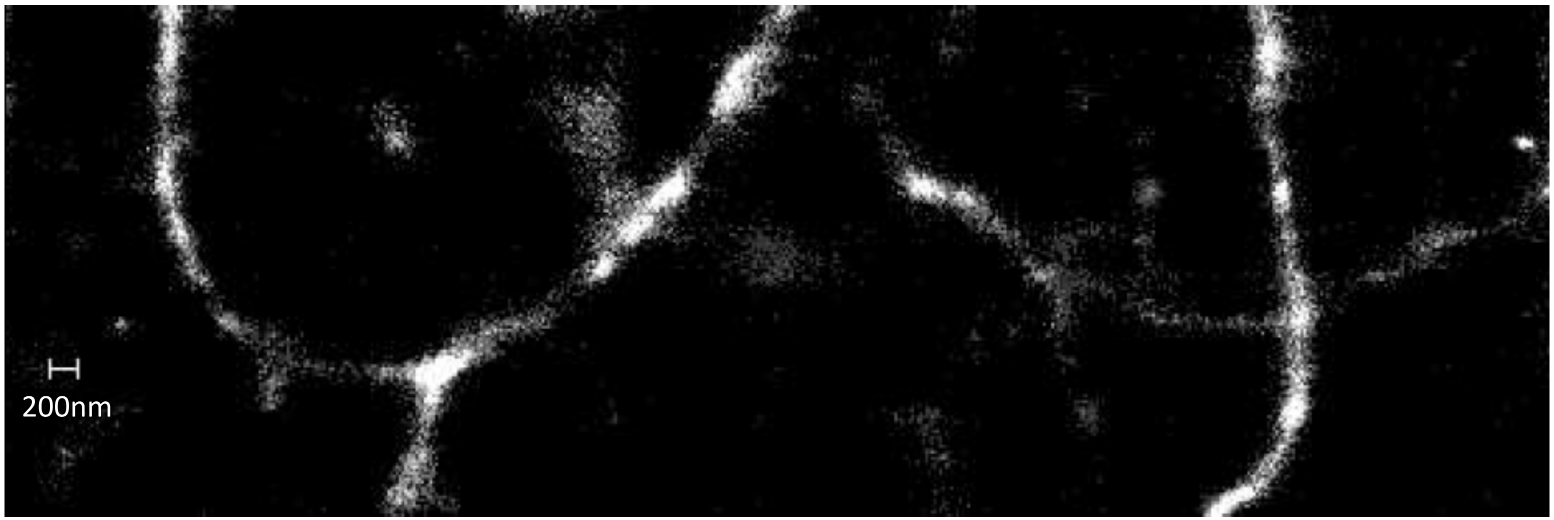
Fill Factor Recovery: Microlenses



J. Mata Pavia et al., Optics Express 2014

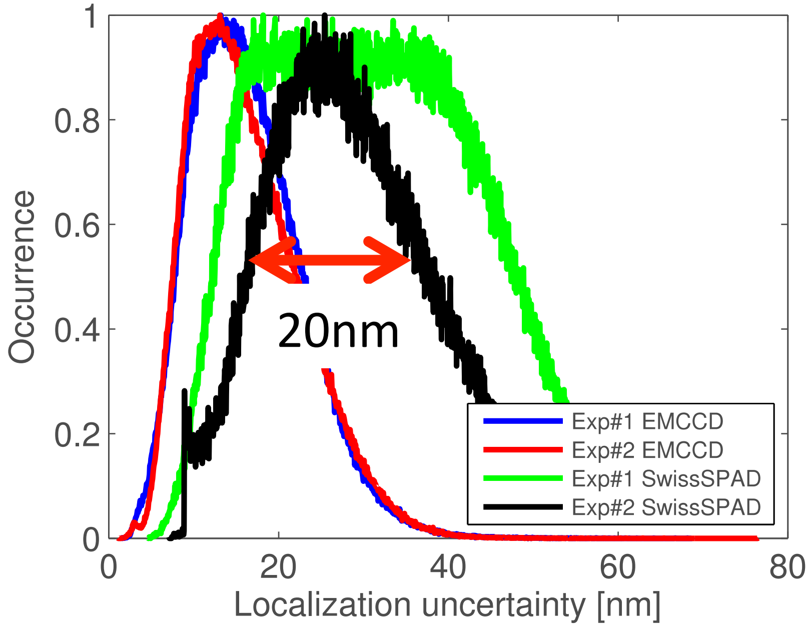
GSDIM Images

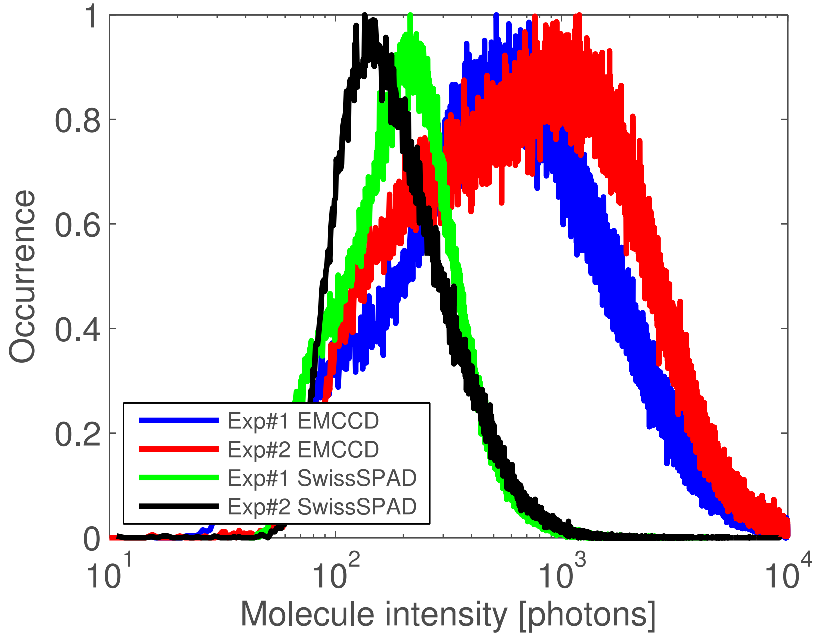




I.M. Antolovic, S. Burri, R. Hoebe, Y. Maruyama, C. Bruschini, E. Charbon, MDPI Sensors, **16**, 1005, 2016

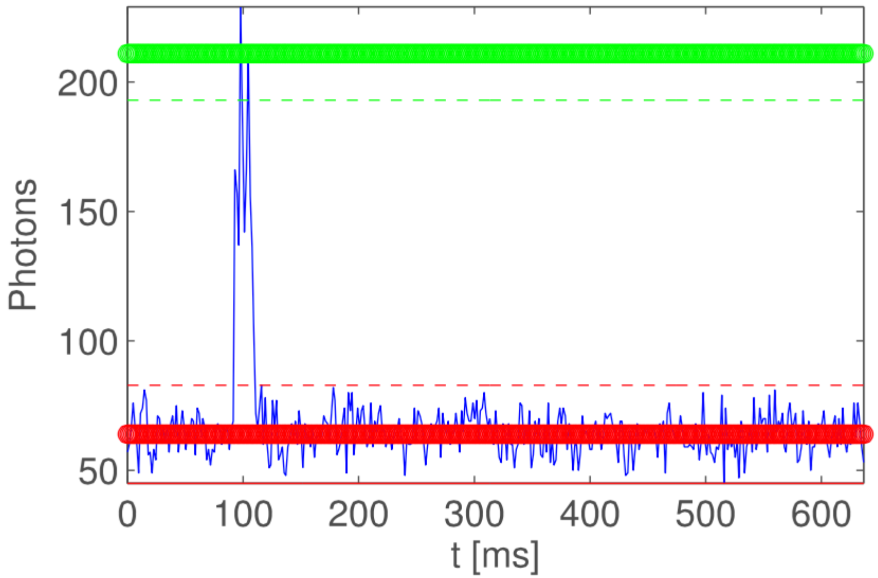
Localization Accuracy



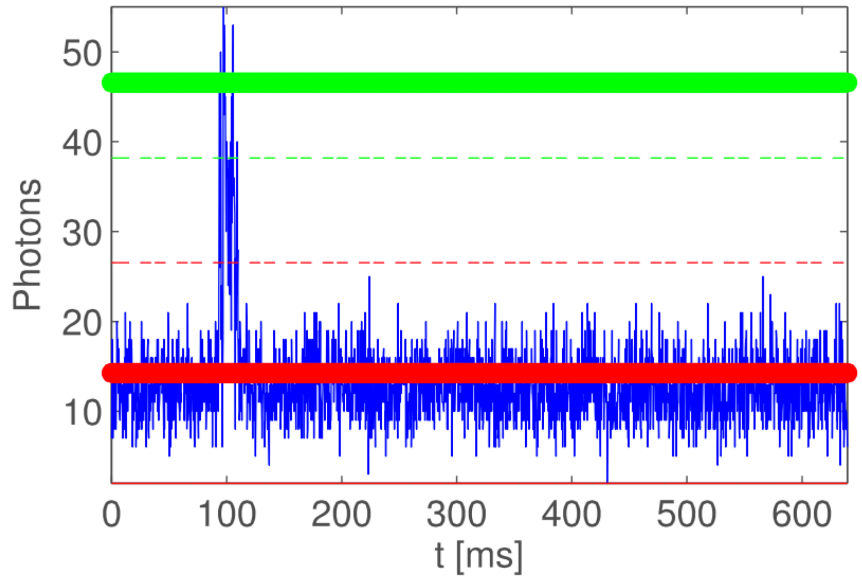


Blinking Statistics

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



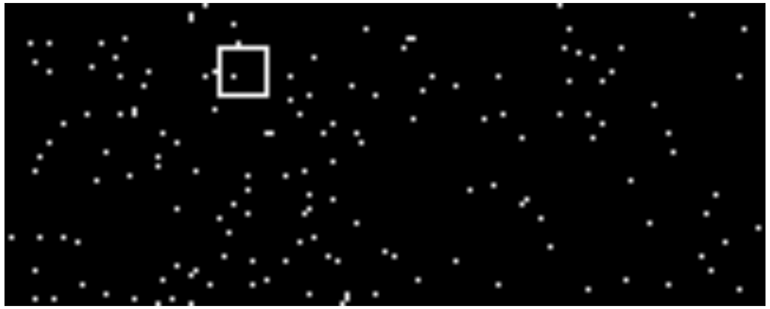
1.6ms resolution



0.3ms resolution

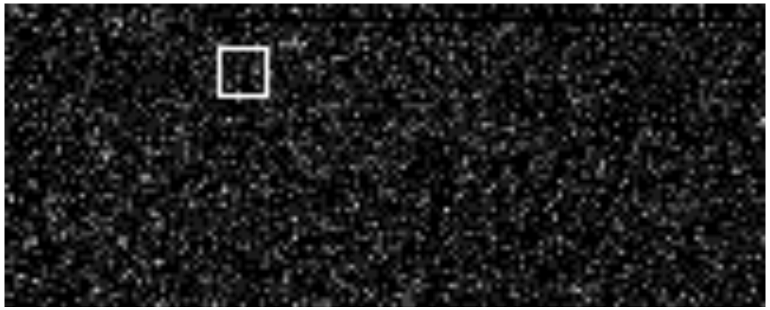
I.M. Antolovic, S. Burri, R. Hoebe, Y. Maruyama, C. Bruschini, E. Charbon, MDPI Sensors, **16**, 1005, 2016

Blinking Effects

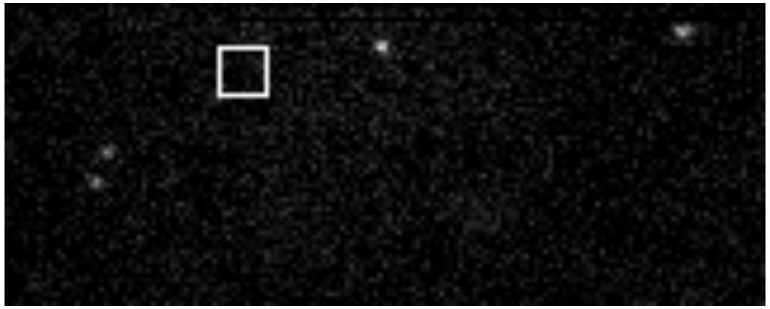


6.4 μs frame time

1.6 ms frame time



0.3 ms frame time



10 ms frame time

Fluorescence Lifetime Microscopy (FLIM)

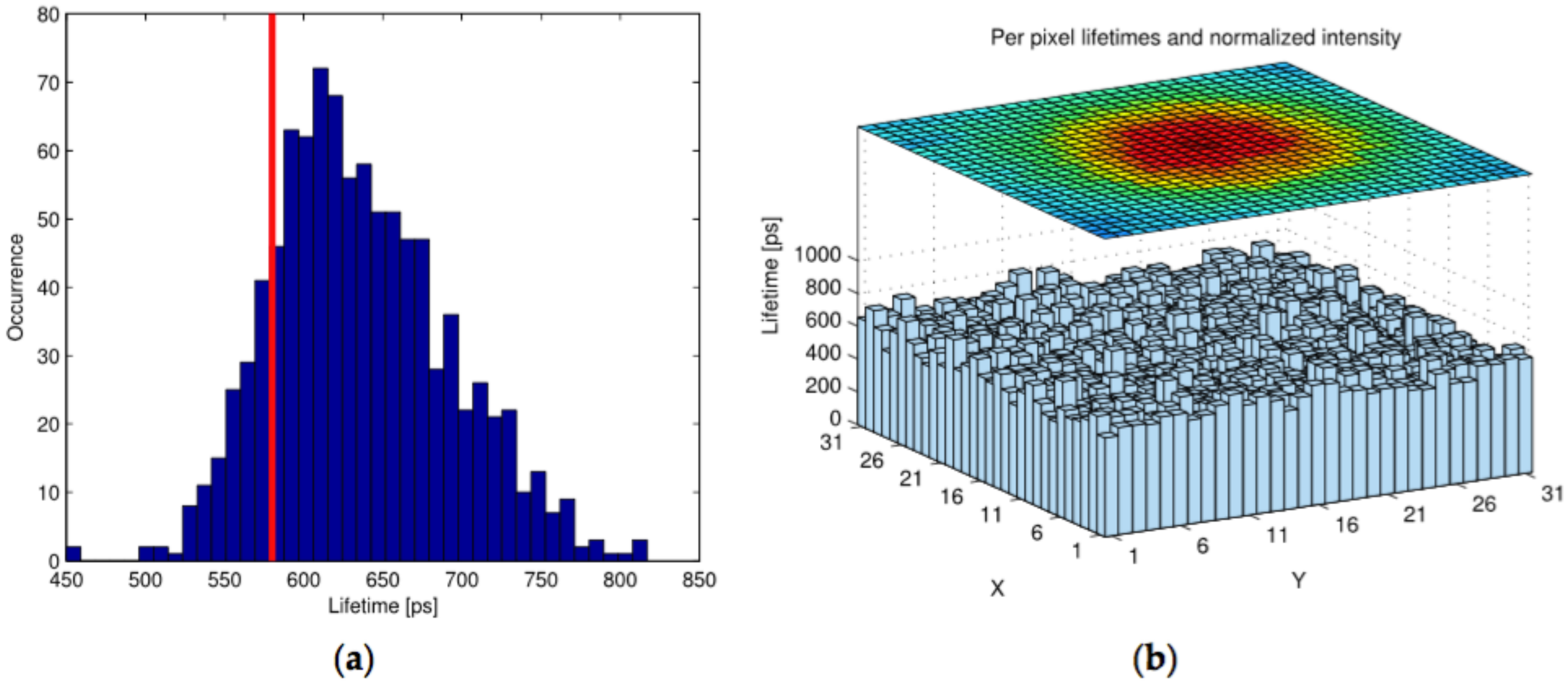
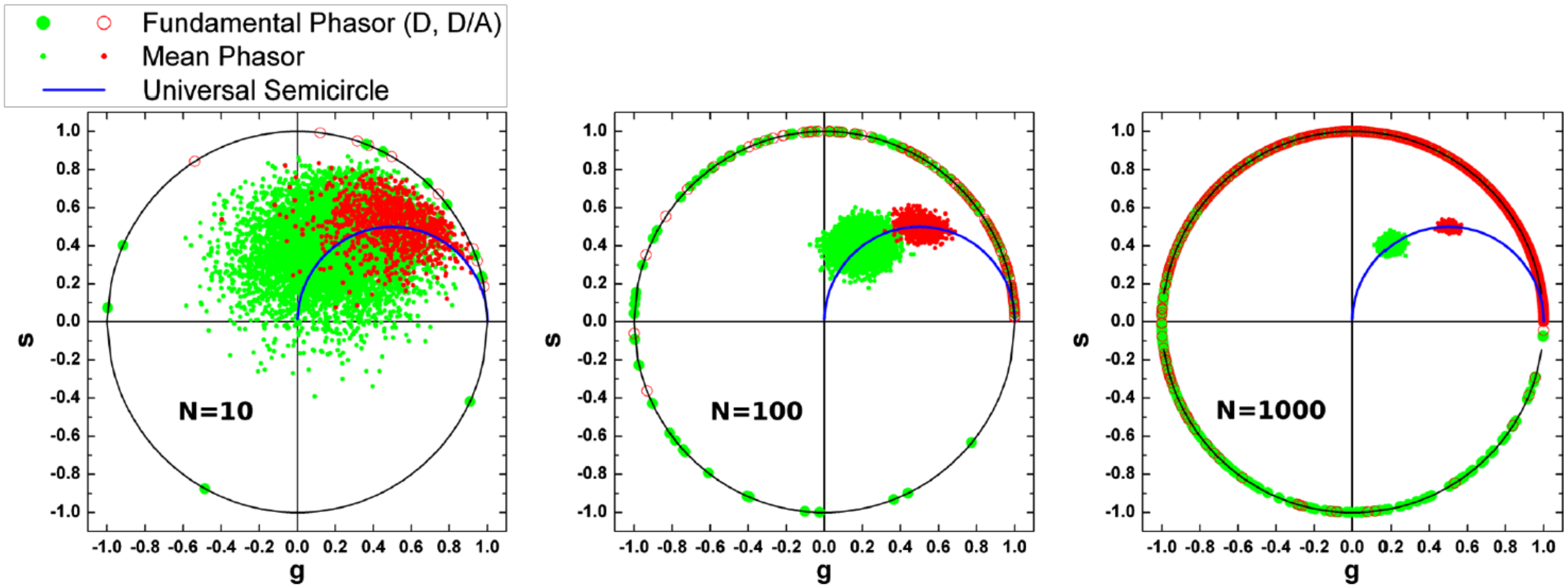


Figure 19. (**a**) FLIM results show extracted lifetimes distribution of 31 × 31 pixels compared to reference lifetime of 40 μM ICG in milk (red). (**b**) shows the comparison of intensity and lifetime per pixel.

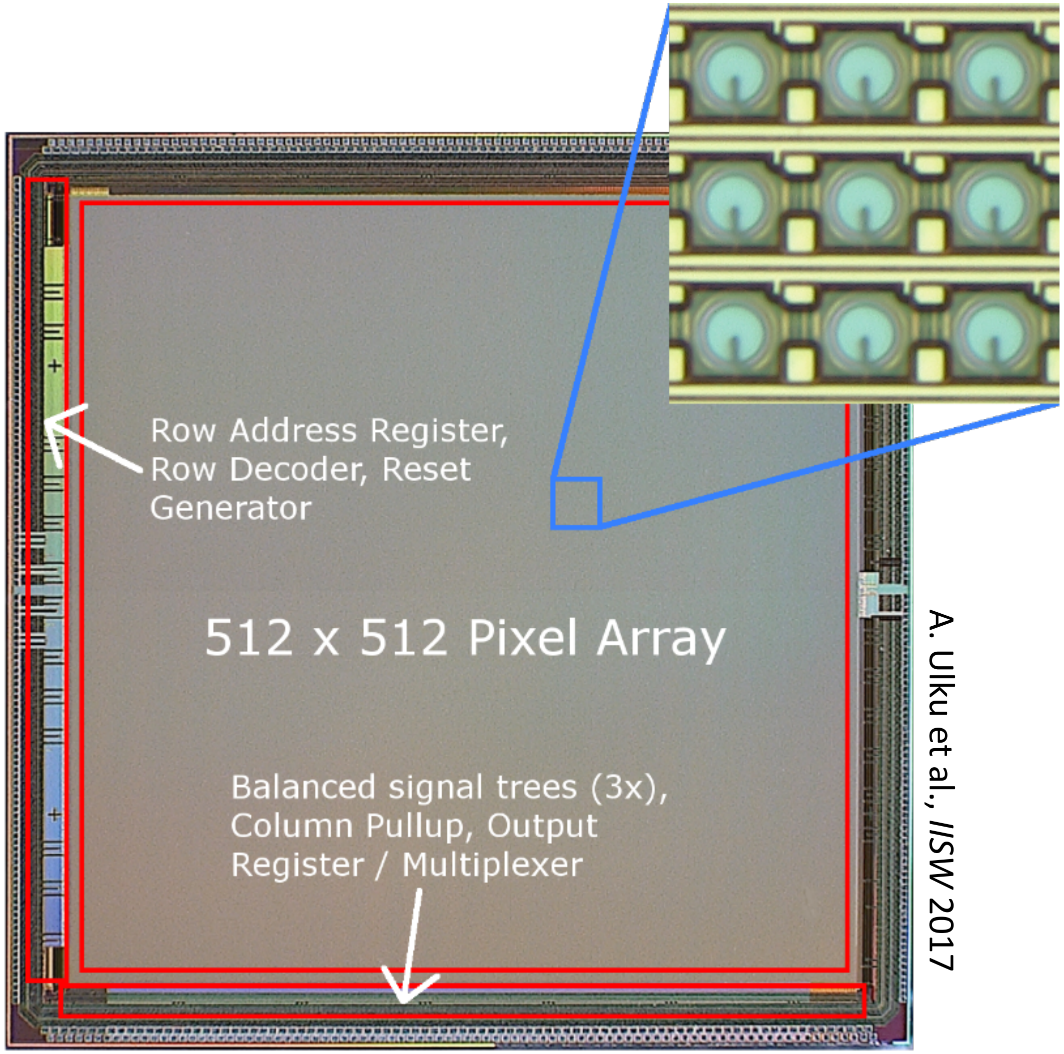
I.M. Antolovic, S. Burri, R. Hoebe, Y. Maruyama, C. Bruschini, E. Charbon, MDPI Sensors, **16**, 1005, 2016

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.

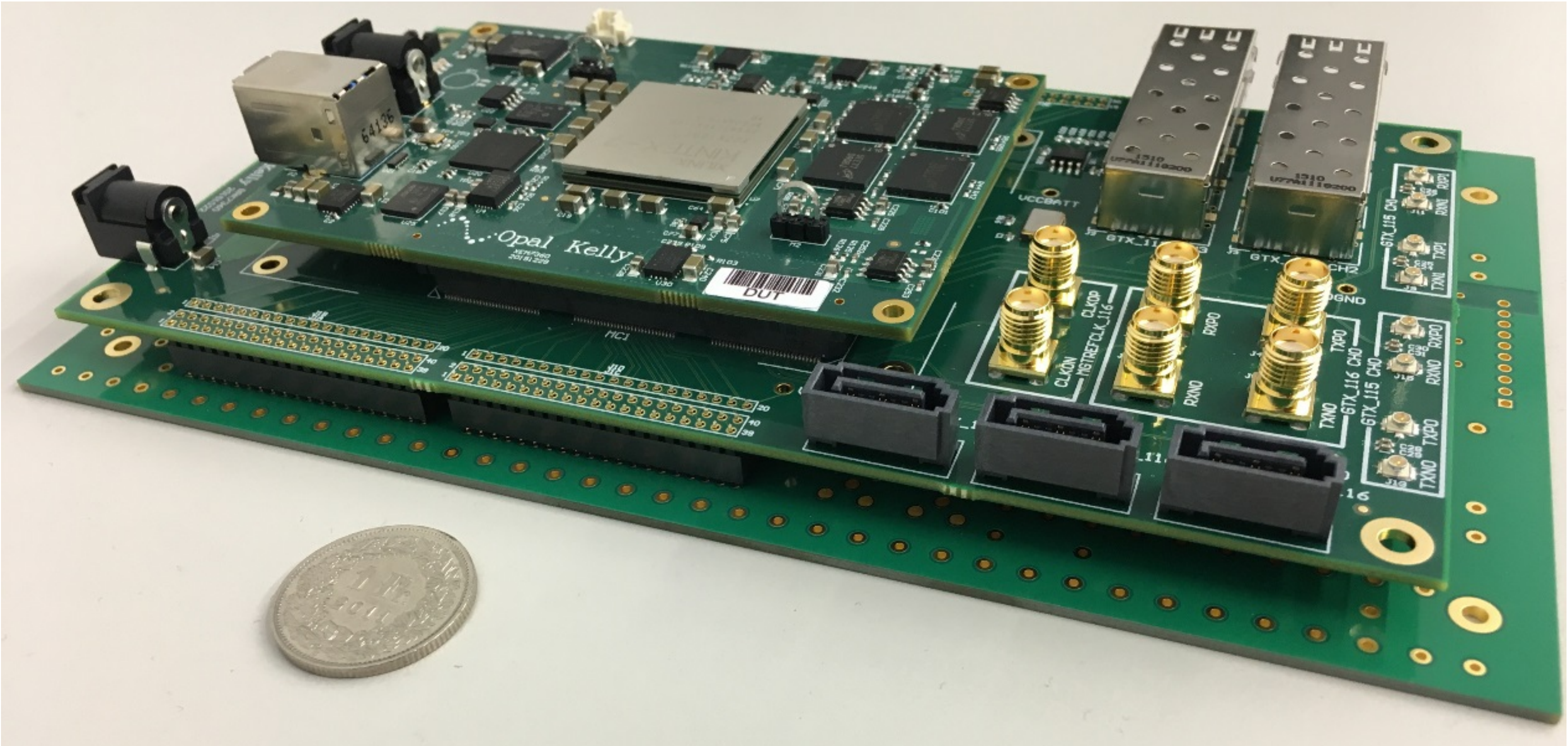


SwissSPAD2



A. Ulku et al., *IISW* 2017

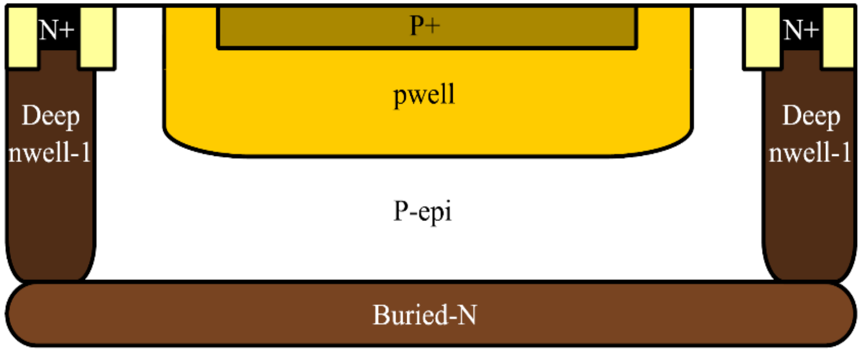
SwissSPAD2 System

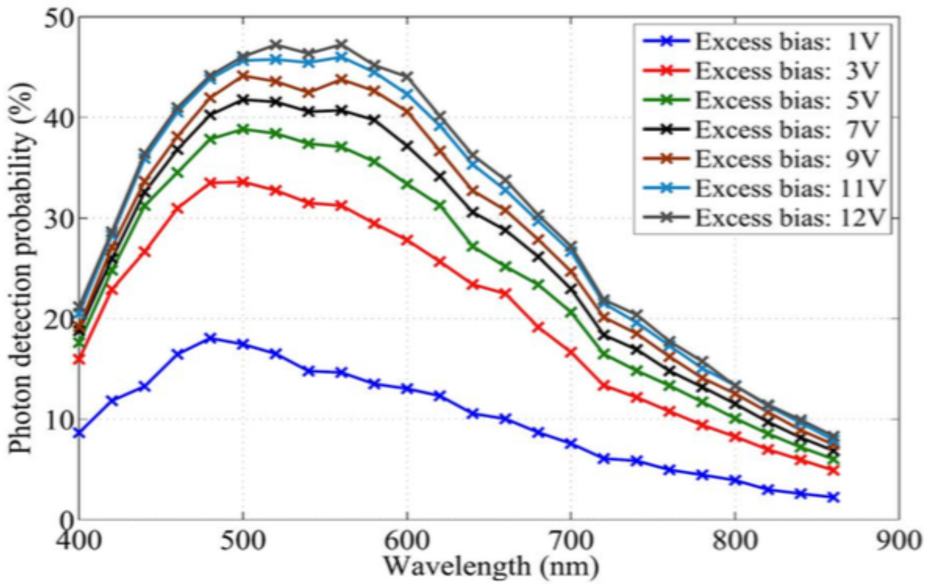


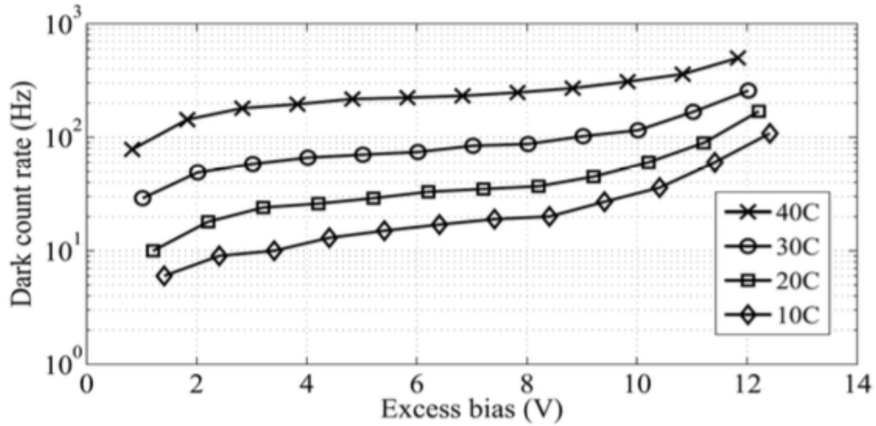
A. Ulku et al., IISW 2017

SwissSPAD2

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



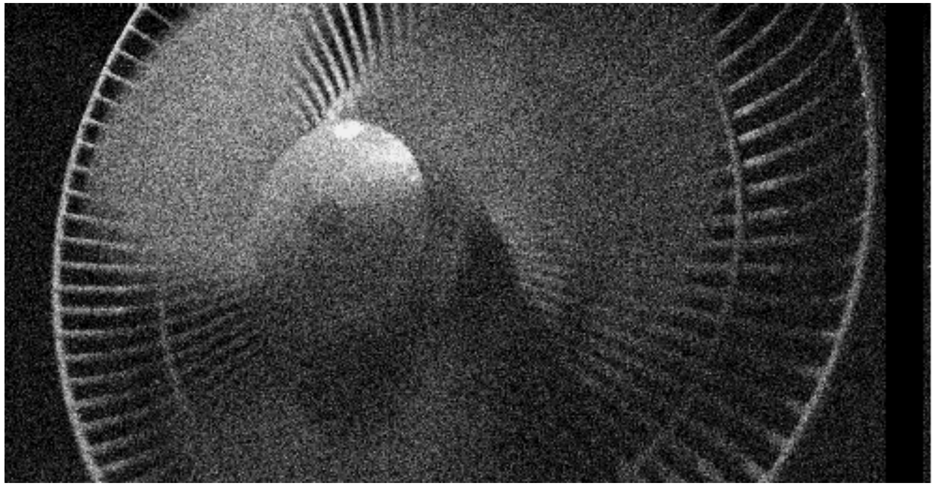




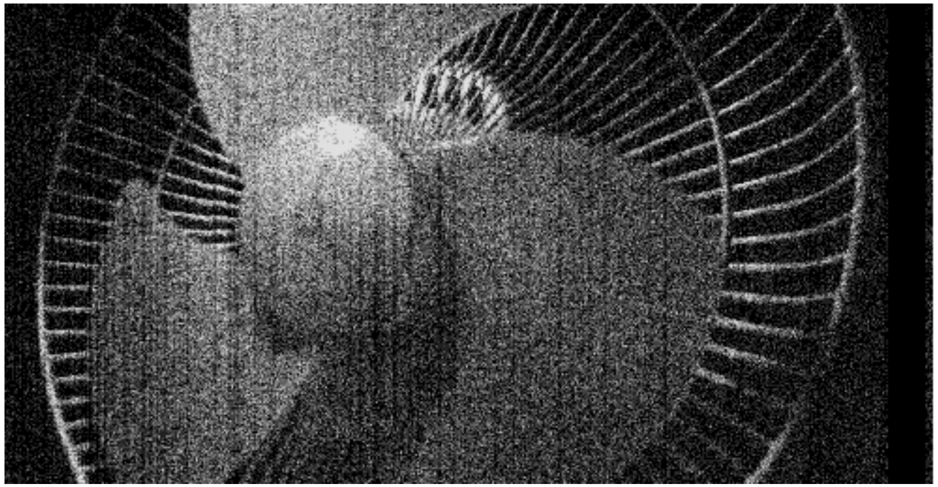
A. Ulku et al., *IISW* 2017

SwissSPAD-2 Speed Trials

10kfps, 3 bits



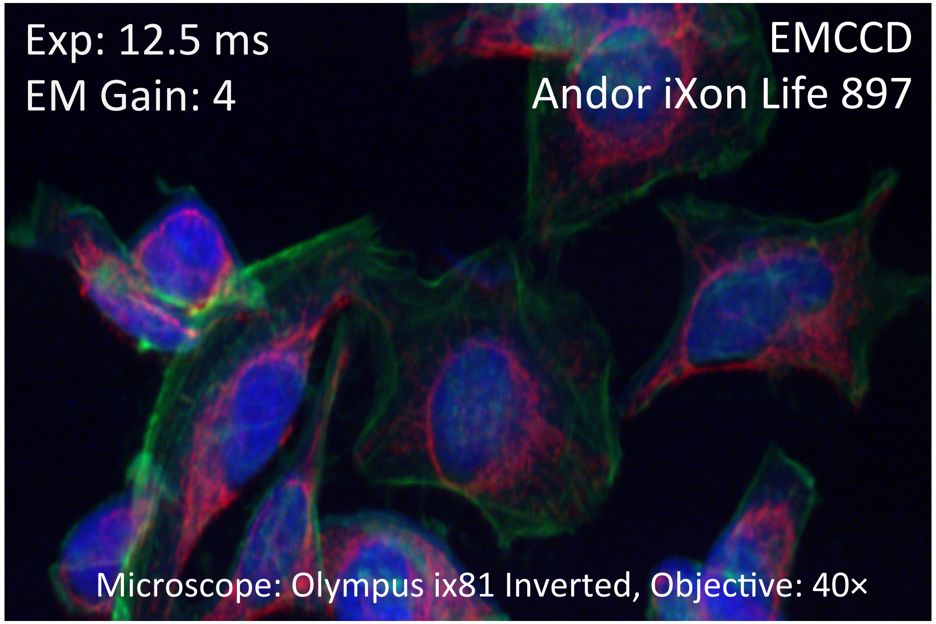
100kfps, 1 bit



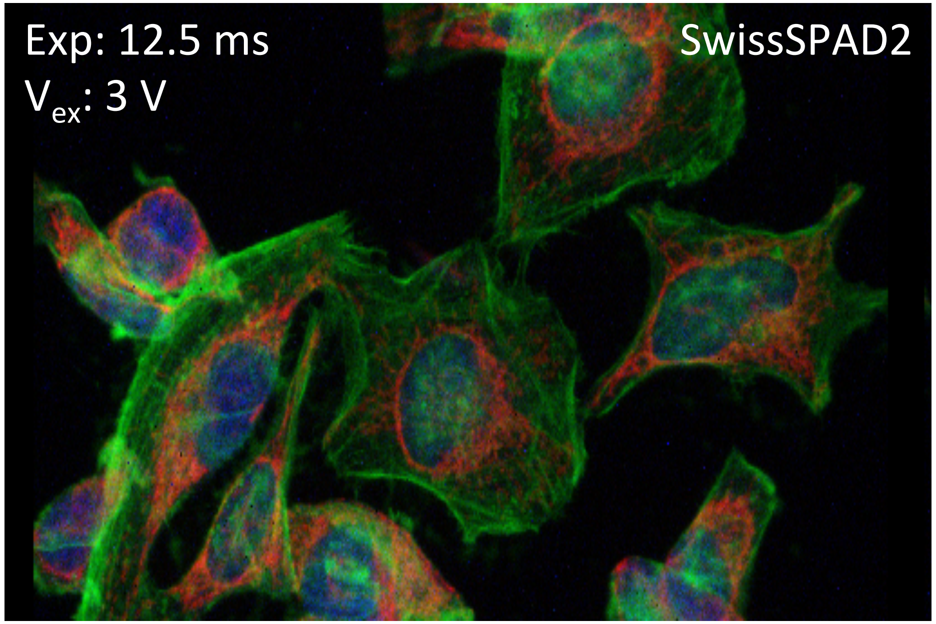
A. Ulku et al., talk at *IISW 2017*

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)



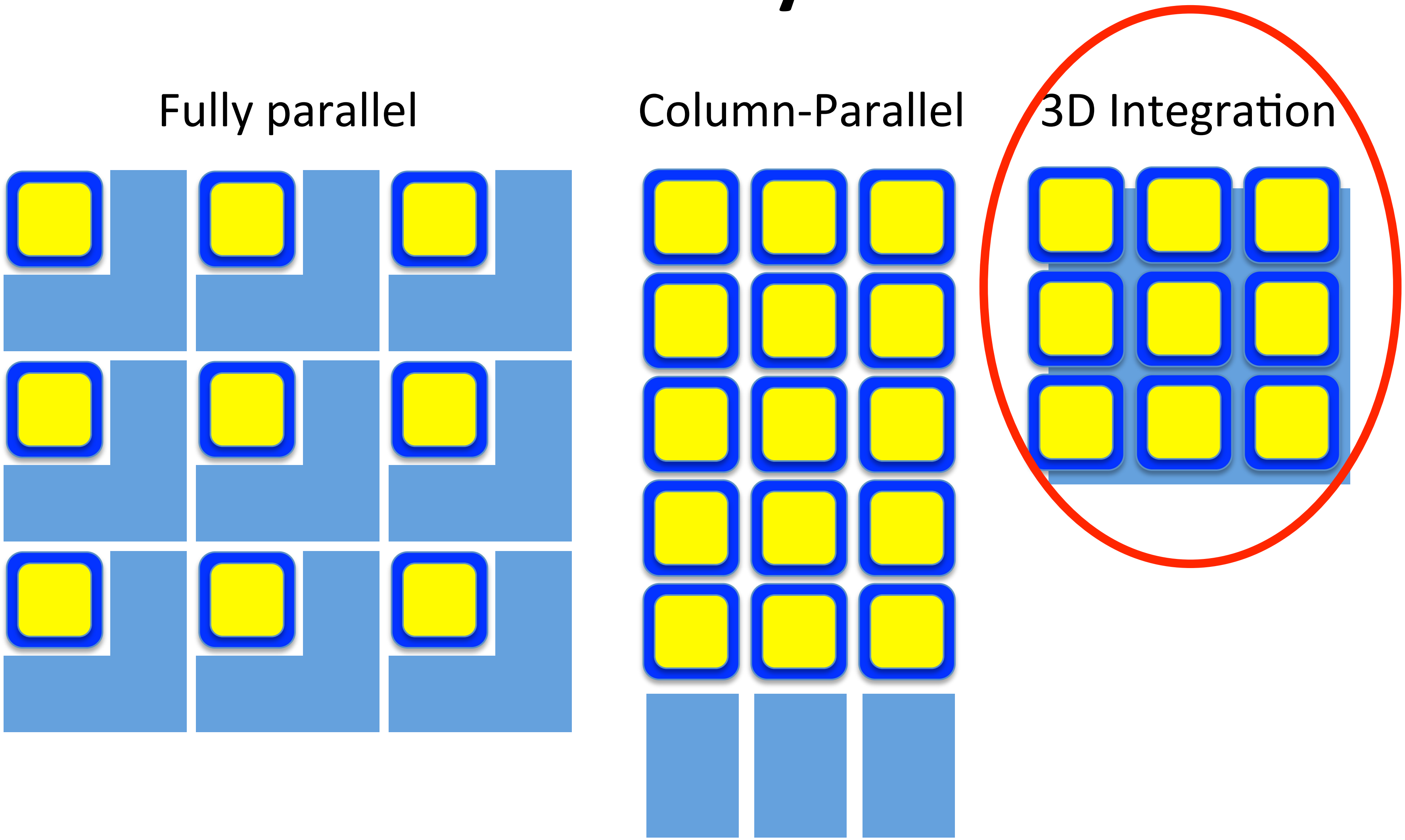
Nucleus:
DAPI (358/461 nm)

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

2D Arrays



3D (IC) for 3D (Imaging)

3D Imaging Techniques

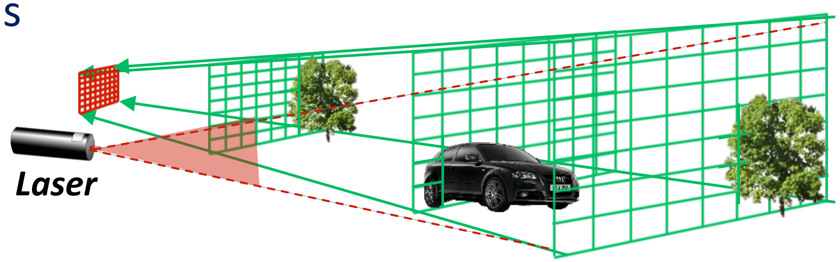
- Direct time-of-flight
  - Explicit measurement of the time
  - No ambiguity but precise chronometer per pixel
- Indirect time-of-flight
  - Implicit measurement through phase
  - Ambiguity but simple to implement

Flash vs. Scanning for Auto LiDAR

"Flash" illumination: elegant but impractical for Auto

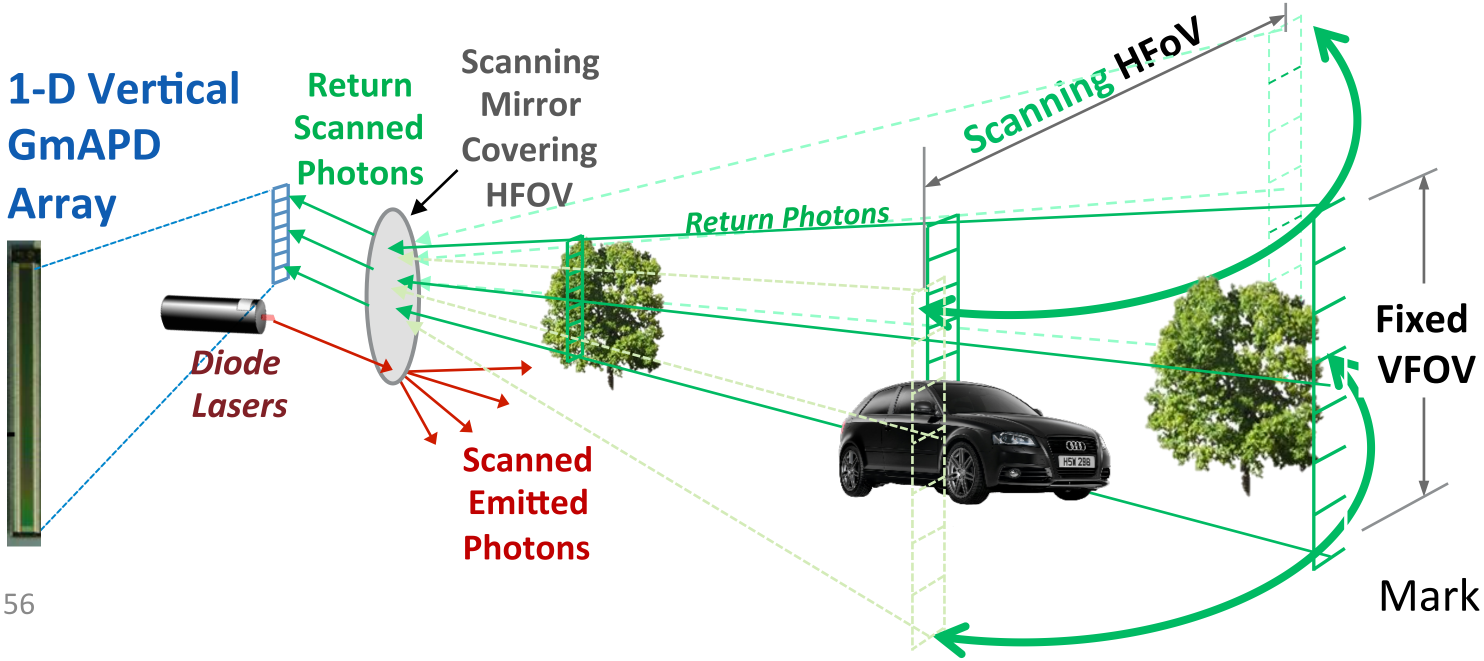
~100° FOV with 0.1° resolution needs 1000 pixels in one direction → ~Mpixel 2D array

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

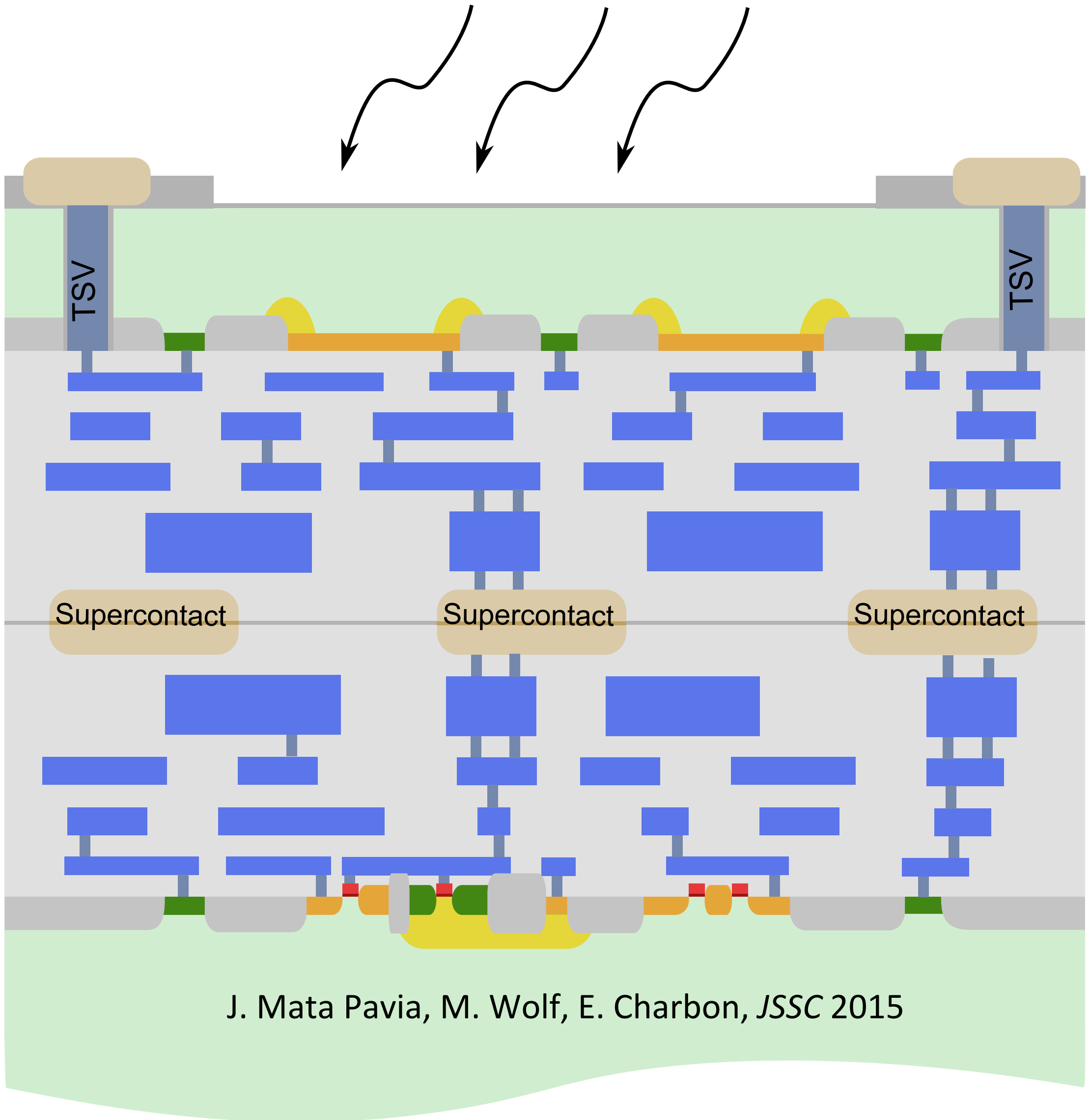
Our Strategy (ISSCC 2018)

- 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>

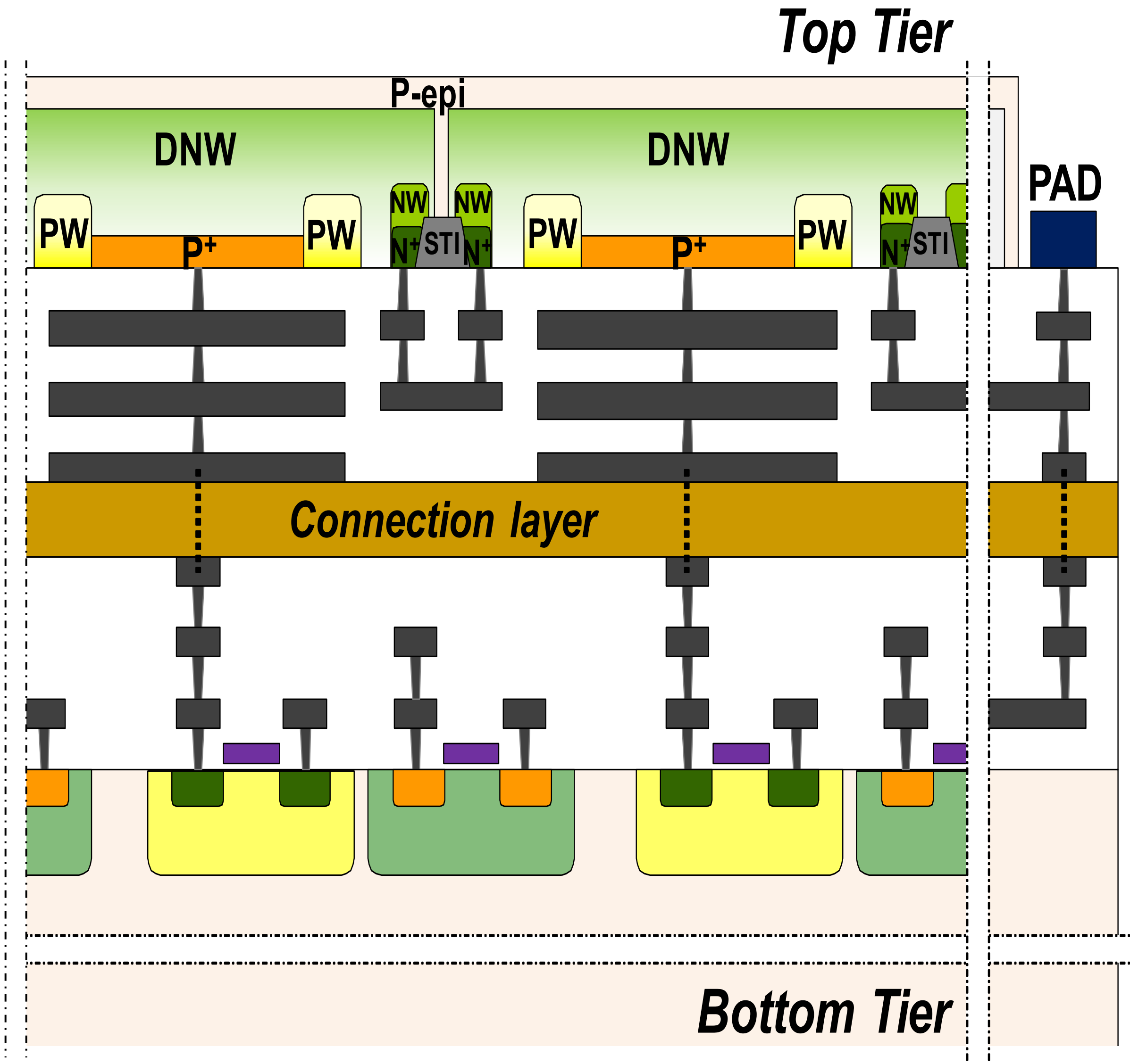
- Closest objects have priority
- Always eye safe, always adequate x-y resolution

Imager Technology: 3D-stacked BSI



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

TSMC's 3D-stacked BSI

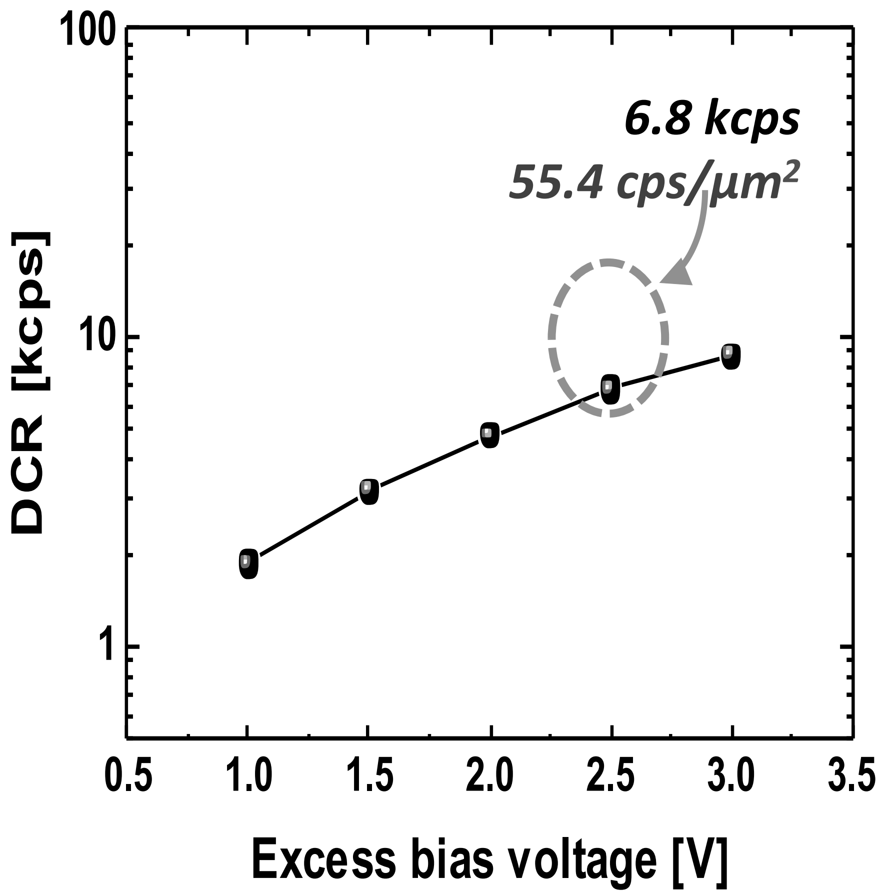


- **Top tier: 45nm CIS**
  (Bottom tier: 65nm CMOS)
  – Pixel pitch: 19.8 µm
  – Active: 12.5 µm diameter
  – Guard ring(GR): 2 µm

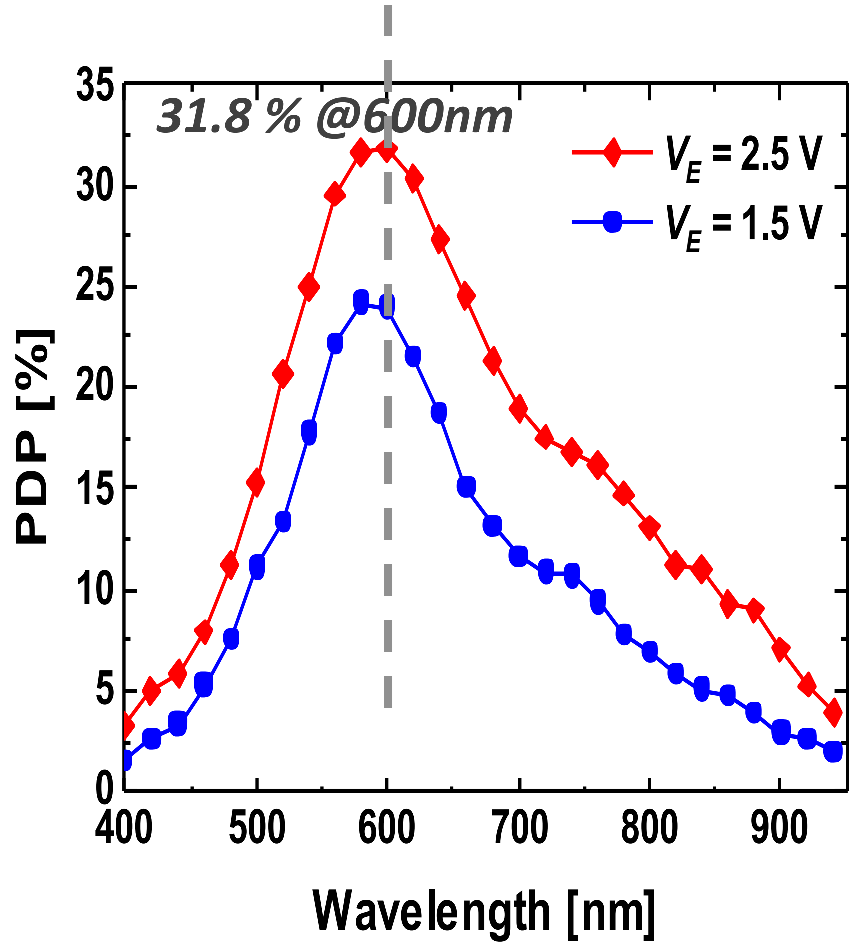
- **High quality backside thinning & 3D stacking technology**
  (w/ BSI process optimization)

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
VE = 2.5 V
VE = 1.5 V

Timing Jitter