Overview of SPAD image sensors and their scientific potential

from single-pixel configuration to mega-pixels arrays

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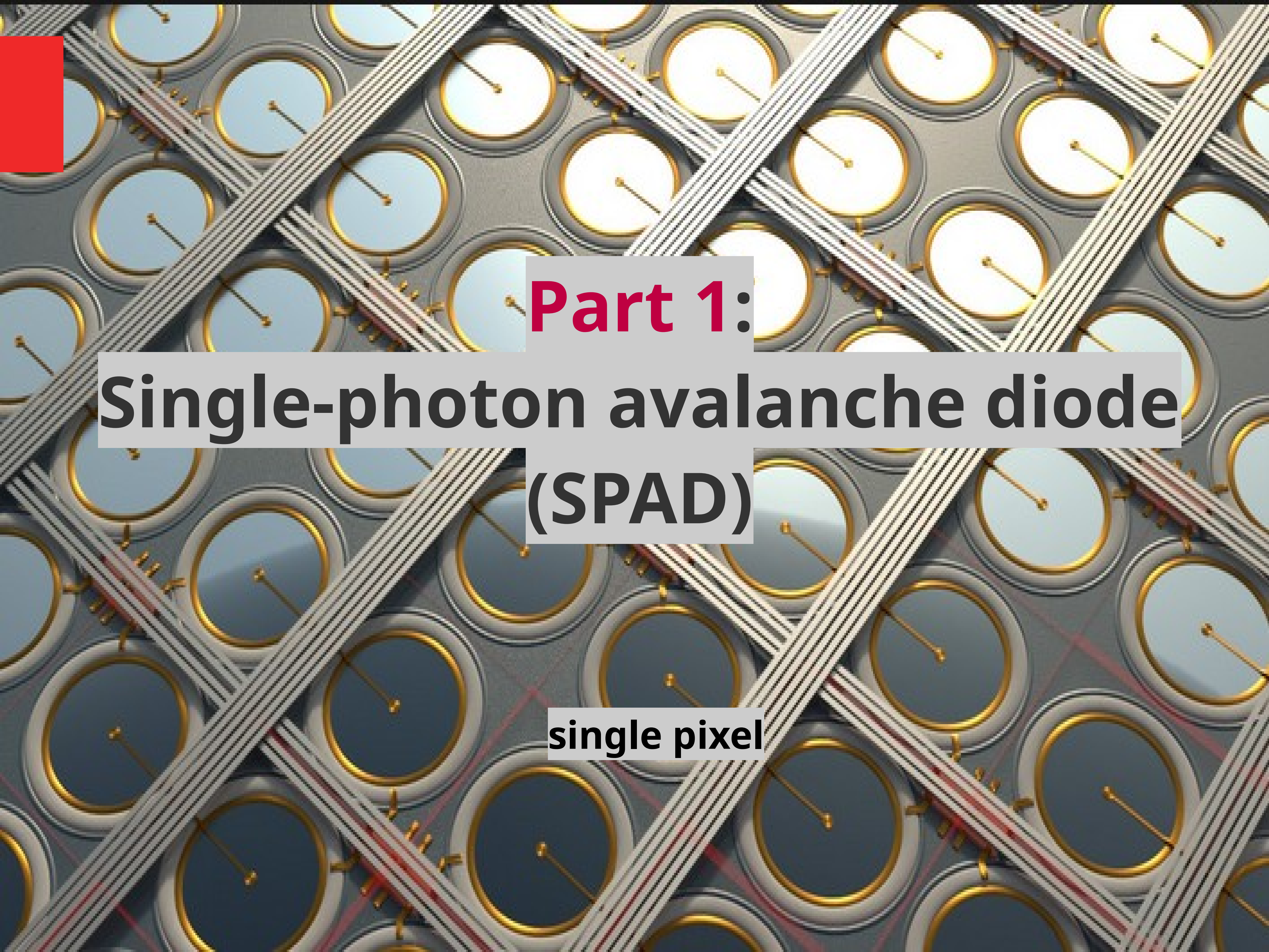
Seminar on photo-detectors for the course
Experimental Techniques in High Energy Physics

Outline

- **Single-photon avalanche diode (SPAD)**
  I. Working principle
  II. Performance parameters
  III. Noise sources
- **SPAD arrays (up to Mpixel size)**
  I. Main architectures
  II. Scaling issue
  III. Recent developments
- **Scientific applications**
  I. Fluorescence Lifetime Imaging (FLIM)
- **Summary**
- **References**



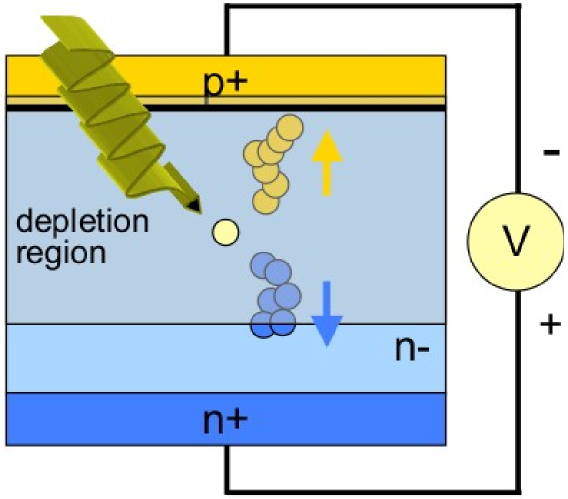
Part 1:
Single-photon avalanche diode (SPAD)

single pixel

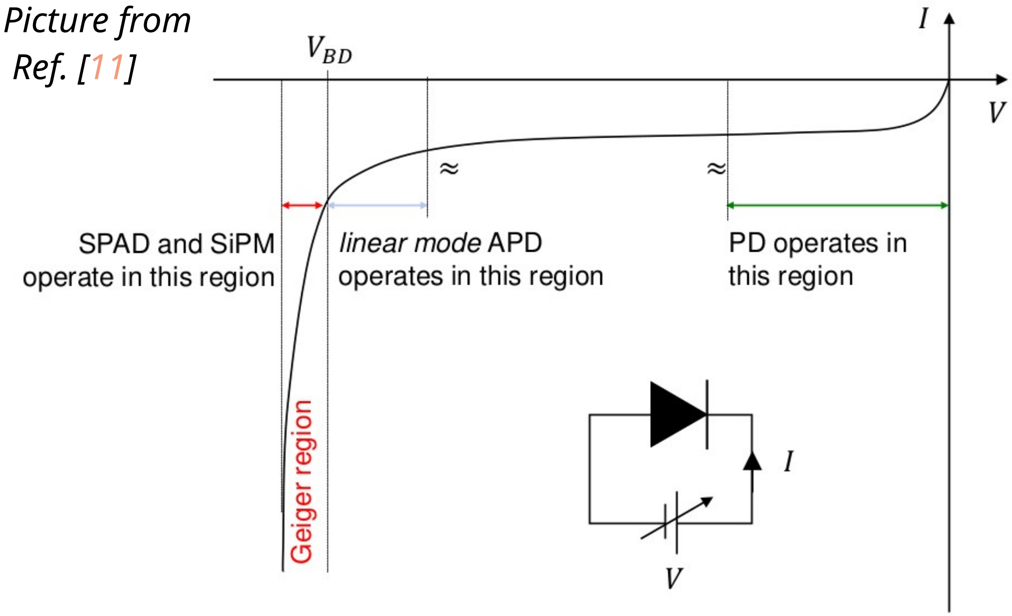
What is a SPAD?

SPAD is basically a **pn junction**, **reverse biased** above **breakdown voltage**, operating in **Geiger regime**

Picture from Ref. [7]



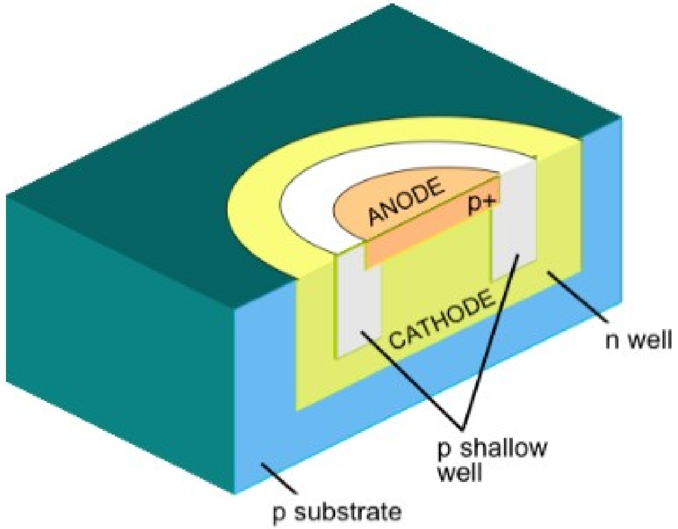
Picture from Ref. [11]



Operation regimes of APD in reverse bias:

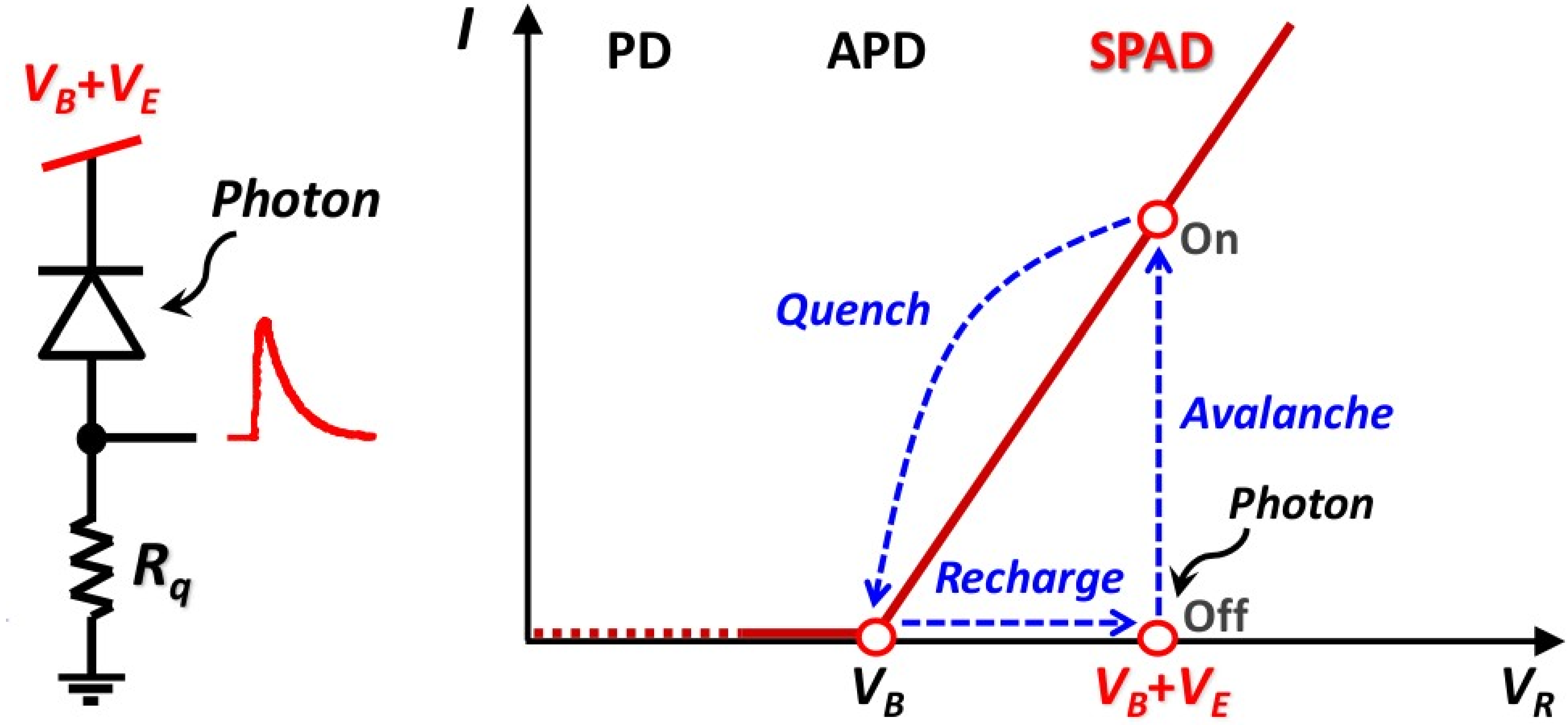
- **Linear** mode $|V_{\text{bias}}| < |V_{\text{breakdown}}|$
  the number of electron-hole pairs (EHP) generated by impact ionization are ≲ 1000. The gain is strongly dependent on V_{bias} and temperature. Thus, it is not suitable for single photon detection

- **Geiger** mode $|V_{\text{bias}}| > |V_{\text{breakdown}}|$
  the electric field is > 10^5 V/cm, such that a single photon impinging on depletion region and producing an EHP can trigger an avalanche generating a macroscopic self-sustaining current



Picture from Ref. [7]

Detection cycle (Passive Quenching)

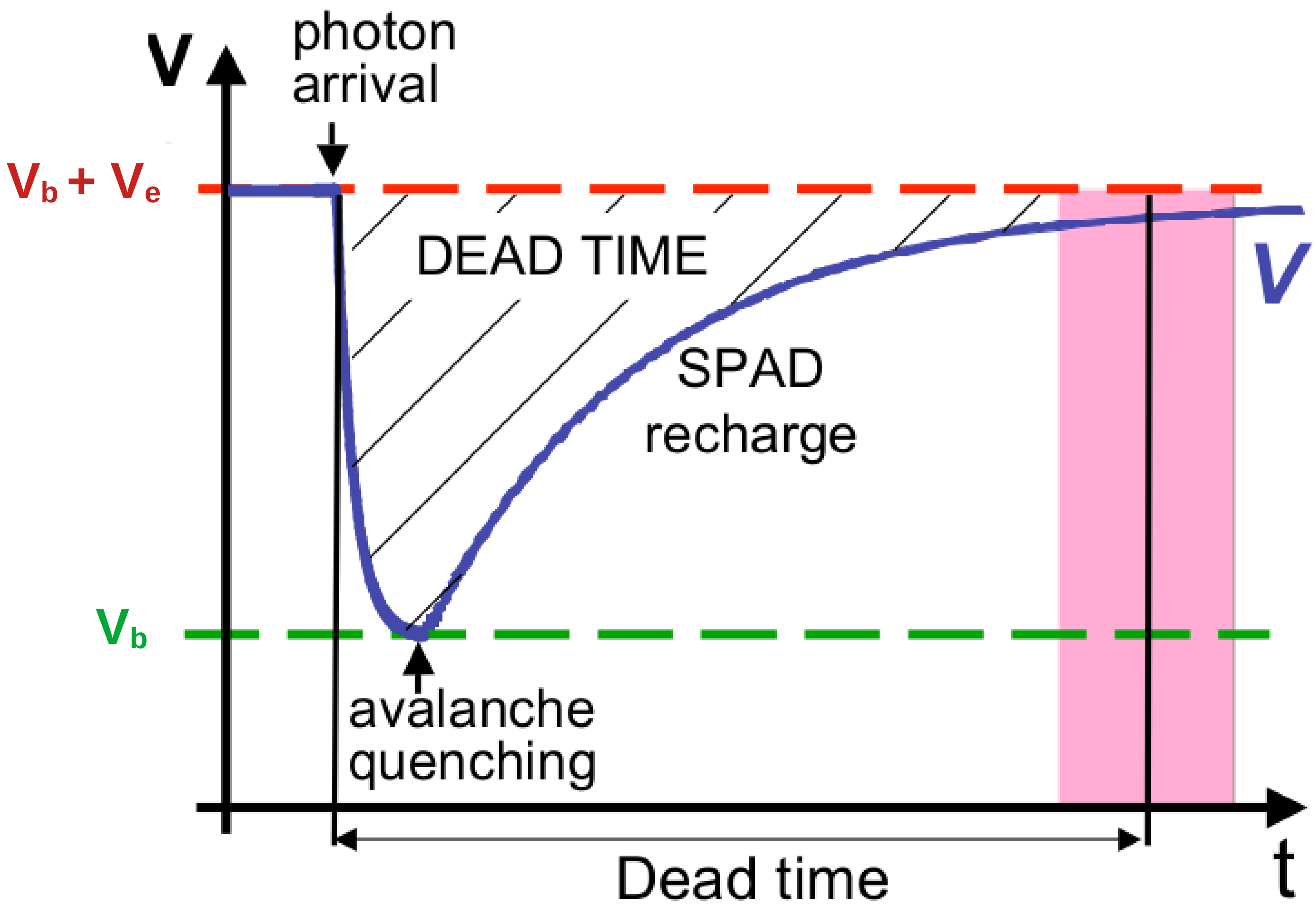


Picture from Ref. [3]

V_B : breakdown voltage

V_E : excess bias voltage
(overvoltage)

Pulse shape



Picture from Ref. [7]

V_B : **breakdown voltage**

V_E : **excess bias voltage**
(overvoltage)

Main SPAD figures of merit

- **Fill Factor (FF)** is the ratio between the active and the pixel areas
- **PDP** (Photon detection probability) is the single-photon sensitivity per unit of active area

$$PDP(V_{bias}, \lambda) = QE(\lambda) \times P_{avalanche}(\lambda)$$

where:

  - QE (λ) is the EHP generation probability for incoming photon
  - $P_{avalanche}(\lambda)$ is the avalanche triggering probability

- **PDE** (Photon detection efficiency)

$$\mathbf{PDE(V_{bias}, \lambda) = PDP \times FF}$$

- **Timing resolution** (or *jitter*) is the distribution width (e.g. FWHM) of the difference between the photon arrival time and the pulse leading-edge

Noise sources for single-pixel SPAD

- **Dark count rate (DCR)** is the main noise source and it consists mainly in EHP that are generated by thermal motion
  - ↑ w.r.t V_{bias}, T
  - ↓ lowering the pixel size
- **Afterpulsing** is due to trapped charged carriers that are later released triggering a spurious avalanche signal
  - ↑ w.r.t V_{bias}, dead time
  - ↓ lowering the pixel size

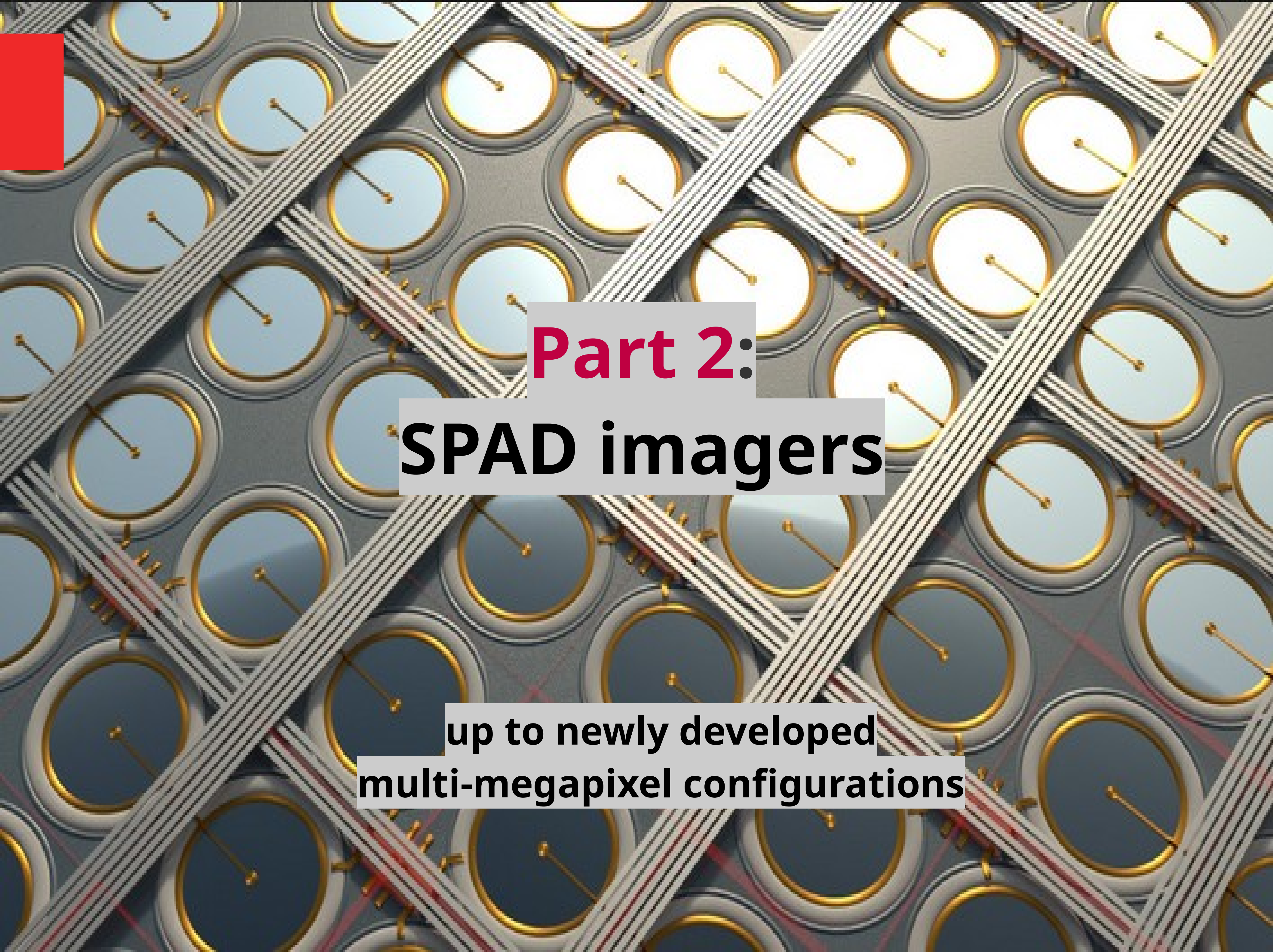
Typical SPAD-pixel specifications

	Value range
SPAD pixel	
Dead time [ns]	10–100
DCR [cps/μm^2]	0.3–100
PDP (peak) [%]	10–50
Fill factor [%]	1–60
Timing resolution [ps]	30–100
Afterpulsing probability [%]	0.1–10

Table from Ref. [6]

Advantages of SPAD sensors

- up to tens of **picosecond timing resolution**
- single photon sensitivity
- manufacturing process scalability for SPAD realized in CMOS-based technologies
- fast gating capabilities
- room temperature operation
- insensitive to magnetic field



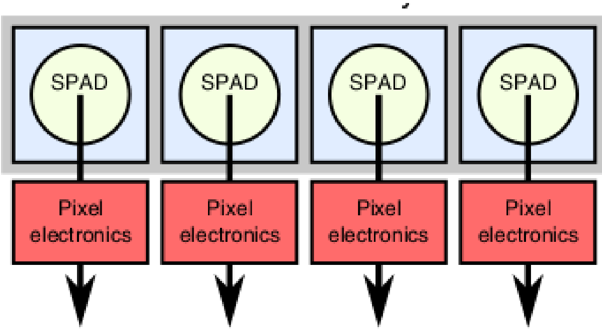
Part 2: SPAD imagers

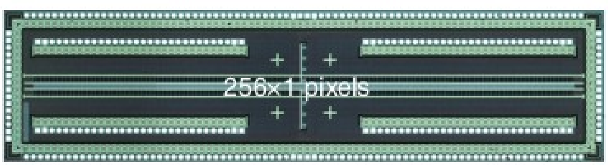
up to newly developed multi-megapixel configurations

SPAD imagers: main architectures

Linear (1D)

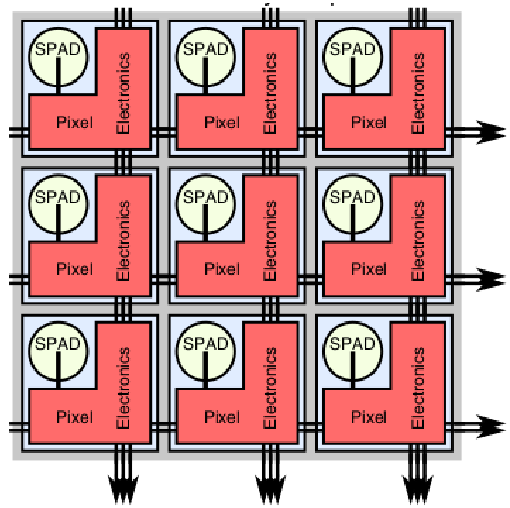
Pictures from Ref. [6]

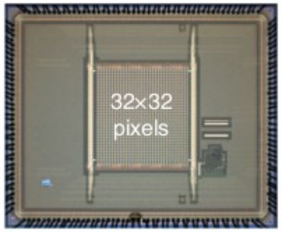




Pros: electronics can be located outside the sensor preserving the fill factor & in parallel operations can be performed
Con: scanning are needed to generate a 2D image

Planar (2D)

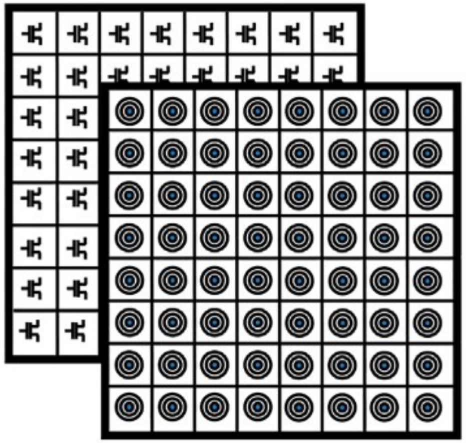


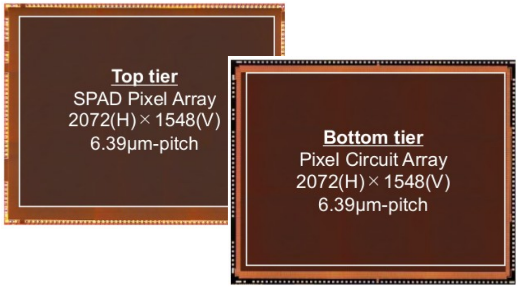


Advantage: bi-dimensional images can be acquired directly with in-pixel processing
Drawbacks : increasing complexity for the integration of in-pixel advance features + dropping of the fill factor

3D-stacked

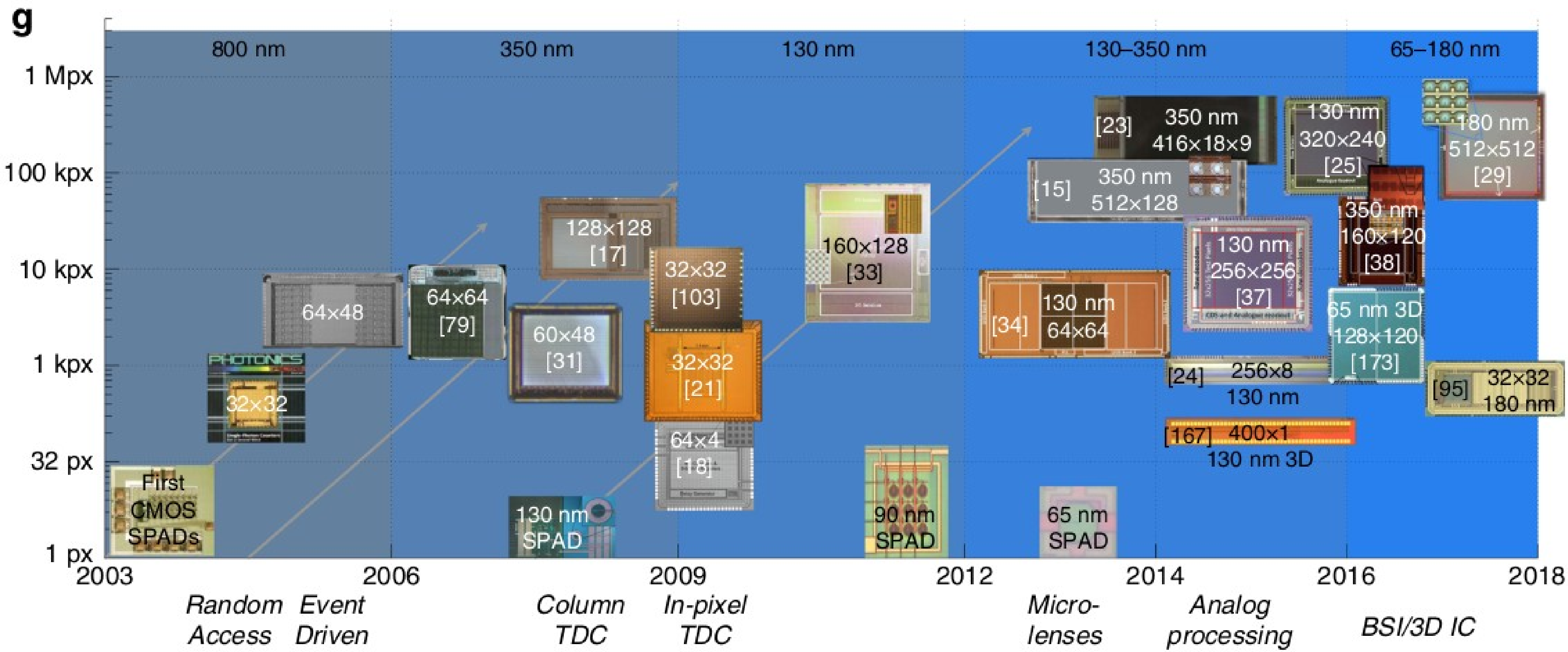
Pictures from Ref. [9]





top : *SPAD* image *sensor*
bottom : *control* and *processing*
layers can be independently optimized to enhance the sensor's performance metrics

Trends in the miniaturization of SPAD arrays



Picture from Ref. [6]

Effects of miniaturization on SPAD figures of merit:

better

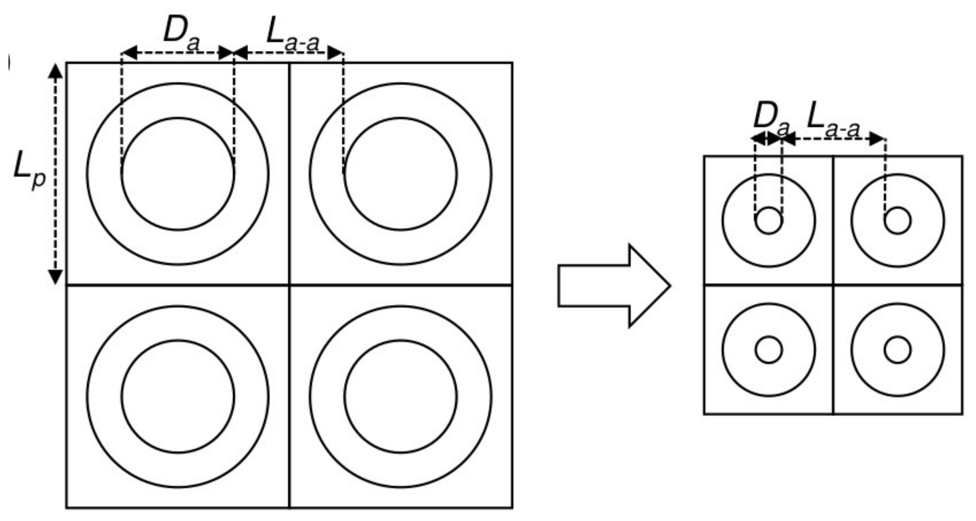
DCR, afterpulsing and timing jitter

worse

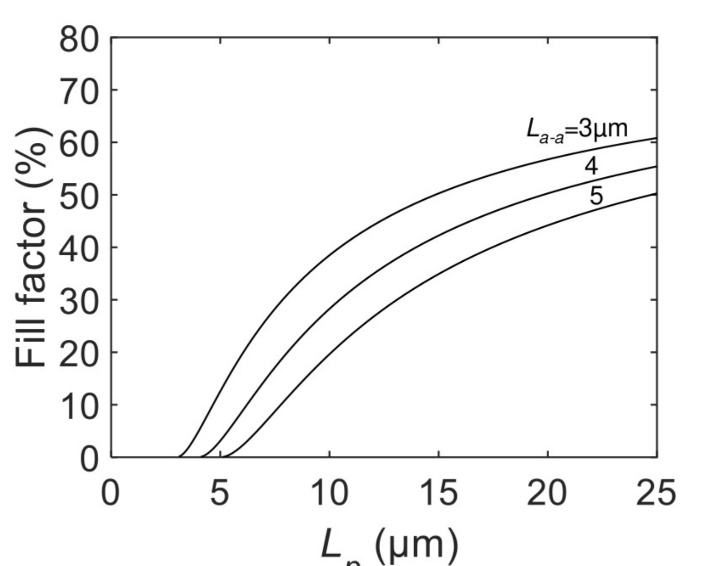
Fill Factor, PDP and, consequently PDE, crosstalk

Main issue in scaling down SPAD pixels

Key Idea: guard-ring width W_{gr} has to be sufficiently large to avoid the **premature edge breakdown**
but
the optimal W_{gr} is independent on the pixel scaling (**1** or **2** μm)



Pictures from Ref. [4]



Definitions:

- $\mathbf{L_p}$ pixel pitch
- $\mathbf{D_a}$ active diameter
- $\mathbf{L_{a-a}}$ active-to-active distance where
  $\mathbf{L_{a-a}}$ is the sum of guard-ring width W_{gr} & isolation width W_{iso}

Assumptions on SPAD pixels:

I. **circular-shaped** active area
II. positioned on **square matrix**
III. **3D-stacked** configuration in which pixel electronics are on separate layer
IV. **active-to-active** distance $\mathbf{L_{a\text{-}a}}$ **not scaled** with pixel size

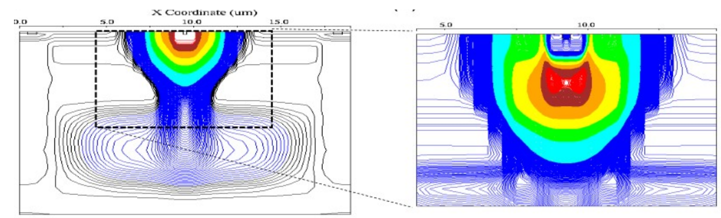
Recent developments: charge-focusing SPADs

Objective: pixel size **< 10 µm**, providing a **high fill factor** while limiting the **dark count rate**

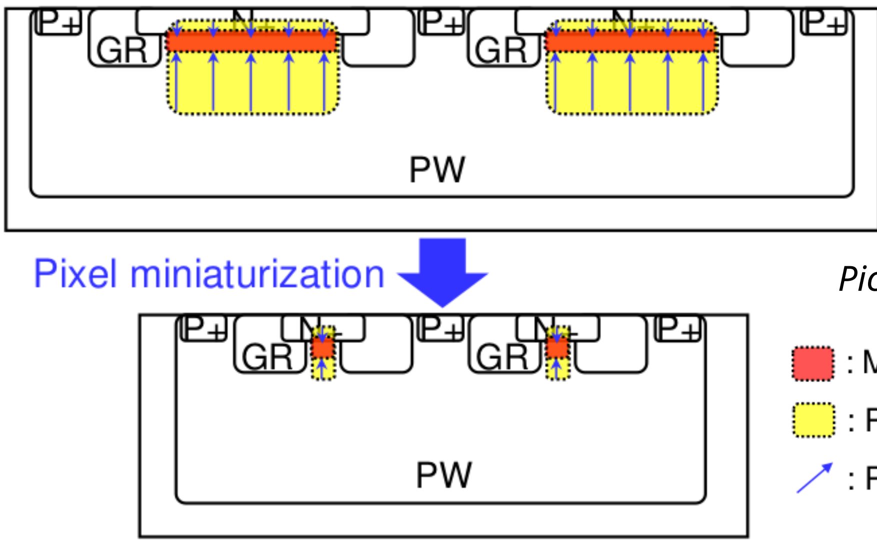
Major design **trade-offs** in conventional SPAD arrays

I. Pixel pitch *vs* **PDE** (~ FF)

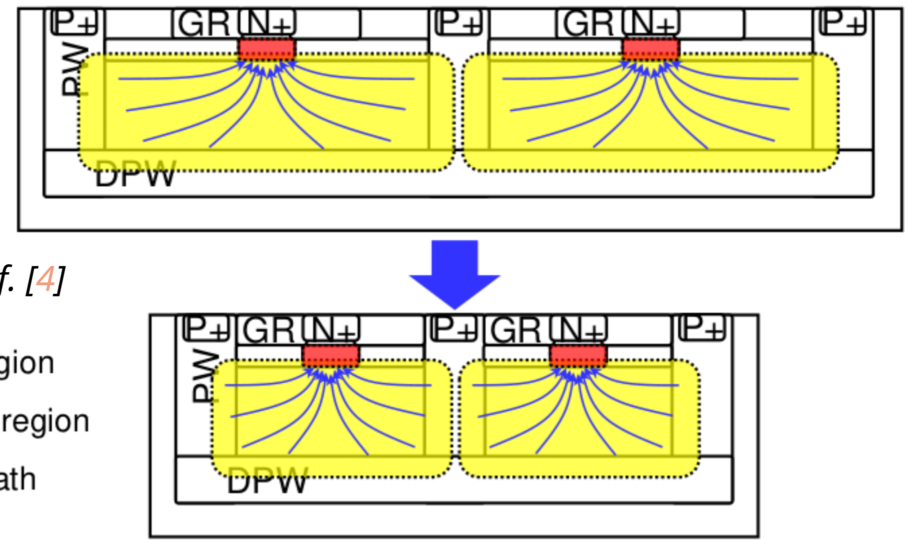
II. PDE *vs* **DCR**



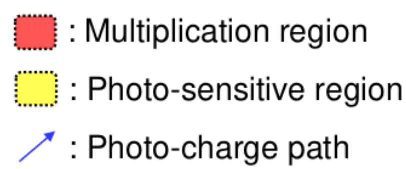
conventional SPAD



charge-focusing SPAD



Pictures from Ref. [4]



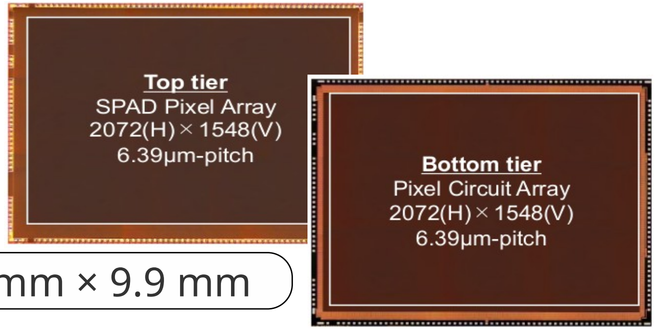
Key Idea of charge-focusing : the electrostatic potential is designed to minimize the multiplication region, while maximizing the photo-sensitive region

CANON© optimized layout and doping profile → **better PDE** + **lower DCR**

+

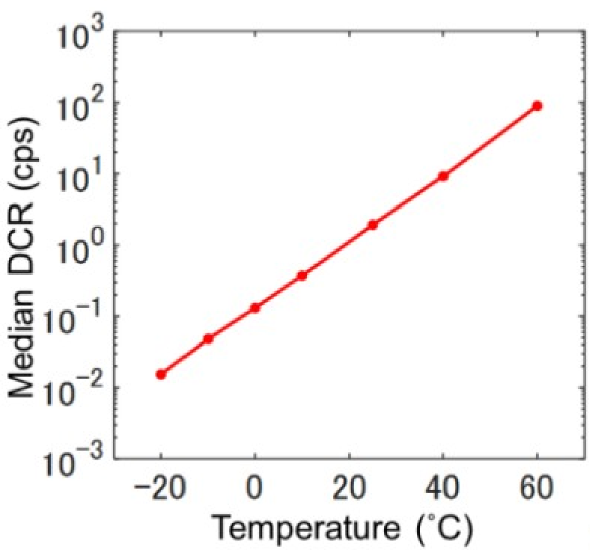
Lower p-n junction **parasitic capacitance** enables further **suppression** of **after-pulsing probability, crosstalk, power consumption & dead time**

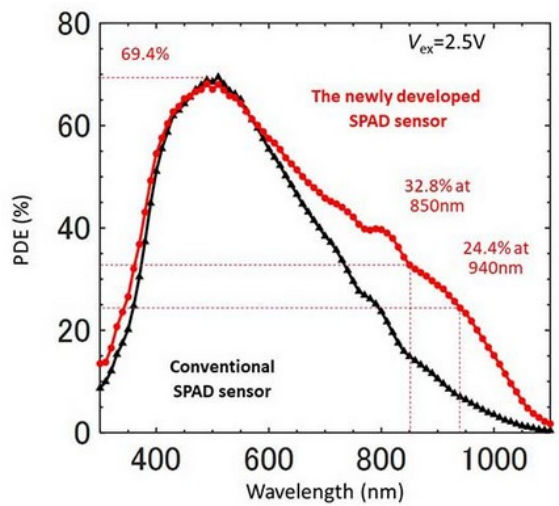
Newly developed 3.2 Mpixel charge-focusing SPAD sensor

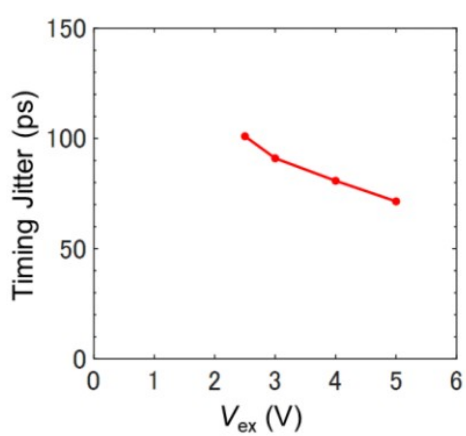


Size 13.2 mm × 9.9 mm

Performance parameters







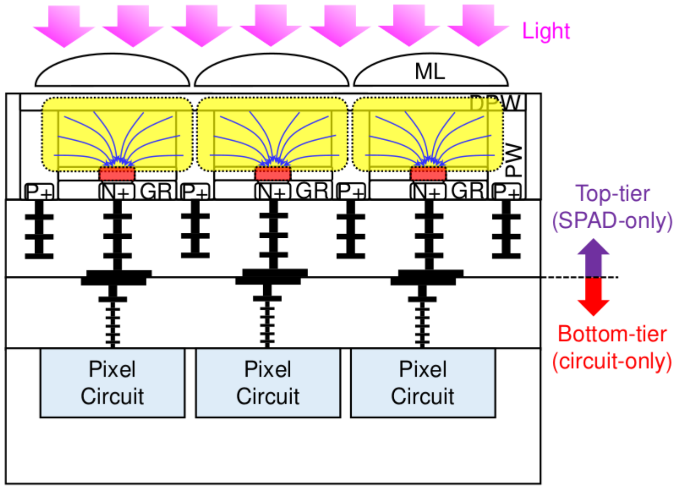
Process technology	**90nm/40nm 3D-BSI**
Pixel pitch (μm)	**6.39**
Pixel array size	**2,072 × 1,548**
Read noise (e^-_{rms})	**0**
Frame rate (fps)	**60**
VB (V)	**30**
Fill factor (%)	**~100**
Max PDE (%)	**69.4 (V_{ex}=2.5V)**
PDE at 940nm (%)	**24.4 (V_{ex}=2.5V)**
Median DCR*1 (cps)	**1.8 (V_{ex}=2.5V)**
DCR per area*2 (cps/μm²)	**0.044 (V_{ex}=2.5V)**
Timing jitter FWHM (ps)	**100 (V_{ex}=2.5V)**

*1At room temperature (25°C) *2No

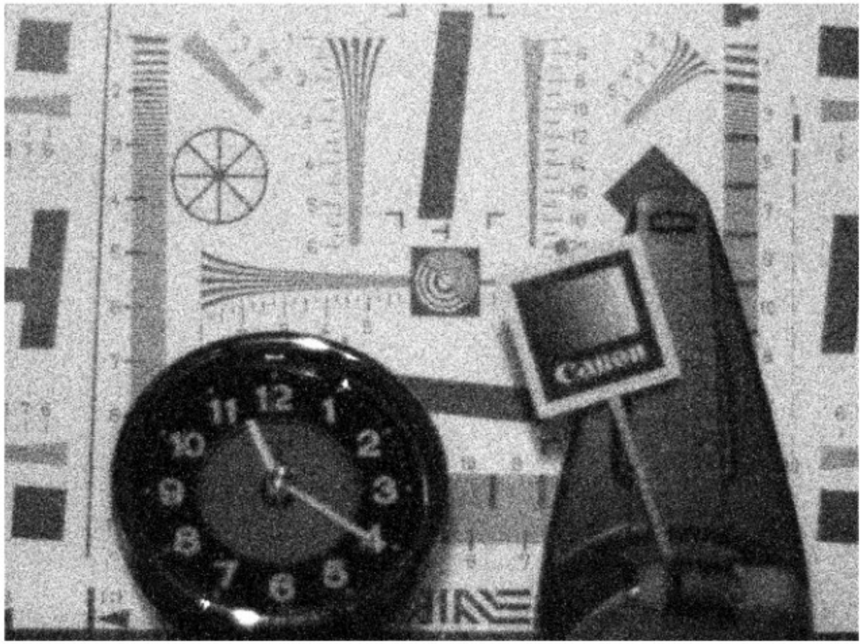
Pictures from Ref. [1]

Newly developed 3.2 Mpixel charge-focusing SPAD sensor

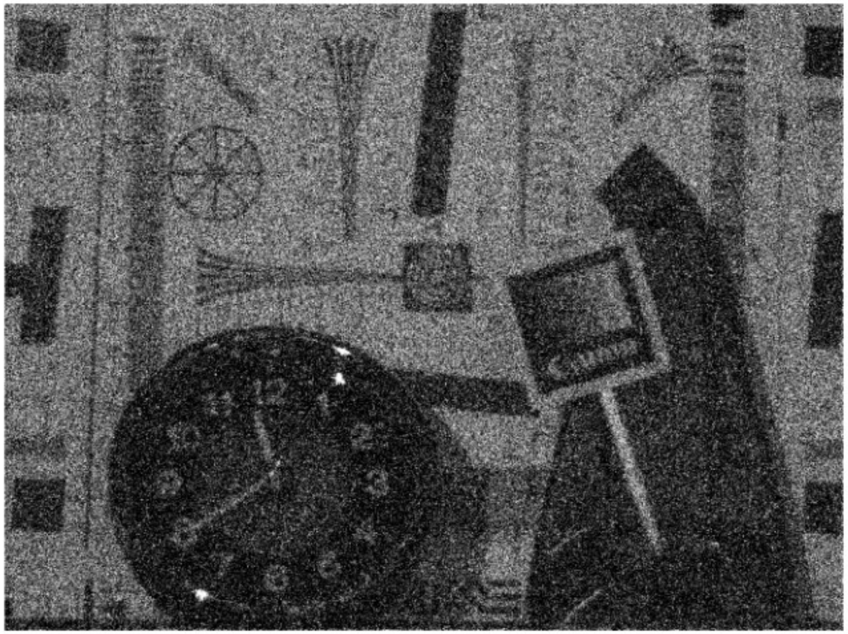
Full-resolution color intensity image captured under **high light** conditions



Pictures from Ref. [1][4]

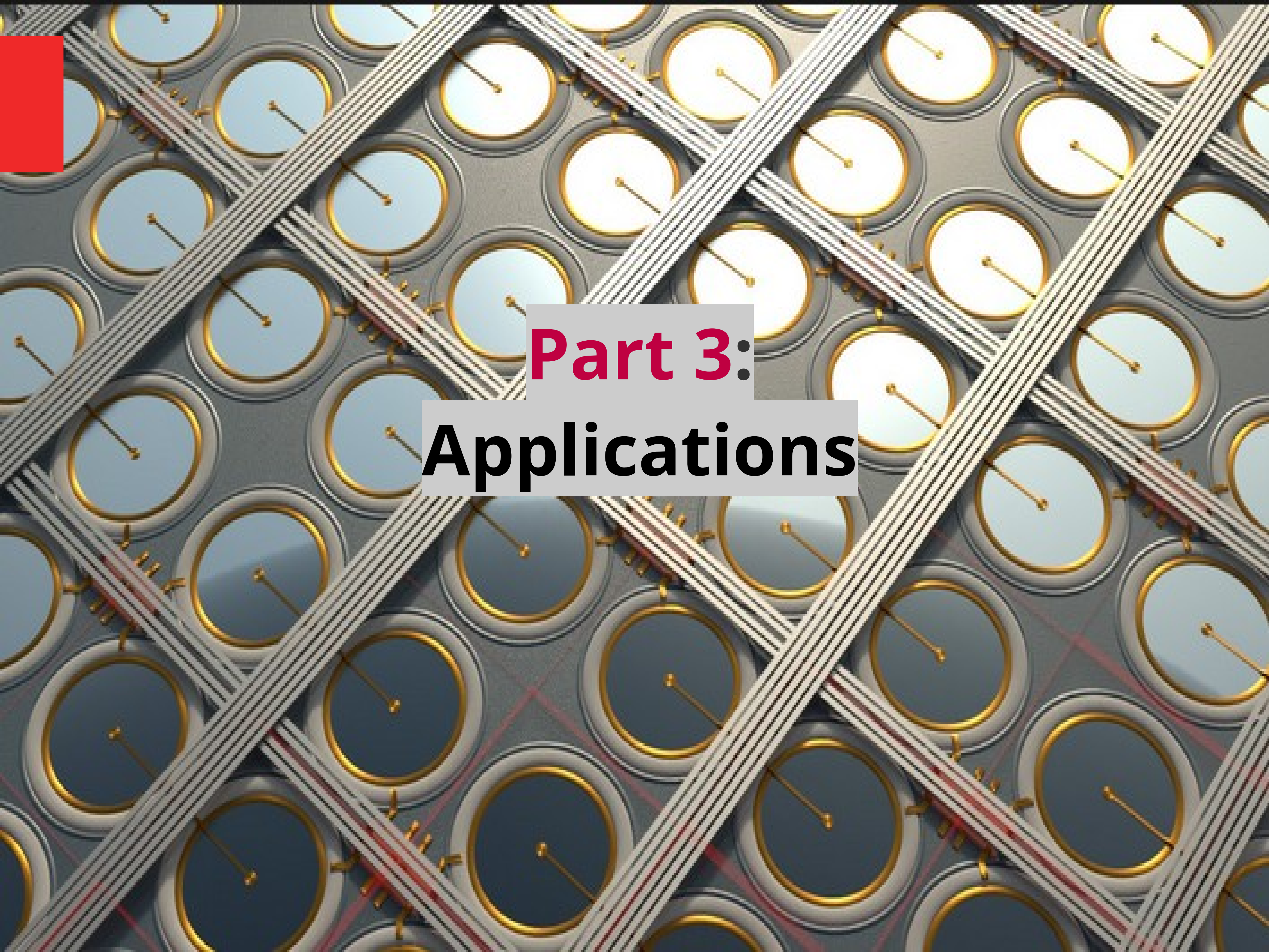


2 mlux w/o **post-processing**
Darker than starless night conditions



0.3 mlux w/o **post-processing**
as when naked eye cannot perceive objects

Part 3: Applications

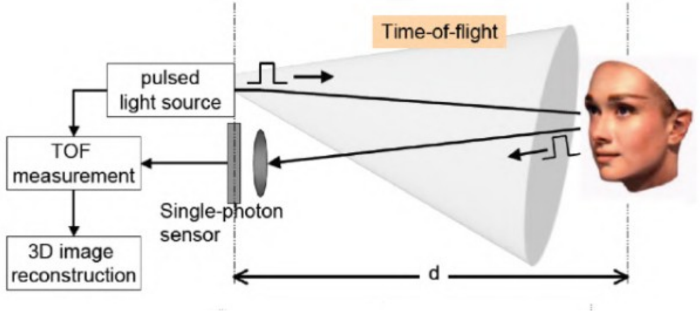


Scientific Applications of SPAD imagers

Large-format SPAD imagers

Time-Gated Raman spectroscopy

Time-of-flight (ToF) imaging

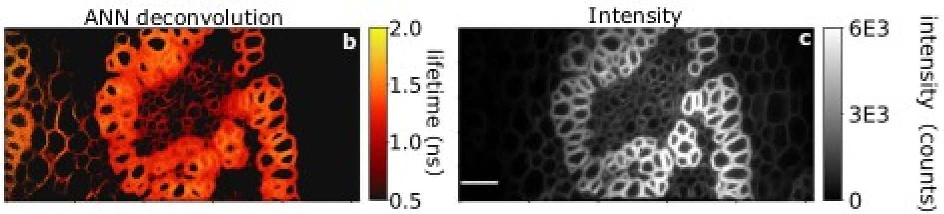


Picture from Ref. [4]

Bioimaging applications

Low-light imaging applications

Wide-field Fluorescence Lifetime Imaging

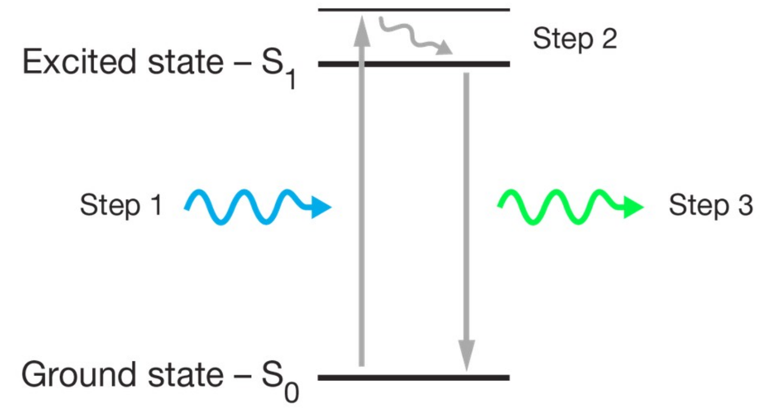


Picture from Ref. [5]

Basics of FLIM

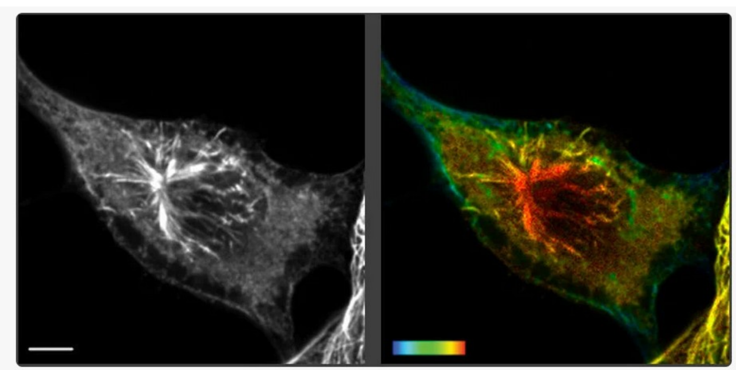
- **fluorescence as 3-stage process**
  - I. Excitation via absorption of light
  - II. Transient w/ loss of energy
  - III. Jump back to ground state w/ photon emission

Picture from https://www.scientifica.uk.com/learning-zone/widefield-fluorescence-microscopy



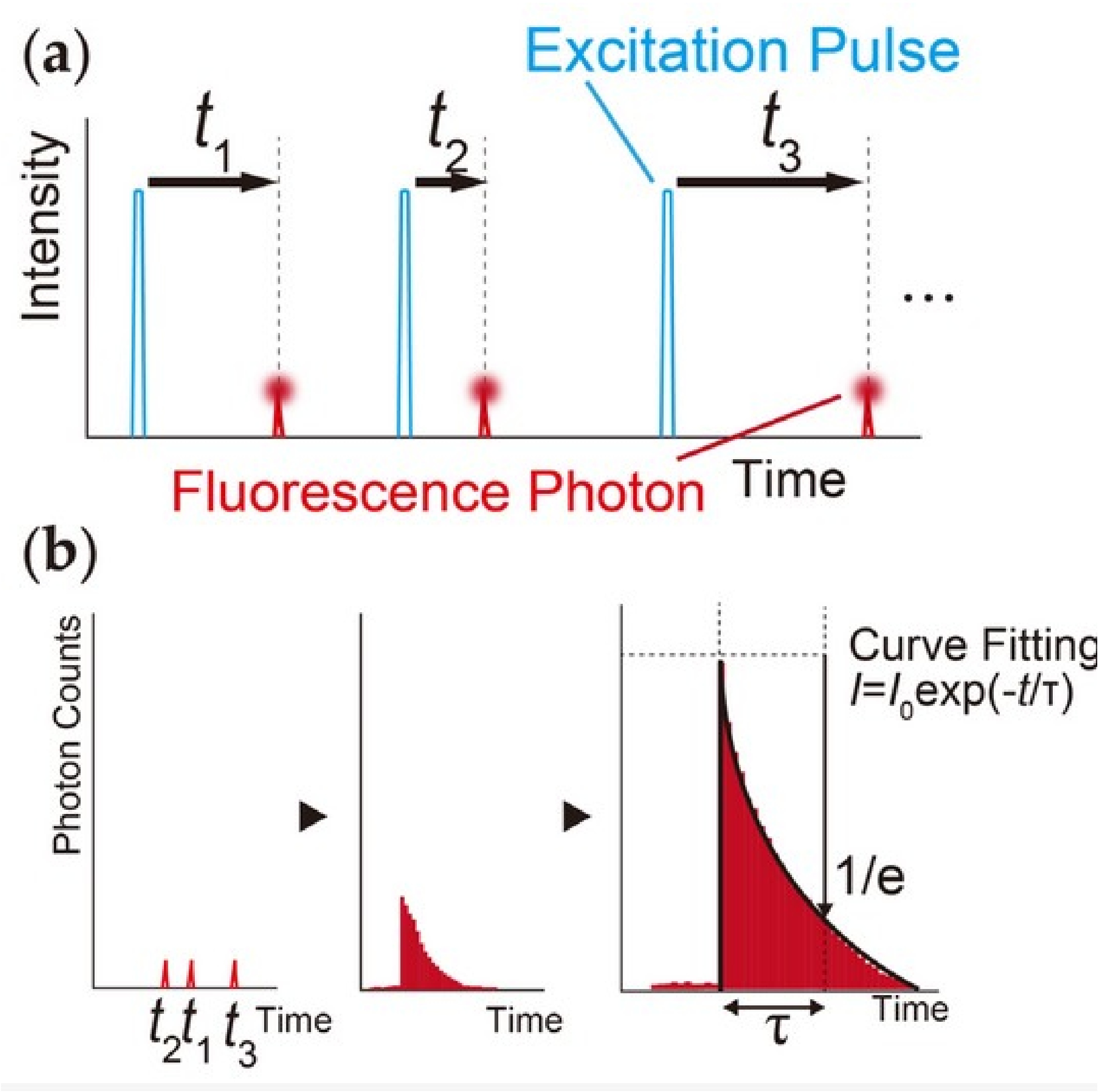
- **fluorescence lifetime microscopy**
  - Exploit the *temporal features of a fluorophore* that are **independent on its concentration** → additional information, enhanced contrast
  - Fluorescence lifetime (τ_{FL}) is affected by **molecular environment** of the fluorophore such as ion concentration, pH, etc.
  - τ_{FL} is on the order of *ns*

Picture from https://www.leica-microsystems.com/science-lab/what-is-flim-fluorescence-lifetime-imaging



Main factor limiting the wide adoption of this technique for routine microscopy applications involving cell imaging is the **speed of the scanning systems**

Working principle of TCSPC FLIM

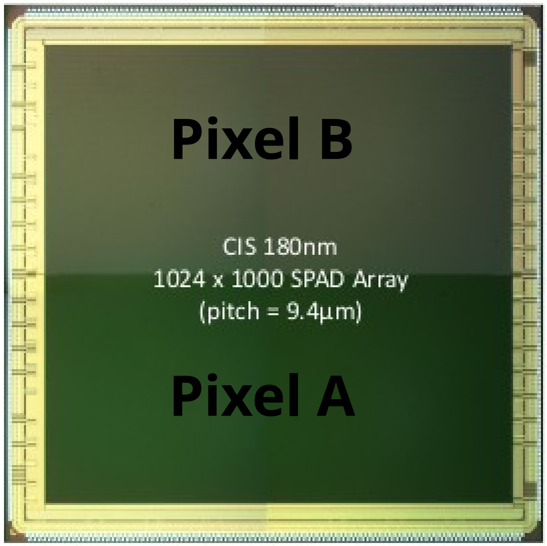


Picture from Ref. [10]

Wide-field FLIM time-gated SPAD camera (0.5 Mpx)

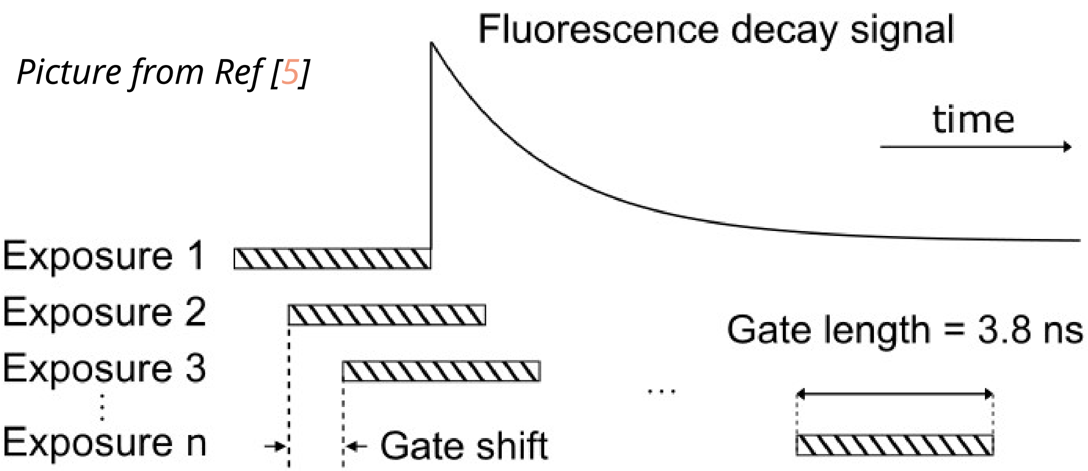
Sensor specifics (Pixel A)

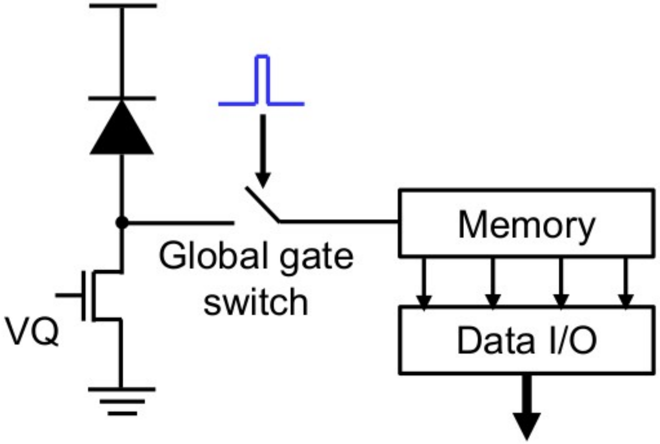
Pitch	9.4μm
Size	1024 x 500
Fill Factor	7%
Data Rate (A+B)	24.5 Gb/s
Gate Length	3.8 ns



Picture from Ref. [3]

Picture from Ref [5]





Picture from Ref. [3]

Wide-field FLIM time-gated SPAD camera (0.5 Mpx)

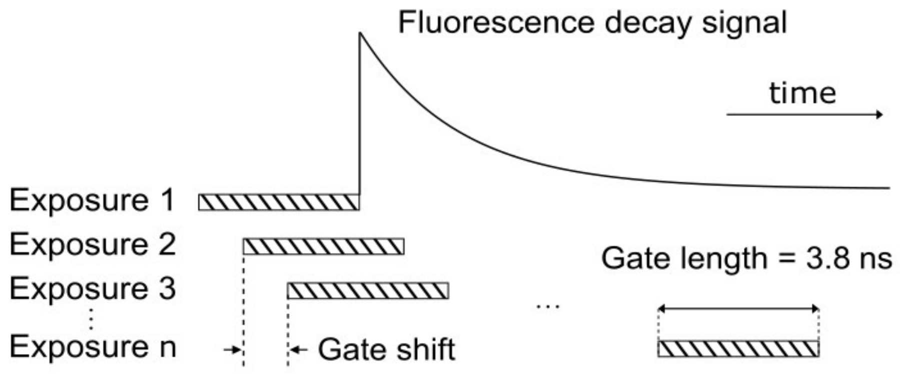
Lifetime Extraction

From the measured signal

$$f_i(t) = d(t) \otimes g(t)$$

where:

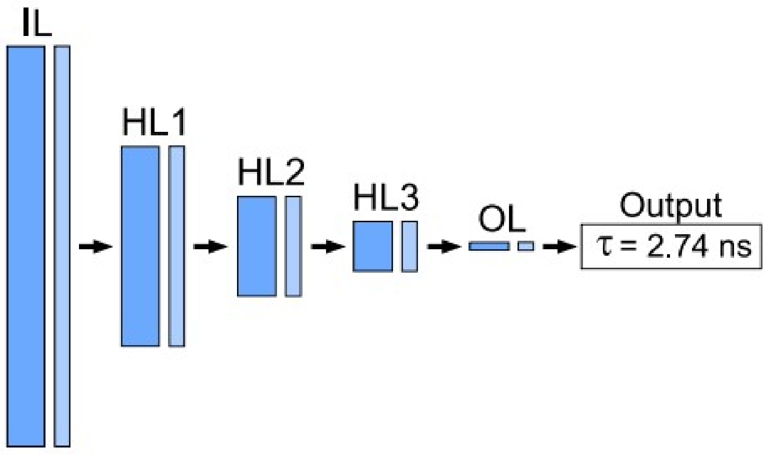
- g(t) is the Impulse Response Function
- d(t) is the decay fluorescence model



To tackle this (not trivial) problem two strategies have been studied in [5]

I. Least square (LSQ) deconvolution

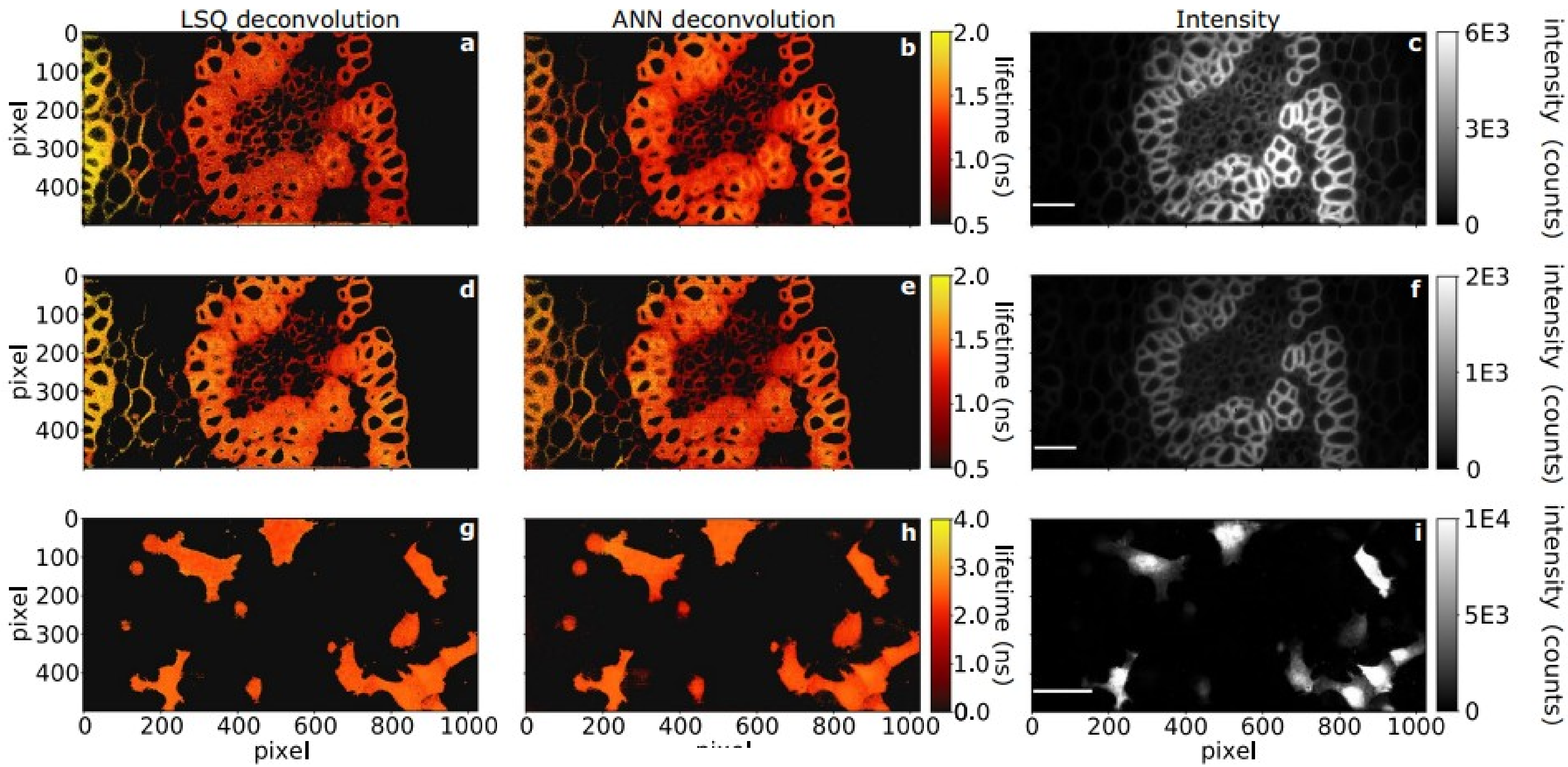
II. Custom-made ANN



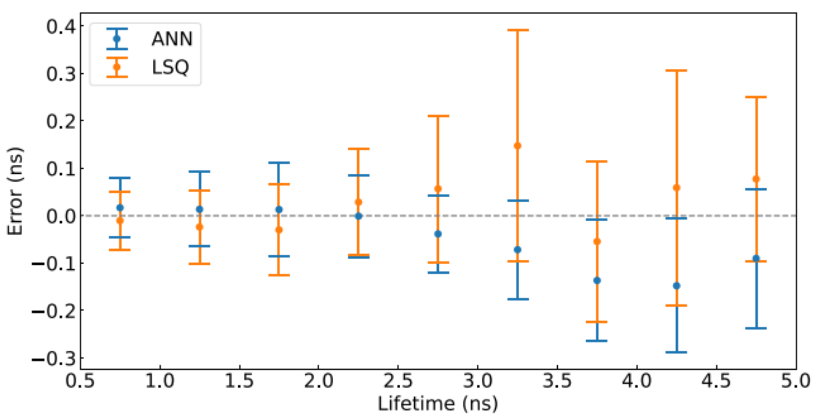
Pictures from Ref [5]

Pre-trained ANN vs LSQ deconvolution performance

Pre-trained ANN is up to **1000x faste**r than LSQ algorithm



Pictures from Ref [5]



Summary

- SPAD tens of **picosecond timing resolution + single photon sensitivity** enable time-resolved low-light imaging , such as FLIM
- Recent developments in SPAD pixel **miniaturization** has overcame the **mega-pixel barrier**, paving the way for compact & low-cost imaging applications with dim light. However **further reduction in the pixel size is very challenging**
- Advancements in 3D-stacked technologies could allow cutting-edge SPAD pixel scaling & sophisticated digital processing *in situ*

References

(1)K. Morimoto et al., *3.2 Megapixel 3D-Stacked Charge Focusing SPAD for Low-Light Imaging and Depth Sensing*," 2021 IEEE International Electron Devices Meeting (IEDM), San Francisco, CA, USA, 2021, pp. 20.2.1-20.2.4, doi: 10.1109/IEDM19574.2021.9720605 available here

(2)K. Morimoto, *Charge-Focusing SPAD Image Sensors for Low Light Imaging Applications*, 2020 International SPAD Sensor Workshop (ISSW)

(3)E. Charbon, C.Bruschini, *Large-format SPAD image sensors for biomedical and HEP applications,* Conference NDIP (9th Conference on new developments in photodetectors), Troyes, France, July 4-8, 2022 available here

(4) K. Morimoto, *Megapixel SPAD cameras for time-resolved applications* (2021) PhD Thesis

(5) Zickus, V., Wu, ML., Morimoto, K. et al. *Fluorescence lifetime imaging with a megapixel SPAD camera and neural network lifetime estimation*. Sci Rep 10, 20986 (2020). https://doi.org/10.1038/s41598-020-77737-0

(6)Bruschini, C., Homulle, H., Antolovic, I.M. et al. *Single-photon avalanche diode imagers in biophotonics: review and outlook*. Light Sci Appl 8, 87 (2019). https://doi.org/10.1038/s41377-019-0191-5https://doi.org/10.1038/s41377-019-0191-5

(7) E. Charbon, *SPAD Pixel Detectors with High Time Resolution,* available here

(8) Vil A, Arbat A, Vilella E, Dieguez A. *Geiger-Mode Avalanche Photodiodes in Standard CMOS Technologies,* Photodetectors. InTech; 2012. Available from: http://dx.doi.org/10.5772/37162

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Thanks

for

your attention