# Single-Photon Time-of-Flight Sensors for Spacecraft Navigation and Landing in CMOS Technologies

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BRUNO KESSLER

Section V.C: Electronic Nanodevices and Technology Trends
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# Outline

- Operation Principle of Geiger-mode APD (SPAD)
- Implementation of CMOS SPADs
- Single-Photon Detectors at FBK: CMOS and Full Custom technologies
- 3D ranging/imaging for space applications
- SPAD-based TOF Sensor Architecture
- Experimental results
- Conclusions

# Acknowledgments

- All my colleagues: IRIS-FBK Team
- Special thanks to: Matteo Perenzoni
- CSEM team (V. Mitev, J. Haesler, C. Pache, T. Herr, A. Pollini)
- European Space Agency
- *Sensor details presented at ISSCC’16 , 1-4 Feb., San Francisco, USA*

# Photodiode, APD, SPAD

- SPAD = photodiode biased beyond its breakdown voltage (Geiger mode)

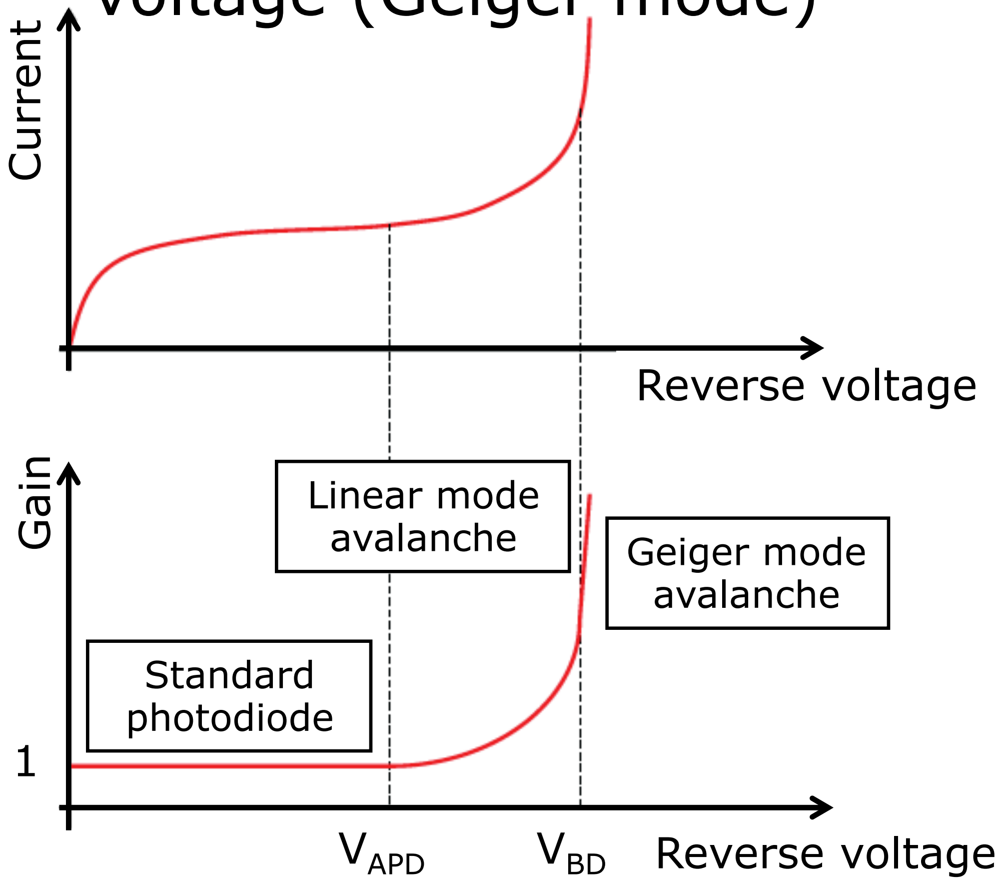
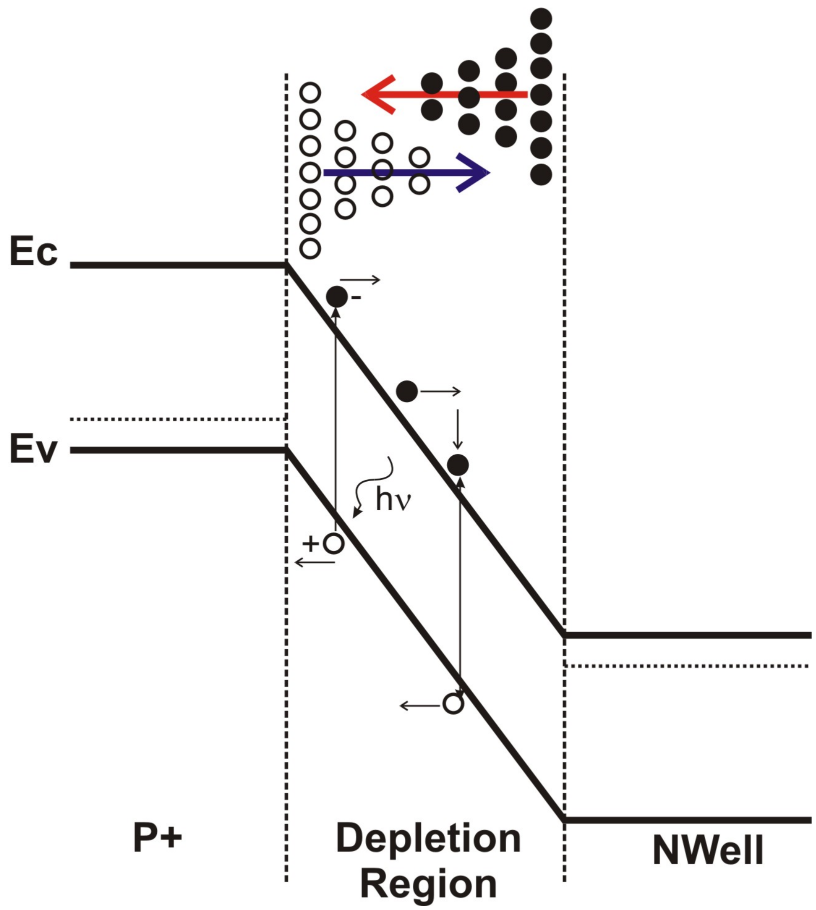



Photo-multiplication effect allows for **SINGLE PHOTON DETECTION**

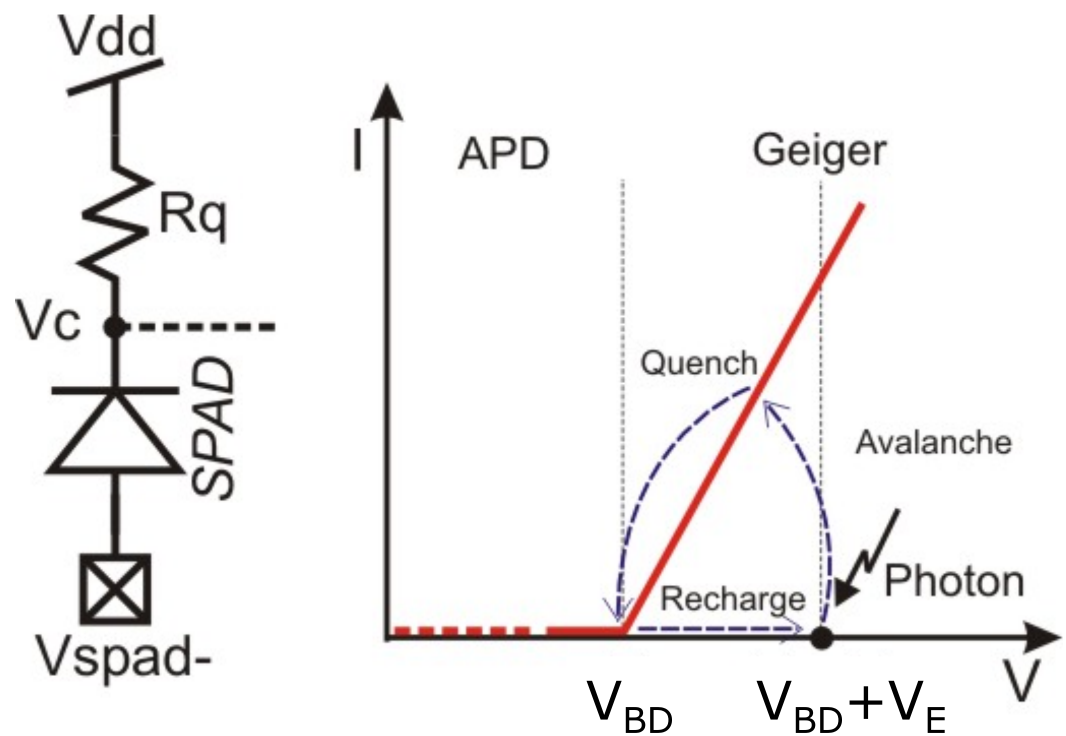
# Avalanche and Breakdown

- High electric field within depletion region needed to reach breakdown



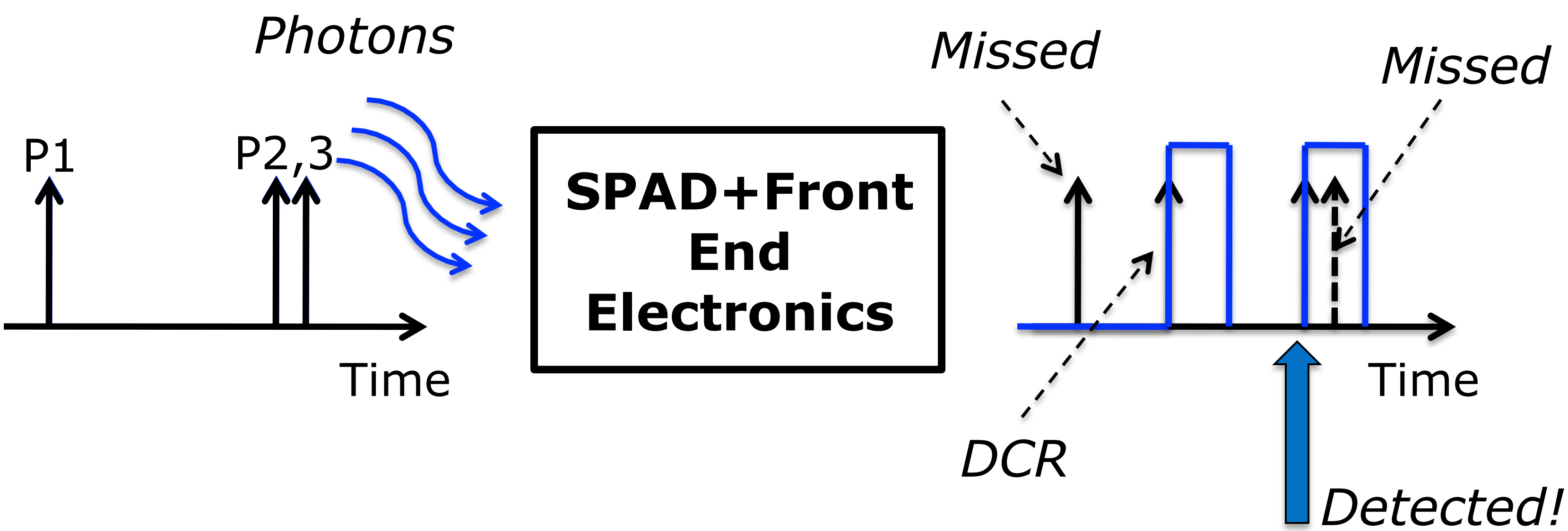
# SPAD Operation

- Operation Loop:
  - 1. Entering the Geiger region at $V_{BD}+V_E$ (meta-stable point)
  - 2. Avalanche
  - 3. Quenching
  - 4. Recharging to 1




$V_E$: Excess bias voltage

# SPAD High Level Behavior




- Detected photons generate digital pulses
- Not all the photons are detected!
- Pulses are generated also in dark condition (DCR noise)
- Jitter noise between detected photon and digital output



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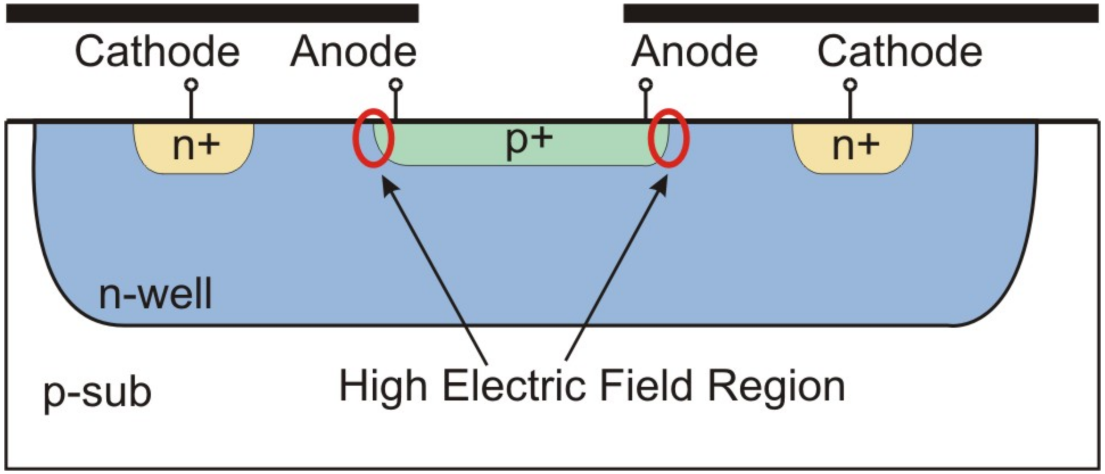
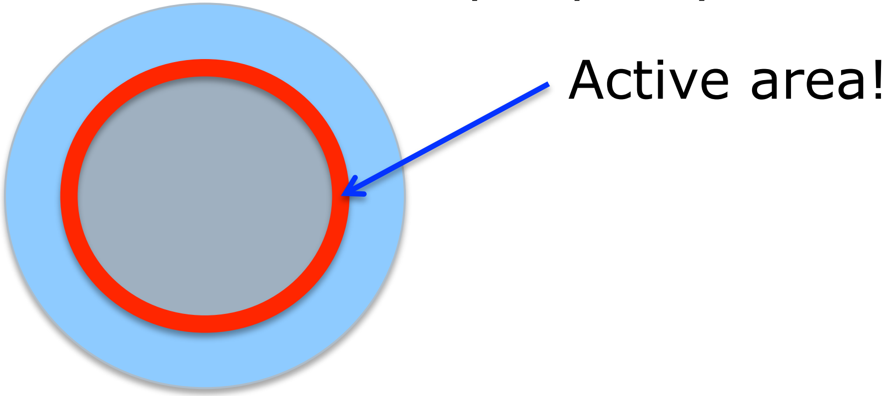
# SPAD with a simple *pn* Junction?




- At the edges (shallow junctions) high electric fields
- Premature breakdown at the sensor periphery



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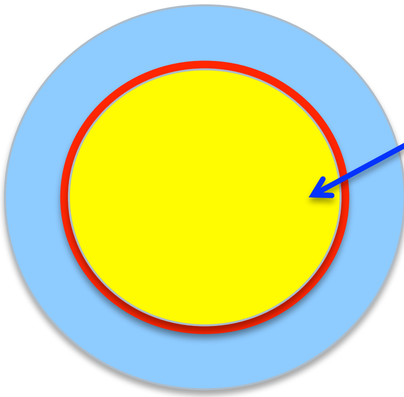
# SPAD with a simple *pn* Junction?




- Guard-ring structure is needed to prevent breakdown at the periphery while keeping the avalanche region confined in the planar area



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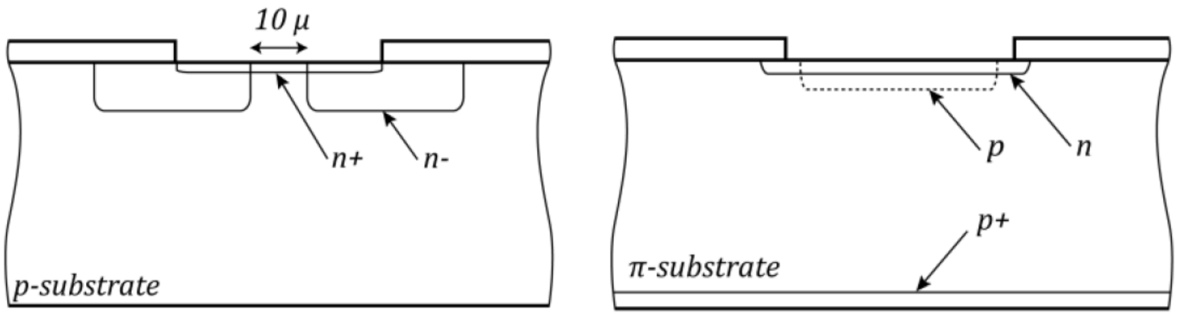
# SPADs out of the Labs (Eventually!)

- SPAD known since 60’s (!)




[1] R. J. McIntyre, *Theory of Microplasma Instability in Silicon*, J. of Applied Physics, pp. 983-995, 1961.
[2] R. H. Haitz, *Model for the Electrical Behavior of a Microplasma*, J. of Applied Physics, pp. 1370-1376, 1964.

- First CMOS implementations about fifteen years ago
- CMOS SPADs entered the market in 2012-2013



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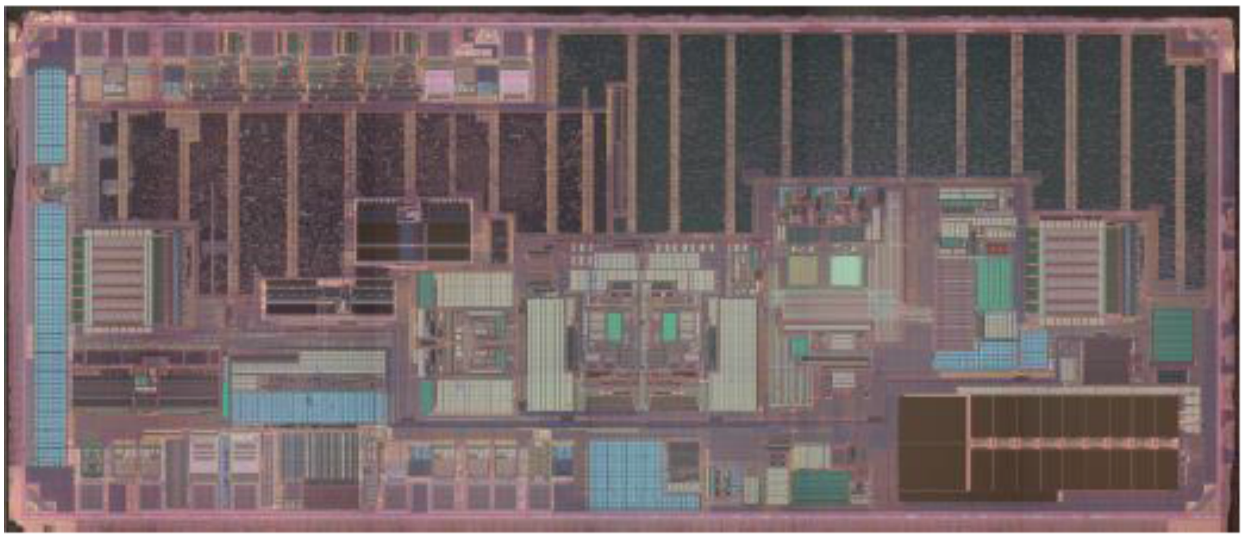
# From high-end applications to consumer

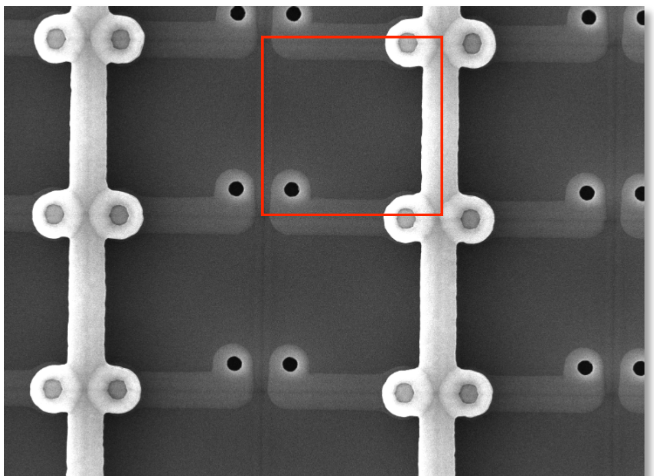
- STM SPAD-based TOF Proximity Sensor



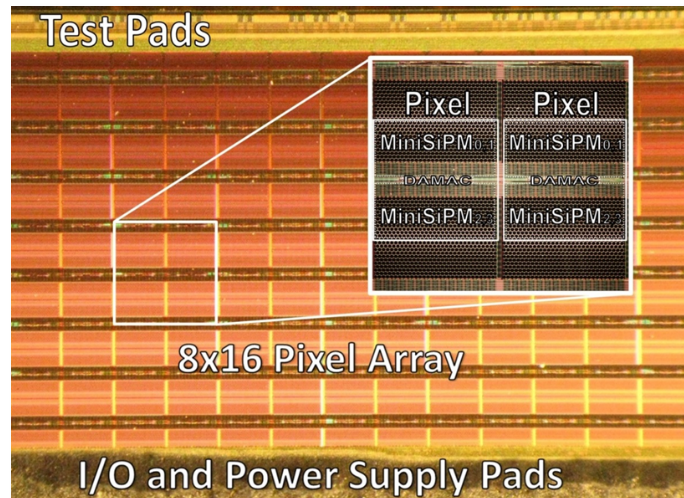
@Chipworks (http://ww2.chipworks.com/e/4202/6180-Time-of-Flight-Sensor-pdf/hwvfs/713665047)

# Single-Photon Detectors at FBK

## Single-Photon Avalanche Diodes



**Custom technology (FBK process):**
- high efficiency
- low noise
- high flexibility




**Standard CMOS technology:**
- smart architecture
- high-level integration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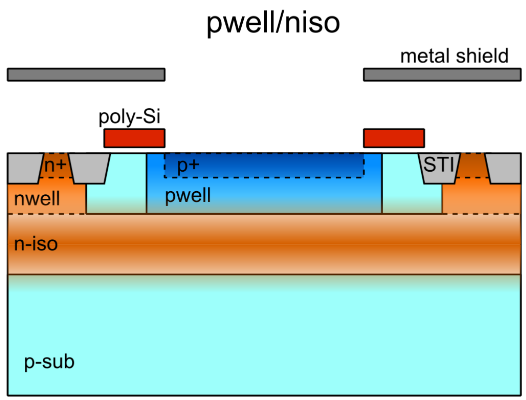
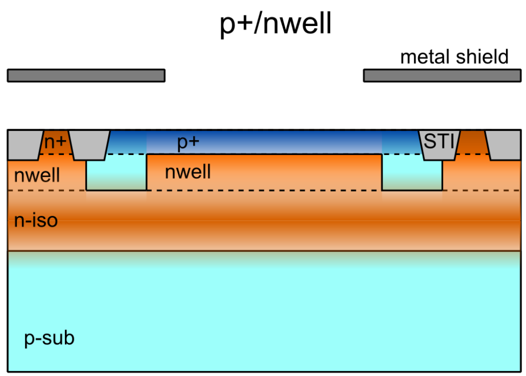
# FBK CMOS SPAD in LFoundry 150nm

- First testchip (Langshut), 2010/2011: two SPADs, published at ESSDERC 2011



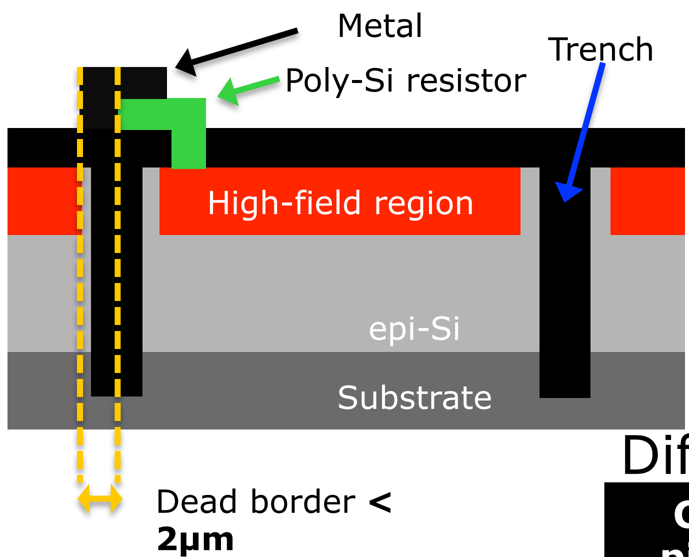

- Deep junction > 0.5µm
- Virtual guard ring
- Graded doping profiles

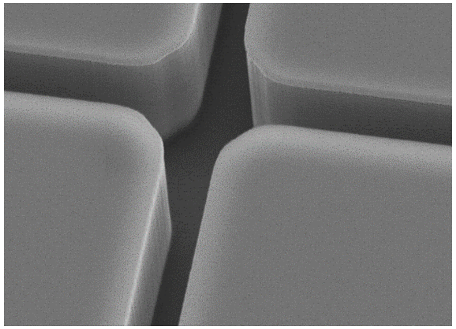


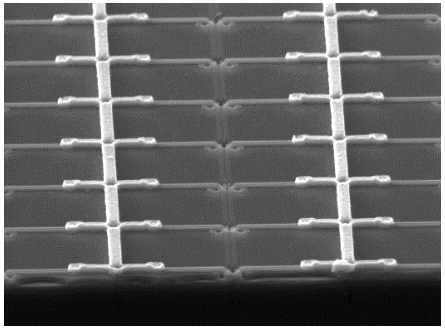

- Shallow junction ~ 0.2µm
- p-sub low-doped guard ring
- Steep p+ doping profile

# Full Custom Technology: FBK SiPM

- Specialized process offers superior performance: DCR<200kHz/mm$^2$





## Different cells…

| Cell pitch | Fill factor |
|---|---|
| 15 µm | 62 % |
| 20 µm | 66 % |
| 25 µm | 73 % |
| 30 µm | 77 % |
| 35 µm | 81 % |
| 40 µm | 83 % |

## Different SiPM layouts

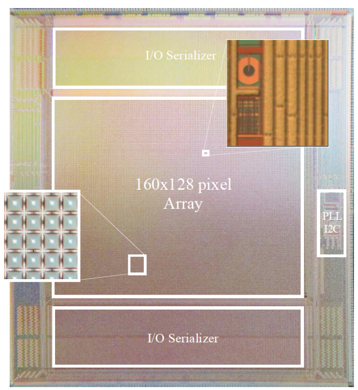
| Active area | Cell pitch |
|---|---|
| 1x1 mm$^2$ | 15 / 20 / 25 / 30 µm |
| **Coming soon** | |
| 1x1 mm$^2$ | 35 / 40 µm |
| 4x4 mm$^2$ | 30 / 35 / 40 µm |
| 6x6 mm$^2$ | 30 µm |

*[28] A. Ferri et Al., NSS'15*

# CMOS SPAD Sensors at FBK

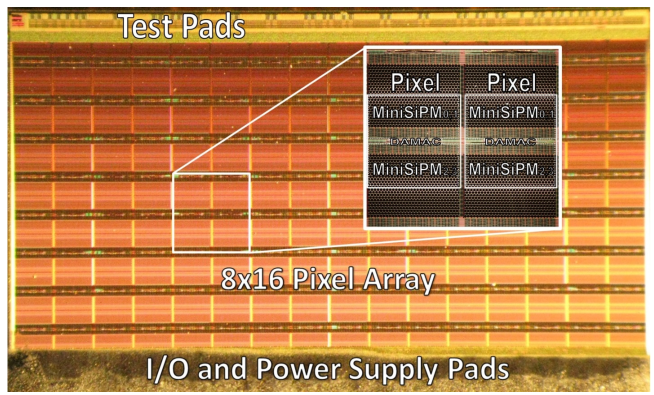
- Developments originally driven by Biomedical applications
- Several different 'families' of sensors developed
- Three examples shown here:

*Lifetime Imaging*



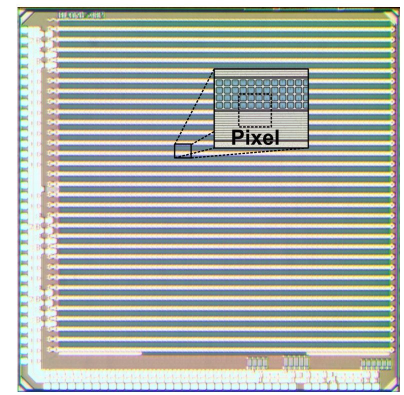

**MEGAFRAME FP7-Project**
www.megaframe.eu
**Single SPAD + TDC**
[Veerappan, ISSCC 2011]

*Positron Emission Tomography*




**SPADnet FP7-Project**
www.spadnet.eu
**D-SiPM + TDCs**
[Braga, ISSCC 2013]

*3D Imaging*




**MILA ESA-Project**
iris.fbk.eu/projects/mila
**D-SiPM + TDC**
[Perenzoni, ISSCC 2016]

# Landing in Space

- Apollo 11 mission on the Moon
- Mars Space Laboratory on Mars
- Rosetta mission on comet 67P/C-G

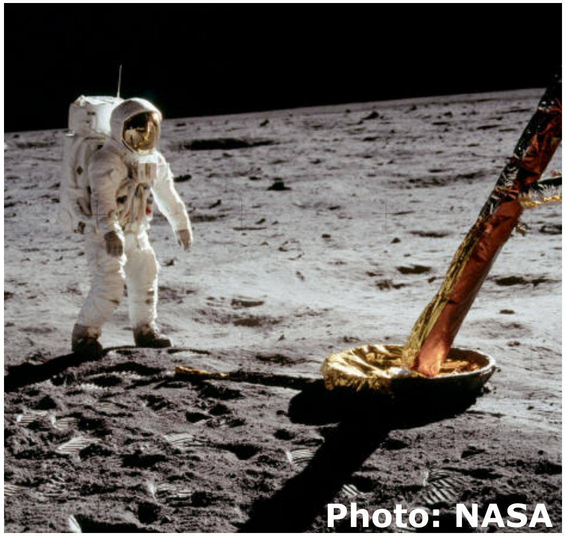


Photo: NASA

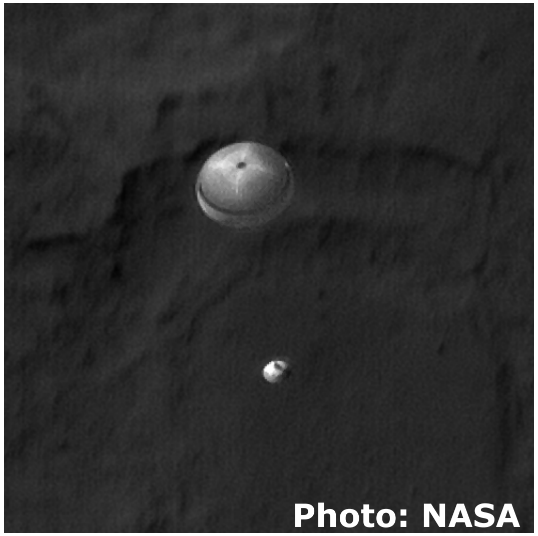


Photo: NASA

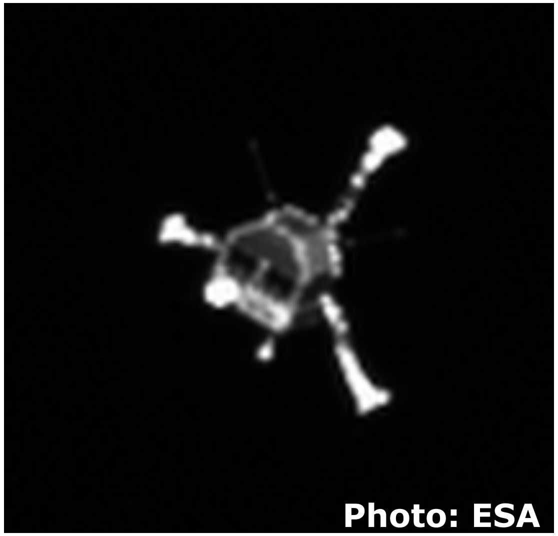


Photo: ESA



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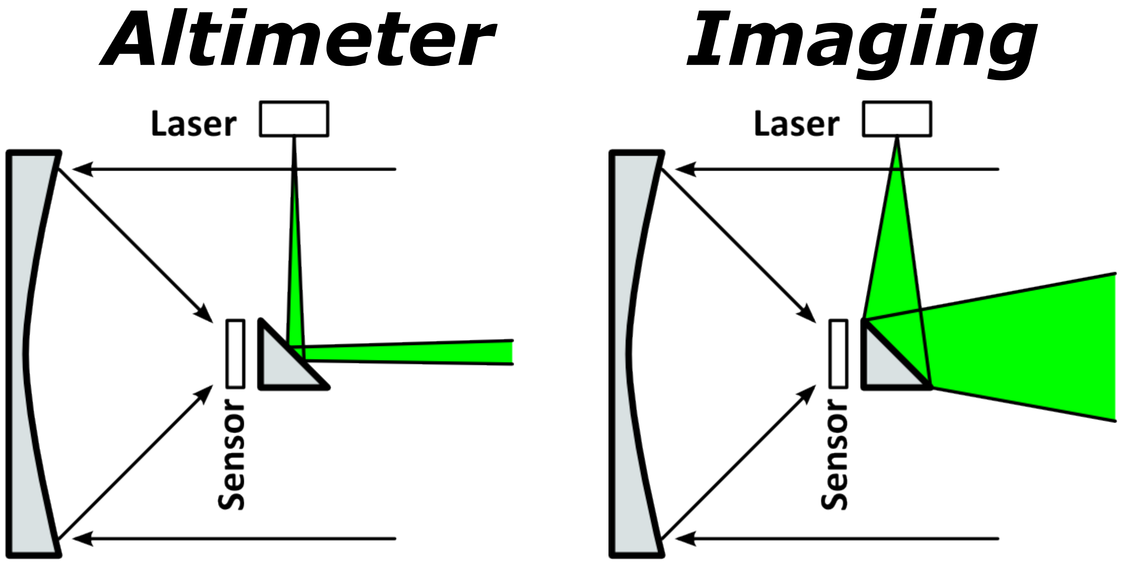
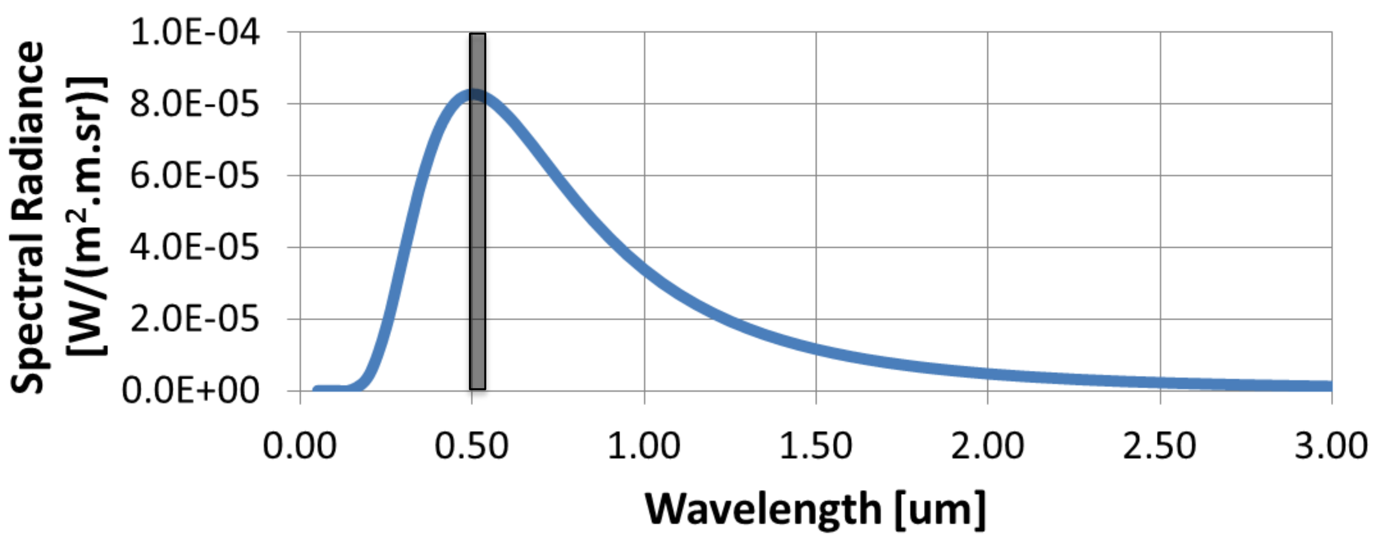
# Long Measurement Range




- Mode: 100m-6km 30m-300m
- Max ToF: 40μs 2μs
- Precision: 1m (6.6ns) 10cm (660ps)

**Wide DR and long light time-of-flight**

# Immunity to background light




- With targeted pixel size and FF:
  - 100 Mph/s (detected)

*5nm filter*
*Albedo <0.4*
*Sun angle 30°*

**High Background Rejection**



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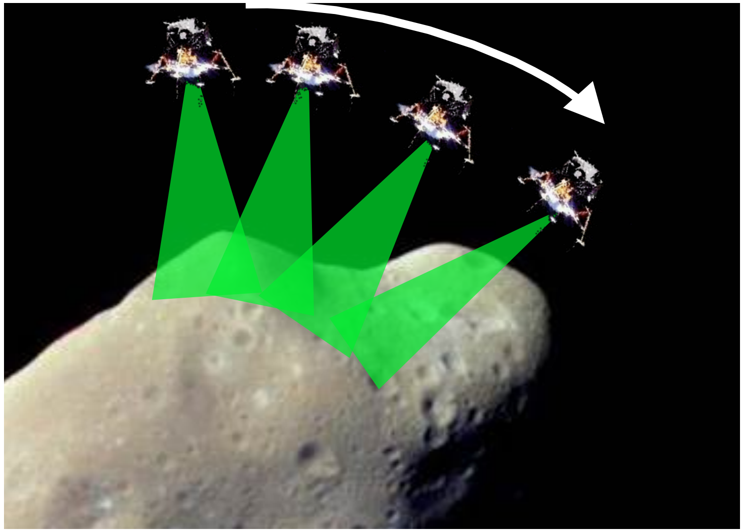
# Acquisition speed



Spacecraft speed:
0.1 m/s - 1.5 m/s

- No artifacts within 1 pixel
  - Fast image acquisition < 2 ms
  - Low frame rate ≈ 2 fps

} *Enabling post-processing*

**Short Acquisition Time**



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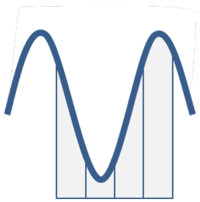
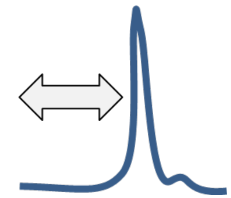
# TOF Ranging Techniques



**TOF**

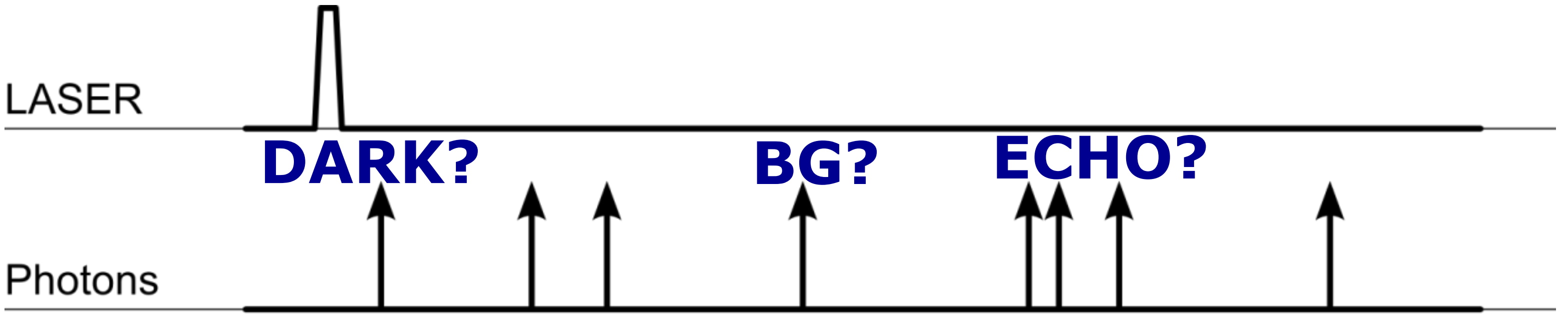


| Indirect TOF | | Direct TOF | |
|---|---|---|---|
| Long integration time | ☹ | ☺ | Fast acquisition |
| Ambiguity | ☹ | ☺ | No ambiguity |
| Analog dynamic range | 😐 | ☺ | Digital dynamic range |
| Large no. of pixels | ☺ | ☹ | Reduced no. of pixels |

**Challenge: single-photon detectors are BG sensitive and noisy**

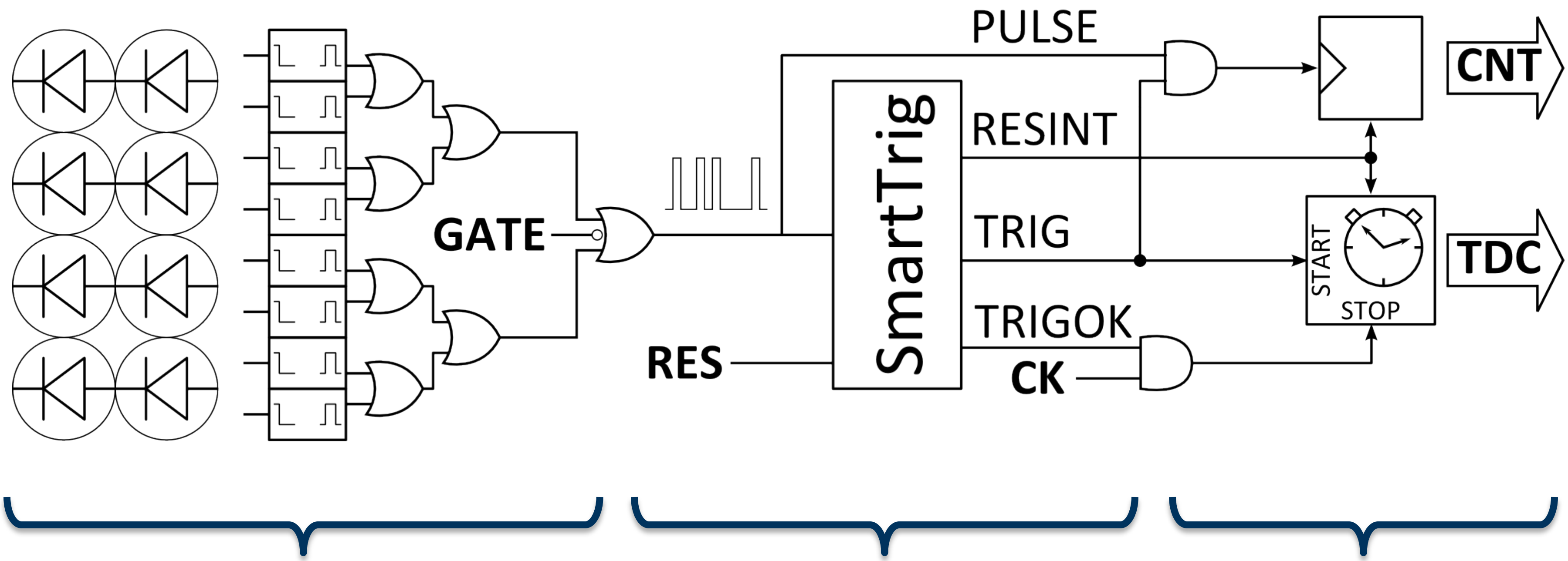
# Previous Solutions Limitations

- **Single SPAD + TDC** [Veerappan, ISSCC 2011]
  - Compact pixel (but low FF) ☺
  - First event (dark, bg, echo…): TDC timestamp ☹



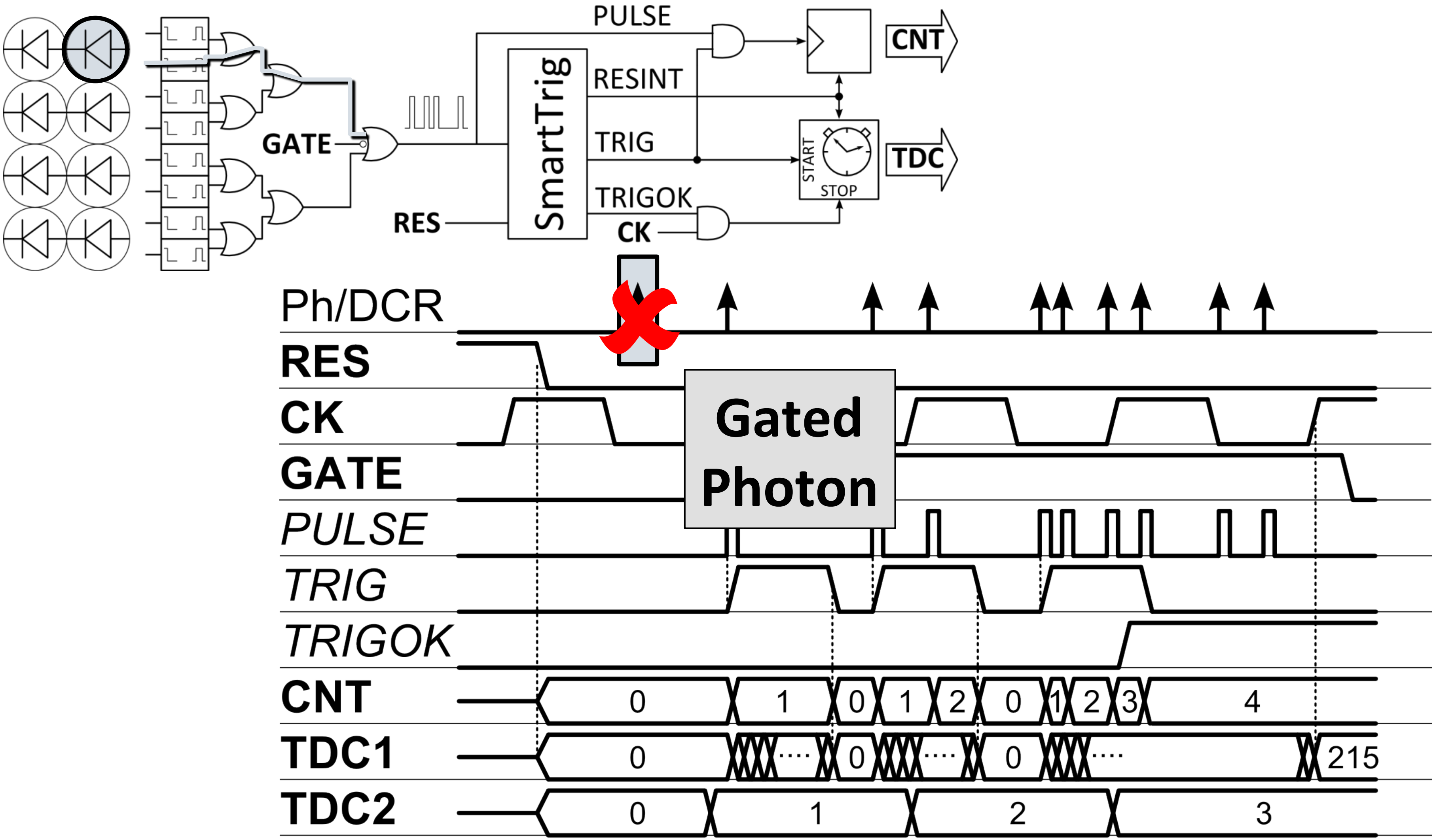

- **Multiple SPAD + TDC** [Niclass, JSSC 2014]
  - First <u>relevant</u> event captured ☺
  - Few pixels, imaging through scanning ☹

# Pixel Schematic




| **Digital SiPM** | **Triggering Logic** | **Counter & TDC** |
|---|---|---|
| Smaller deadtime | Identify echo | Timestamp and count |

# Detailed Operation (1)



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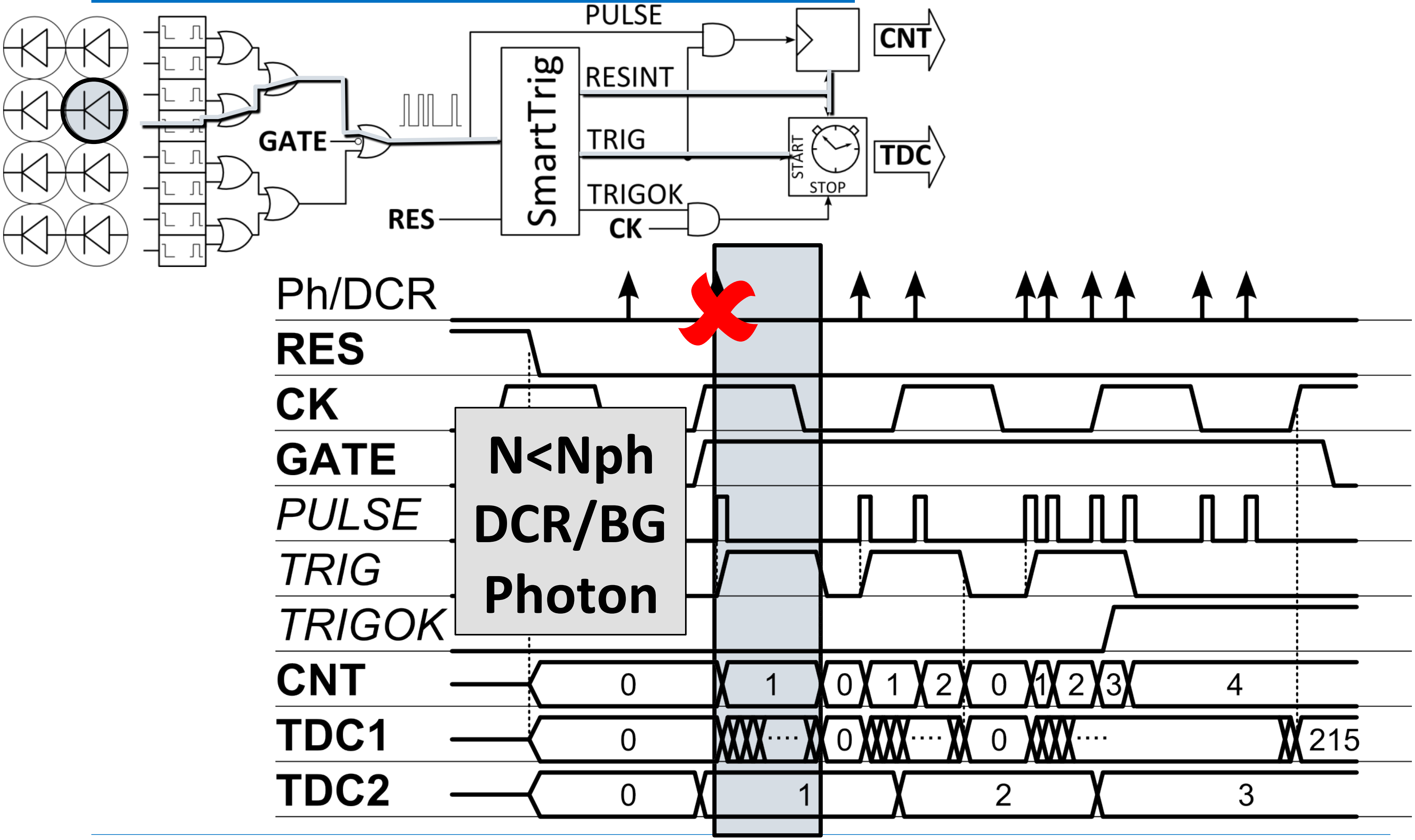
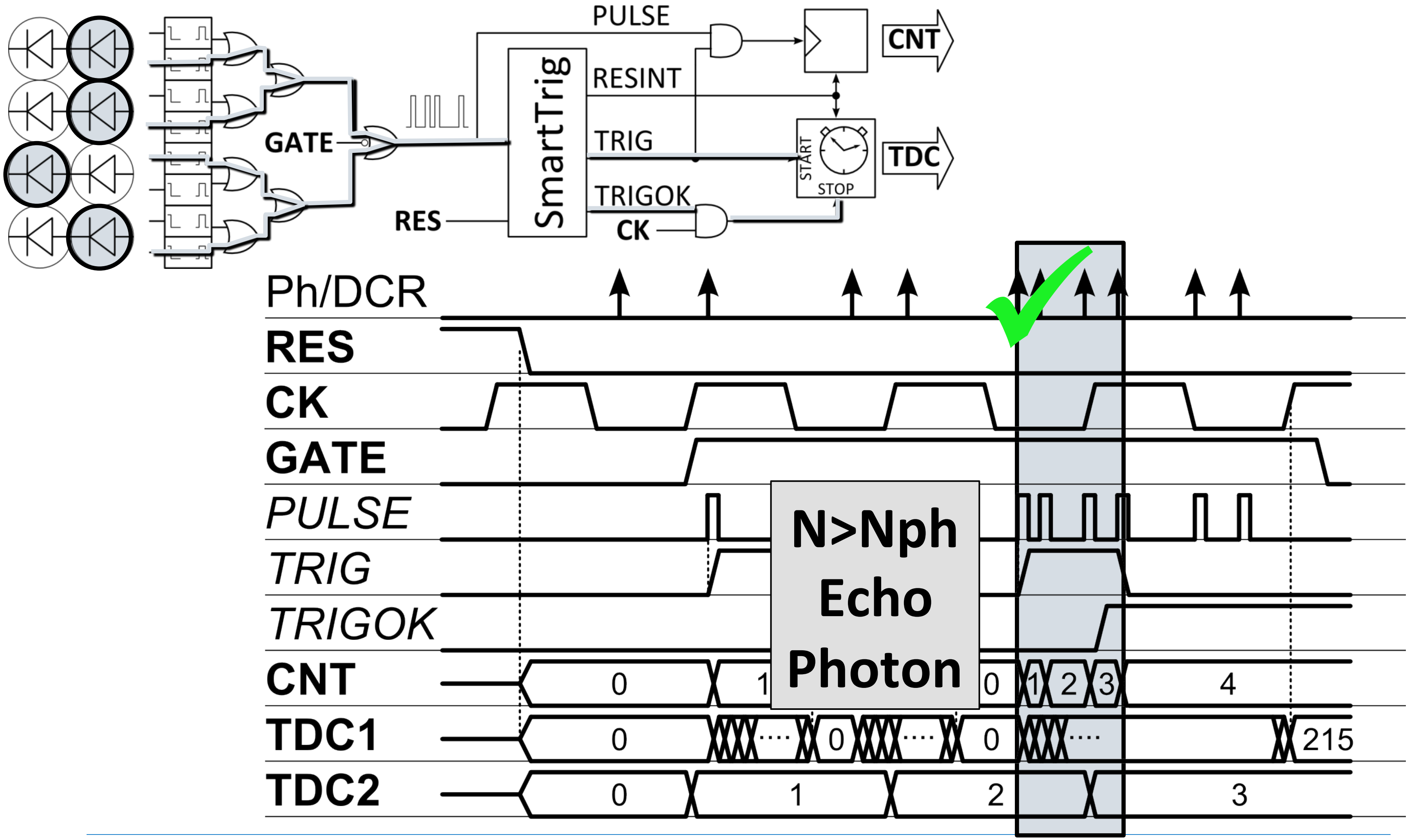
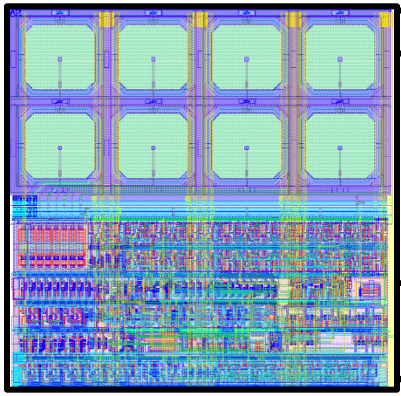
# Detailed Operation (2)

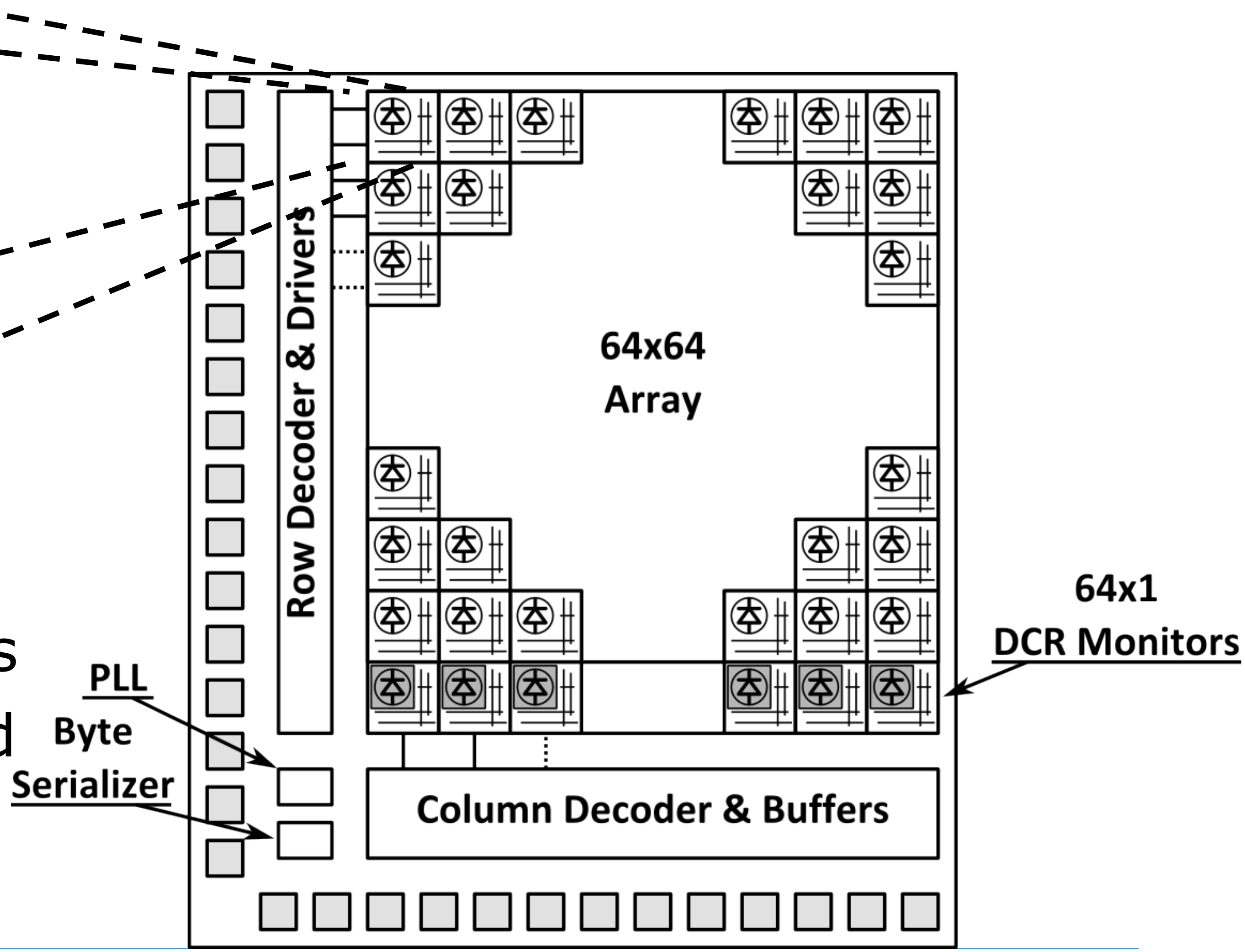


# Detailed Operation (3)



# Chip Architecture

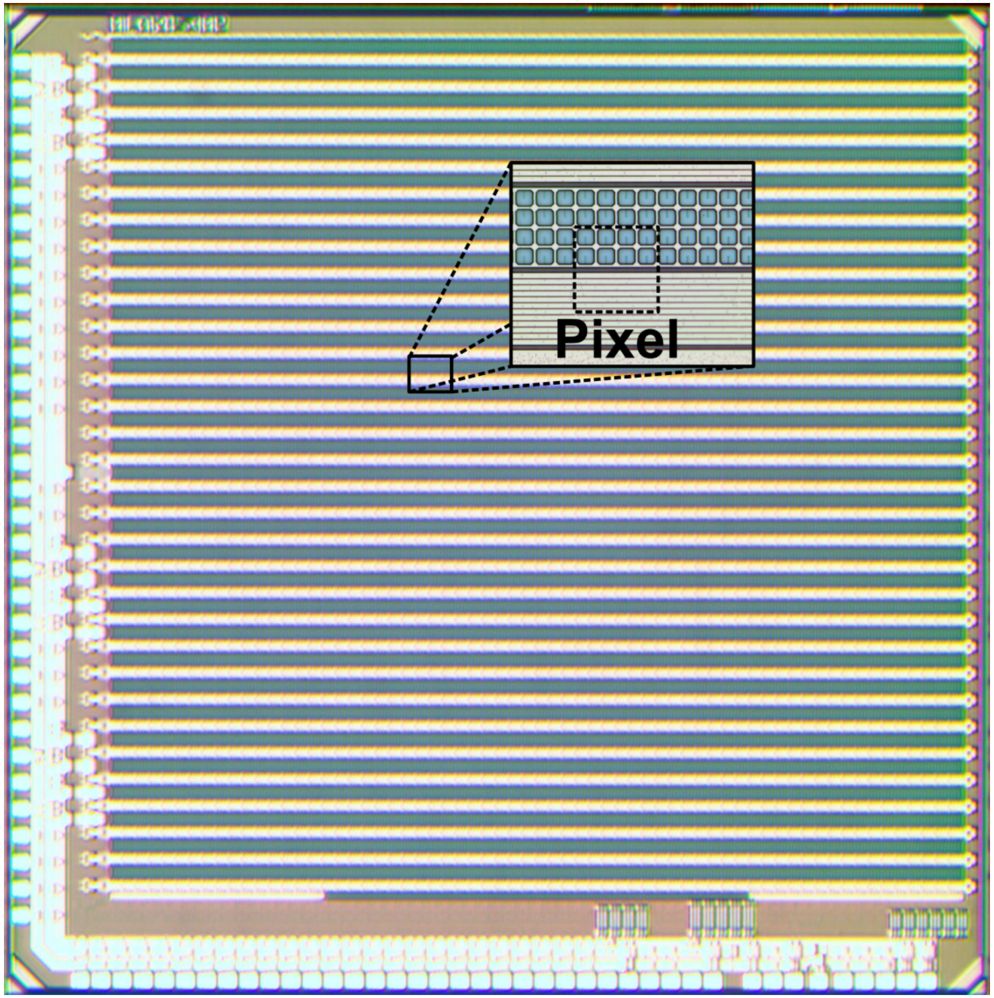





- 60-μm pitch
- 26.5% FF
- 16-bit TDC
  - LSB 250ps
  - PLL-locked
- 4-bit CNT

# Chip Micrograph

- 150nm CMOS
- $4.4 \times 4.4 mm^2$
- $P_{el}$ = 47.7mW
- $P_{SPAD}$ = 45.8mW
- 1920 fps



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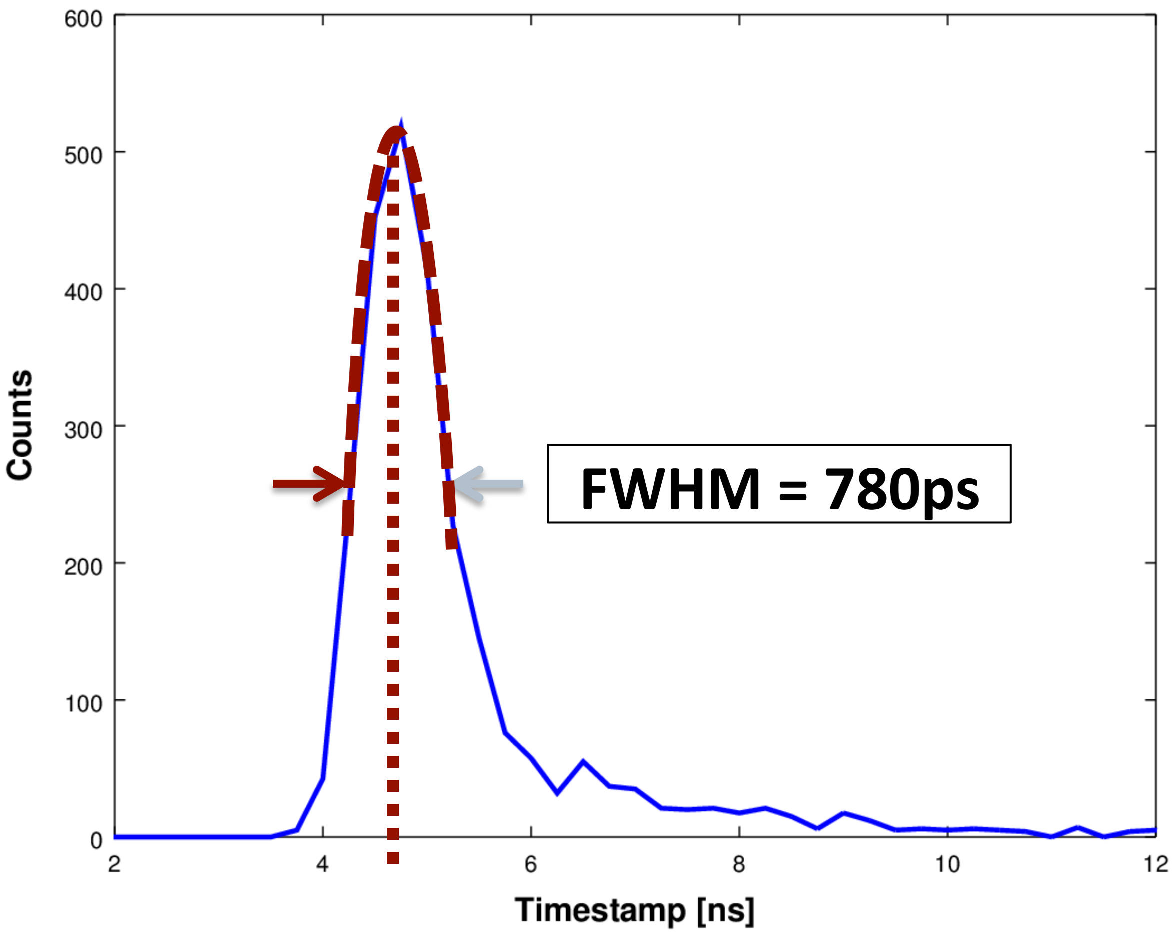
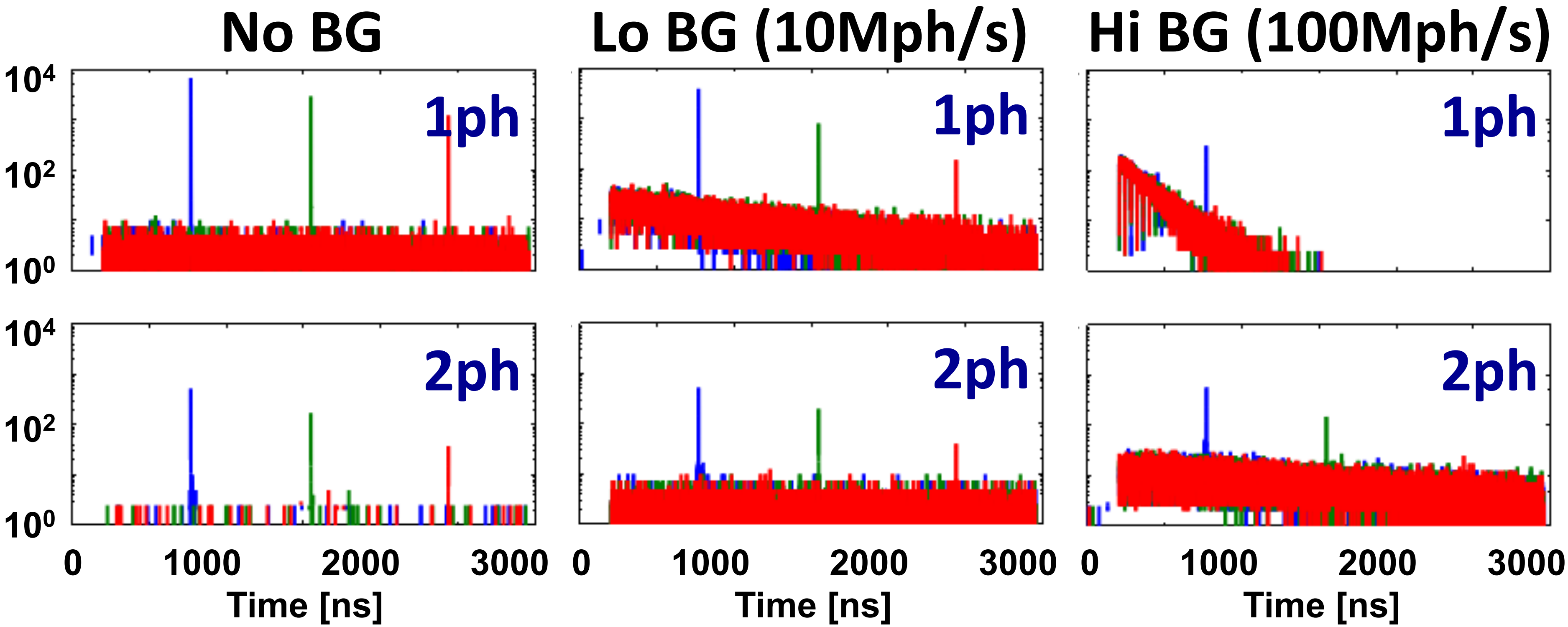
# Timing Resolution




- Conditions:
  - 70-ps Laser (attenuated)
  - 5000 frames
  - Single pixel
  - 250-ps LSB

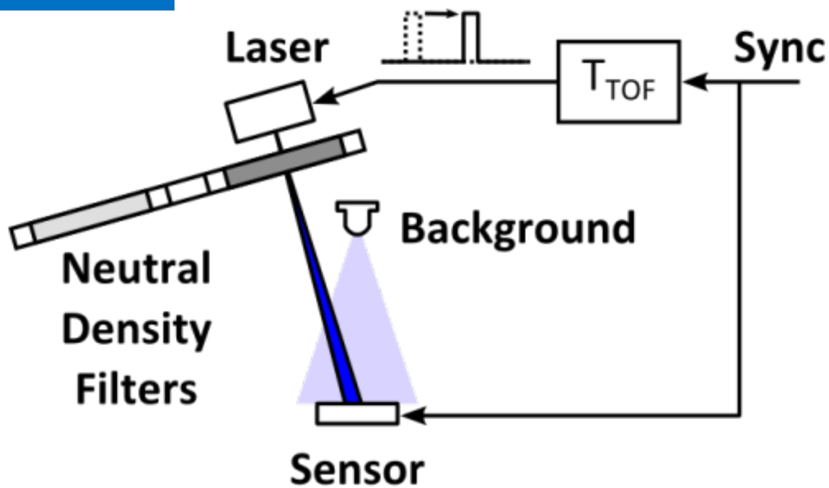
# Pile-up With Smart Trigger

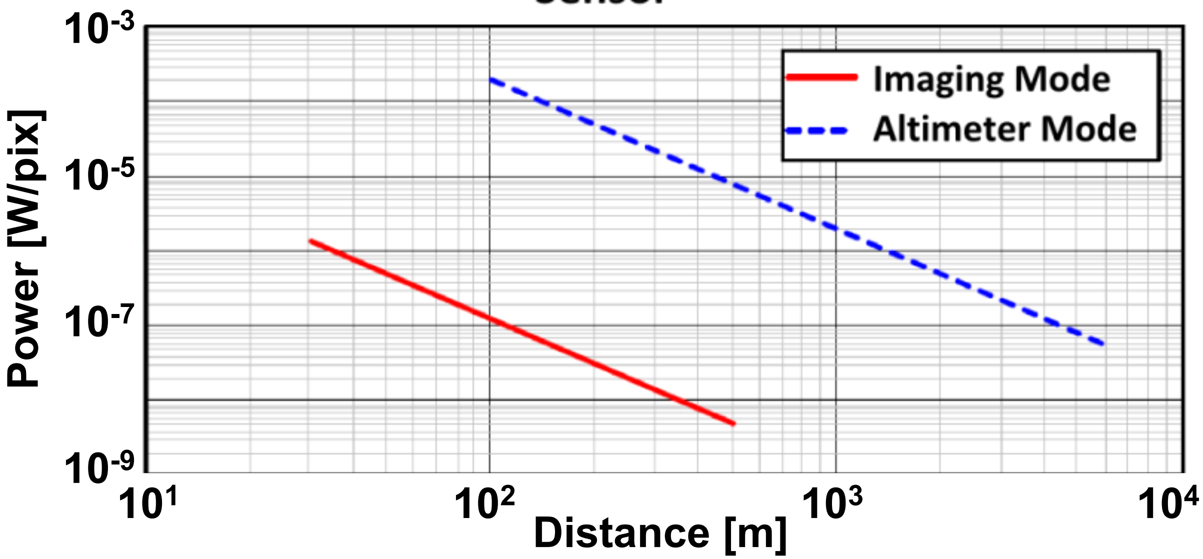



– Strong background/DCR is rejected
– Smaller laser peaks

# Real Conditions Emulation

- Test vehicle conditions:
  - Laser: $P_{pk}$=7.5kW
  - 50% albedo
  - 2x2 sensors
  - F#=0.8
- 250-pts acq



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# 3D Imaging Example

- <add here CSEM results>

*Courtesy of CSEM team (V. Mitev, J. Haesler, C. Pache, T. Herr, A. Pollini)*

# Conclusions

- FBK is developing CMOS SPAD for different applications
- This talk focuses on TOF sensor:
  - Imager with d-SiPM based pixel
  - Per-pixel multiple photon time correlation
  - Improved dark/BG counts rejection

- Future developments
  - Irradiation tests
  - Larger sensor



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