Front-end Readout ASIC Design for Ultra-Fast Sensors used in Muon Detectors

Annual Meeting of DDAp/DDEIT and HIRSAP 2025

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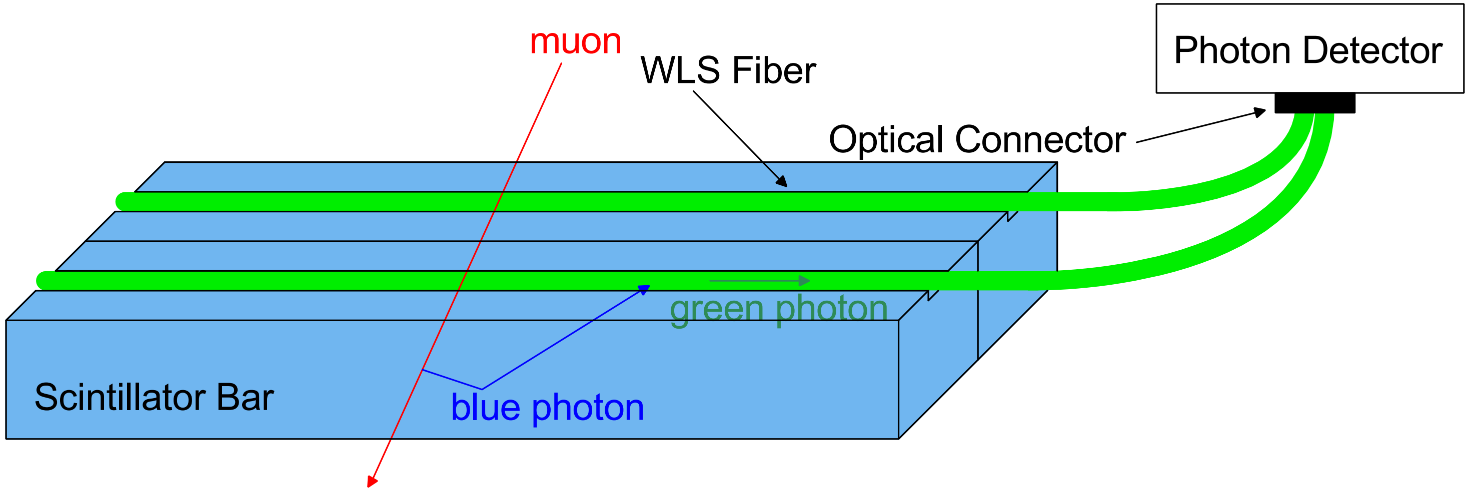
- Introduction
- ANDESPix
  - Overview
  - Pixel Measurements
  - TDC Measurements
- Conclusion and Outlook

Scintillator Based Muon Detection at ANDES

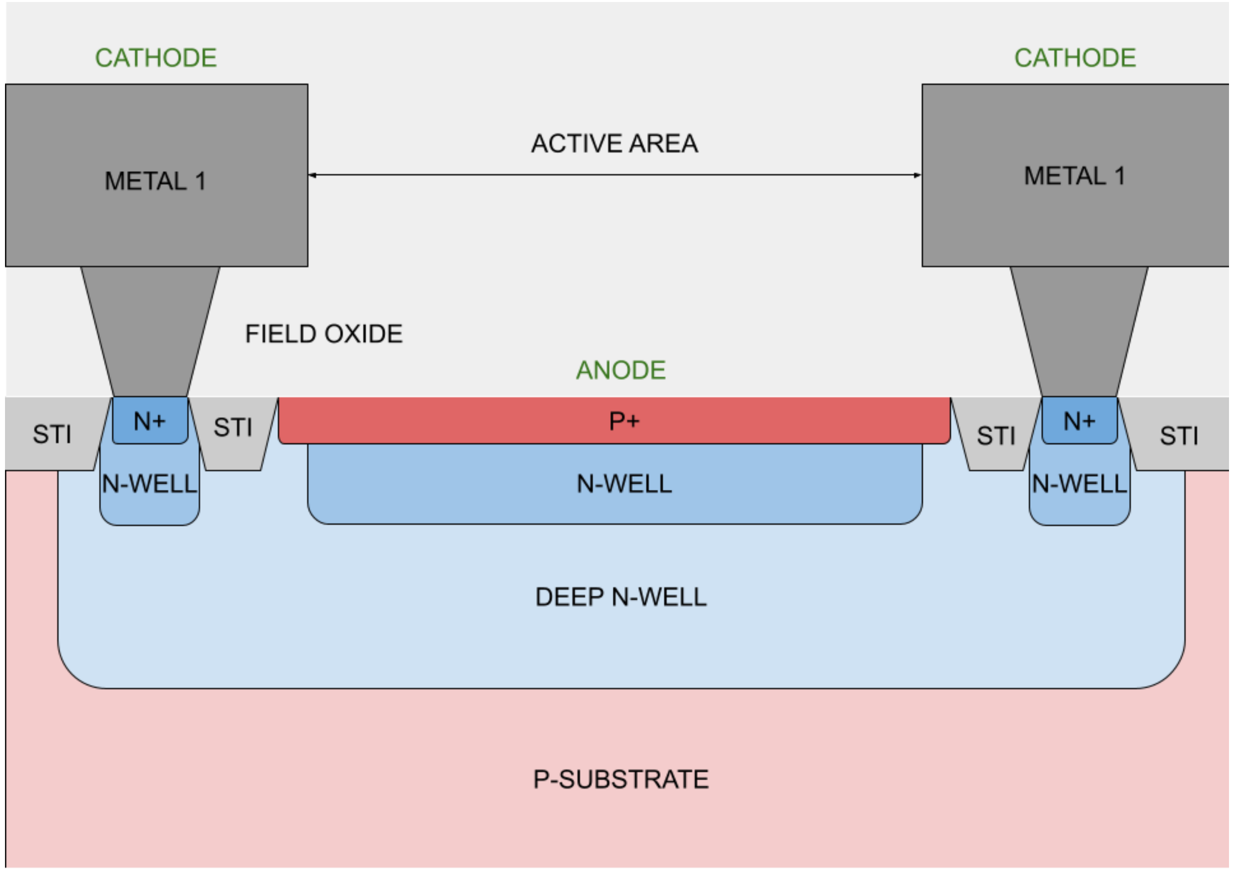
- ANDES laboratory (*andeslab.org*) will be 1750 m deep underground as part of the Agua Negra International Tunnel between Argentina and Chile
- Effective shield against cosmic radiation providing low cosmic background necessary for e.g. dark matter or neutrino experiments
- Necessary to detect remaining muons with scintillators for muon-veto
- Photon Detector (SiPM) to detect **<50 photons/muon** from WLS fiber



Overview and working principle of the muon detector

X. Bertou, "The ANDES Deep Underground Laboratory," Sci. Rev. - End World, vol. 1, no. 4, Art. no. 4, Sep. 2020, doi: 10.52712/sciencereviews.v1i4.24.
M. Platino et al., "AMIGA at the Auger Observatory: the scintillator module testing system," J. Inst., vol. 6, no. 06, pp. P06006–P06006, Jun. 2011, doi: 10.1088/1748-0221/6/06/P06006.
A. Aab et al., "Muon counting using silicon photomultipliers in the AMIGA detector of the Pierre Auger observatory," J. Inst., vol. 12, no.03, pp. P03002–P03002, Mar. 2017, doi: 10.1088/1748-0221/12/03/P03002

Single Photon Avalanche Diode (SPAD)

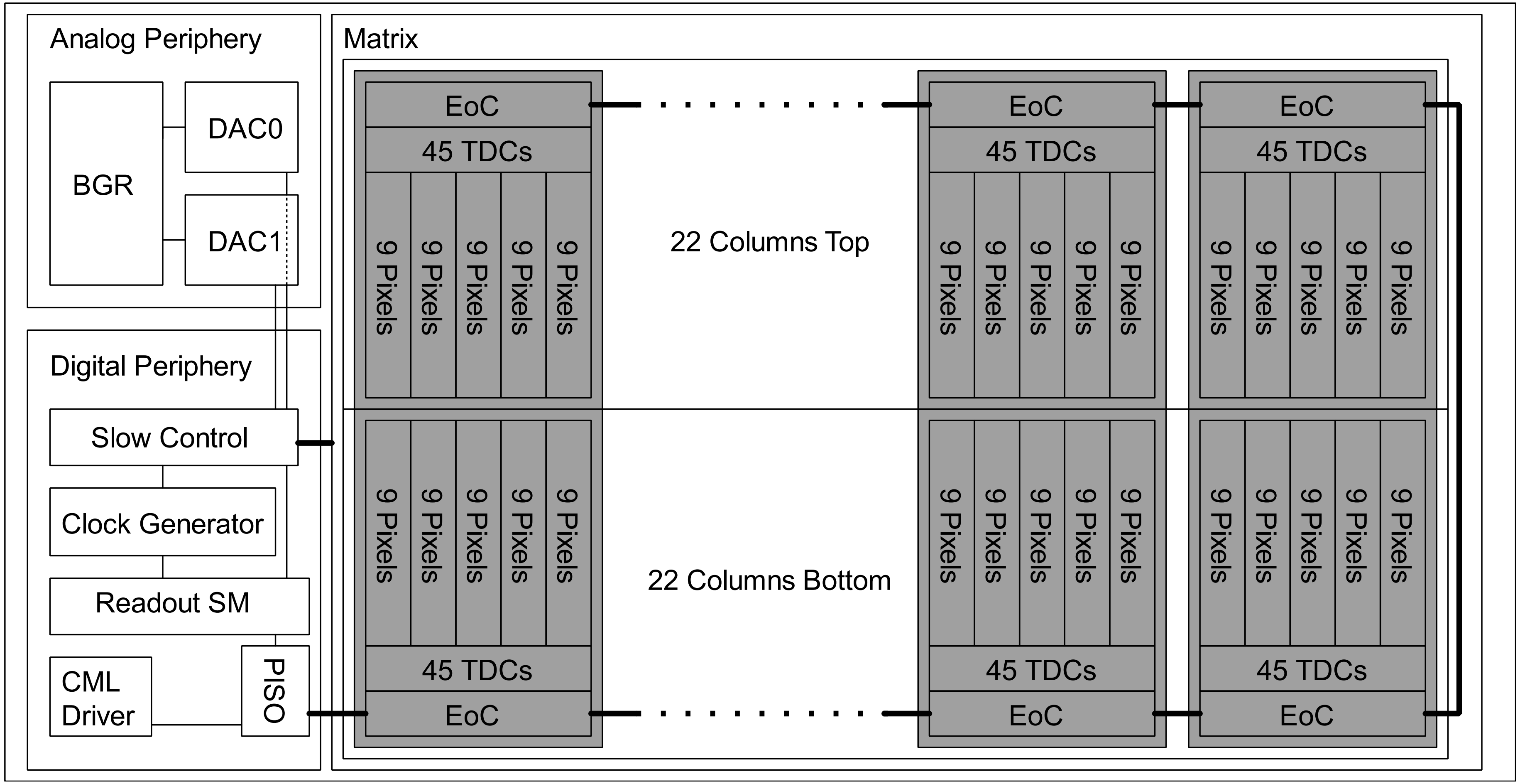


Exemplary Cross Section of a CMOS SPAD

- SPAD is working in Geiger mode
  - When hit by a photon it generates a large avalanche current (it “fires”)
  - Avalanche current must be quenched to restore pre-hit conditions
    - Passive Quenching: Resistor
    - Active Quenching: Transistor switch

M. Moreno-García, H. Xu, L. Gasparini and M. Perenzoni, "Low-Noise Single Photon Avalanche Diodes in a 110nm CIS Technology," 2018 48th European Solid-State Device Research Conference (ESSDERC), Dresden, Germany, 2018, pp. 94-97, doi: 10.1109/ESSDERC.2018.8486883.

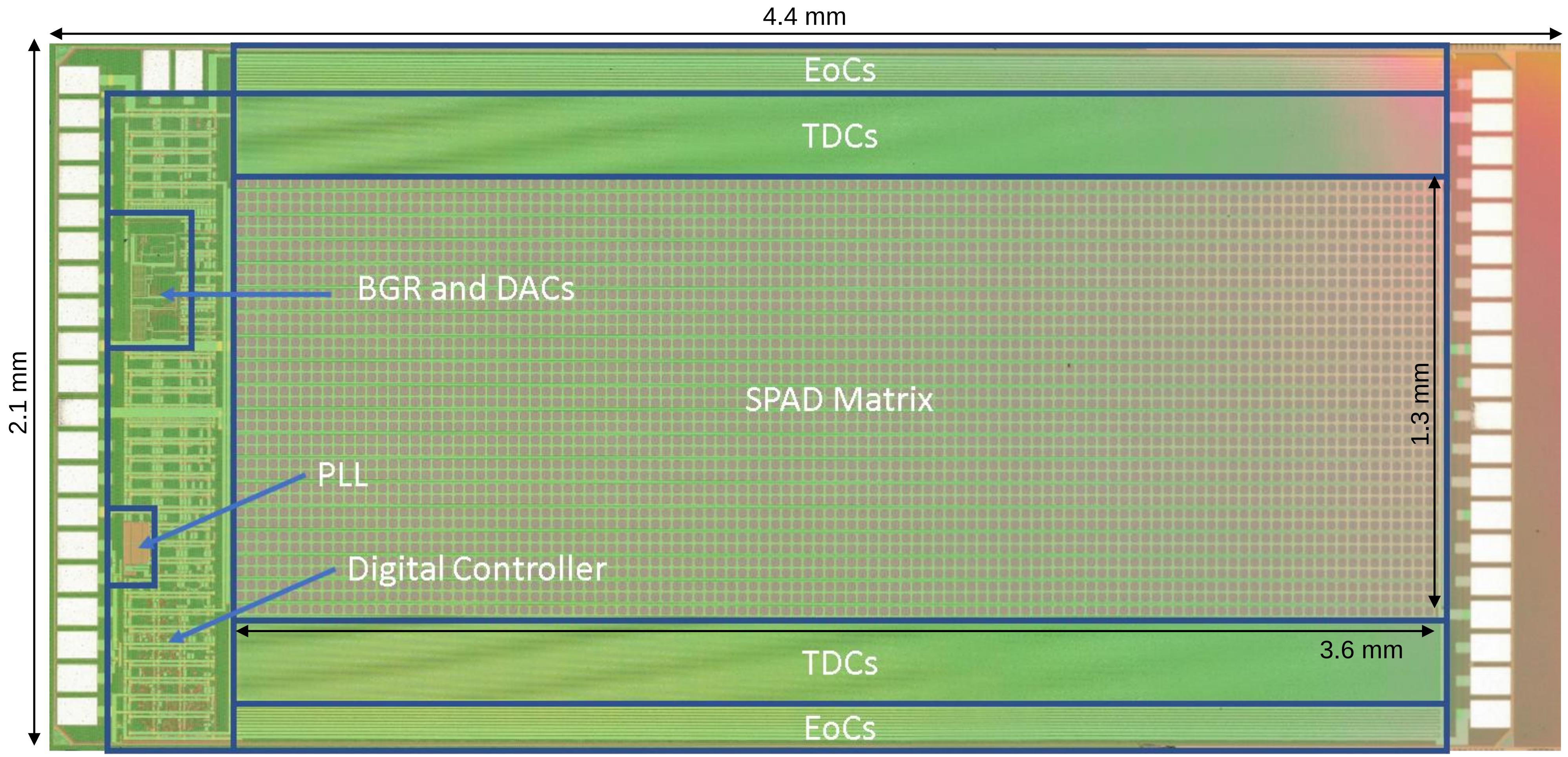
ANDESPix - a Digital SiPM for Muon Detectors



Overview of Top-Level of ANDESPix

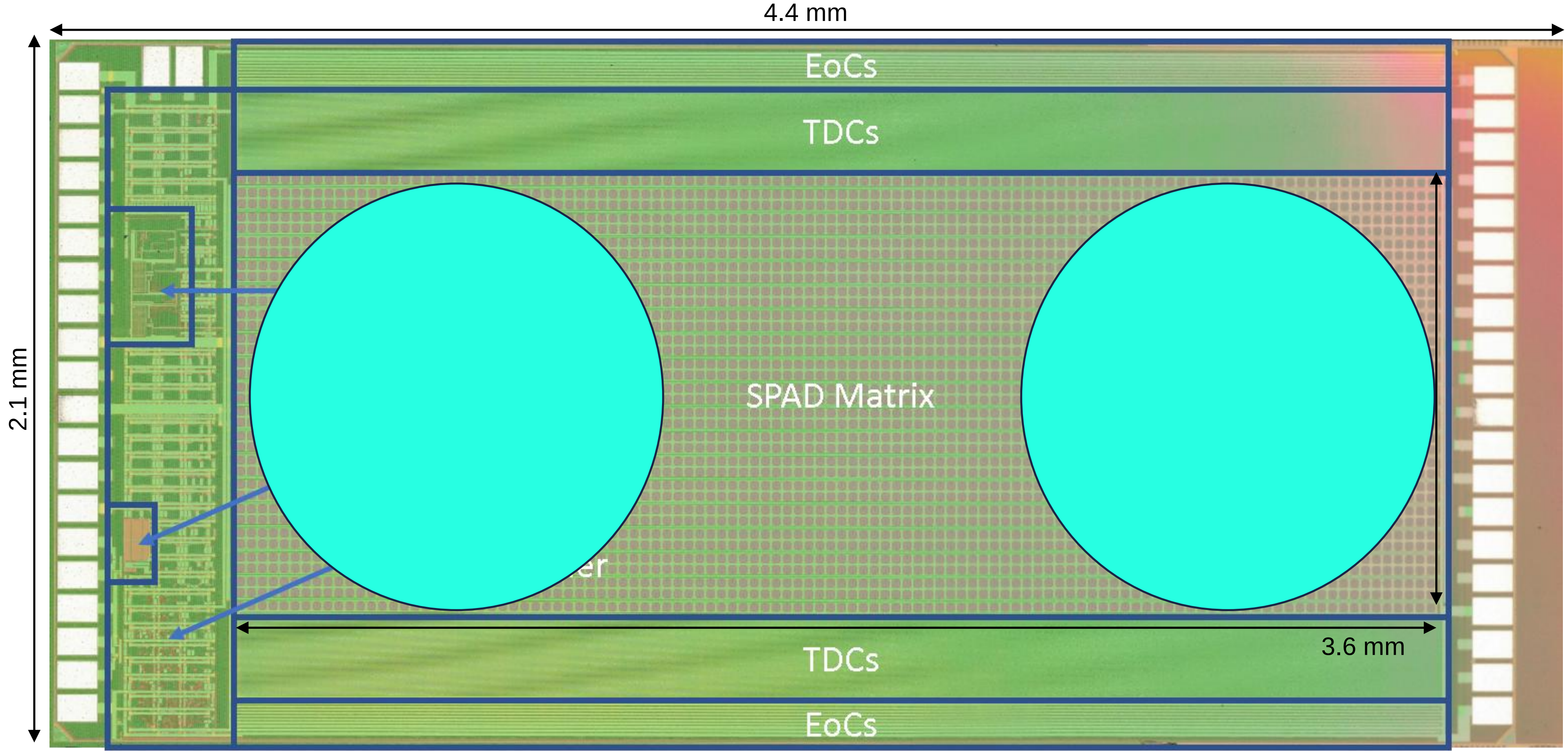
- Technology: LFoundry 110 nm incl. SPAD addon by FBK
- Pixel matrix can host two scintillating fibers
- One time-to-digital converter (TDC) per pixel
- Goal: 100 ps time resolution and high photon-detection efficiency (PDE)

ANDESPix



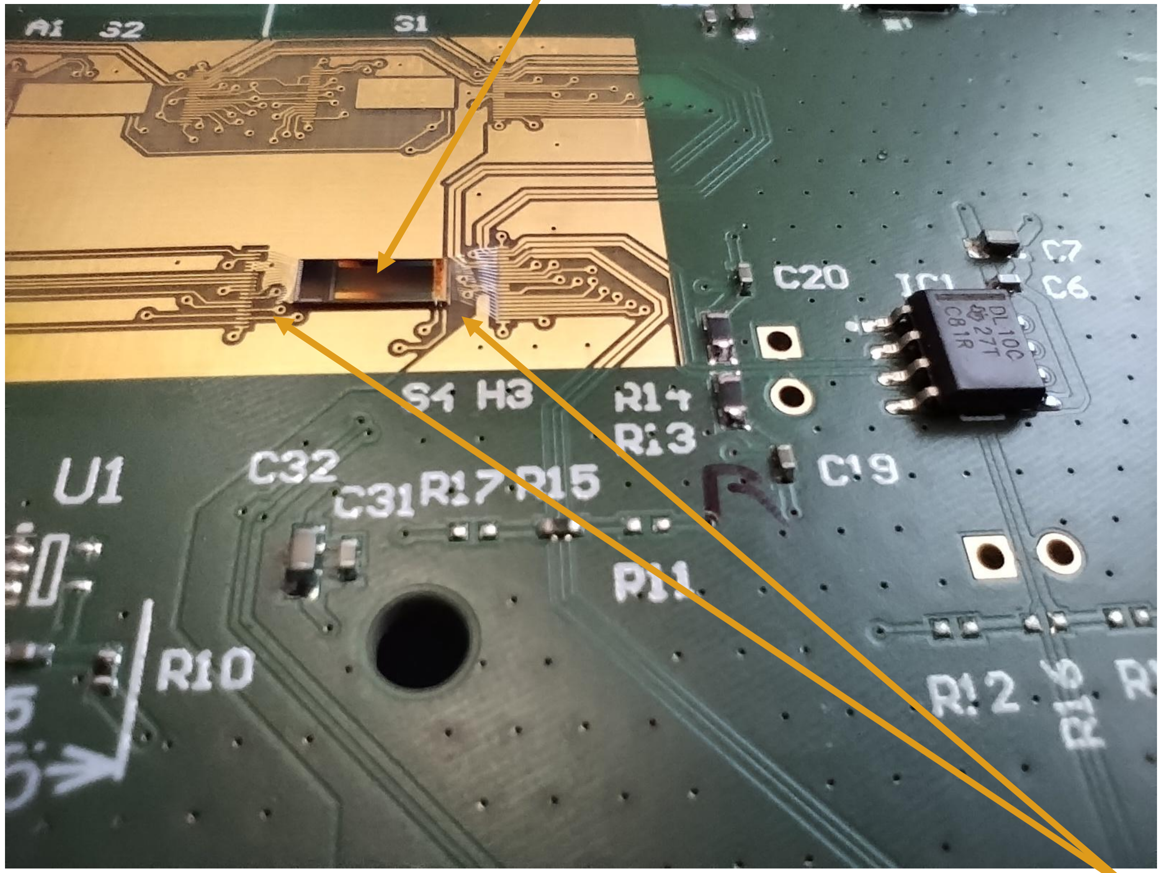
Microscope image of ANDESPix

ANDESPix

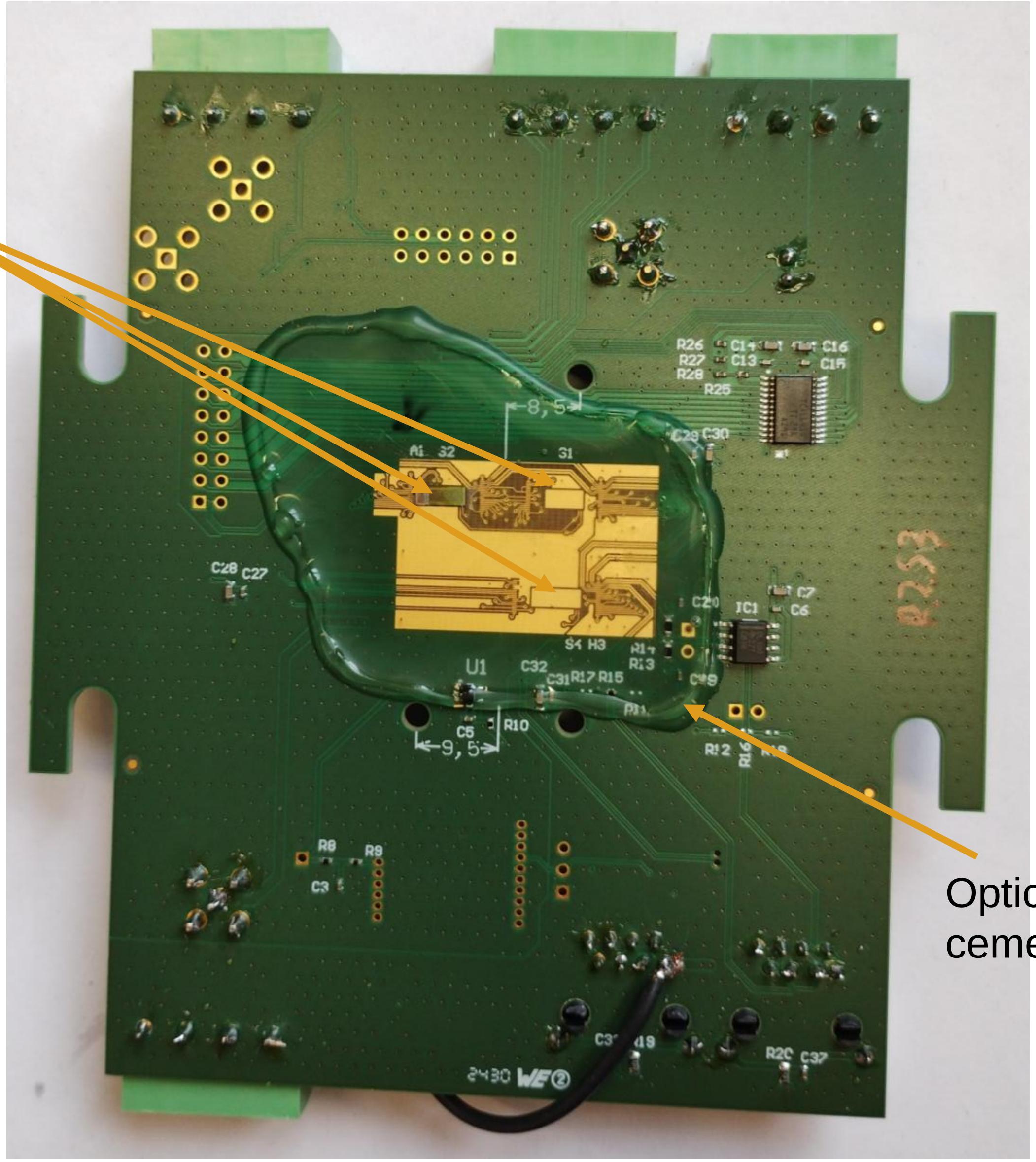


Microscope image of ANDESPix

Test PCB

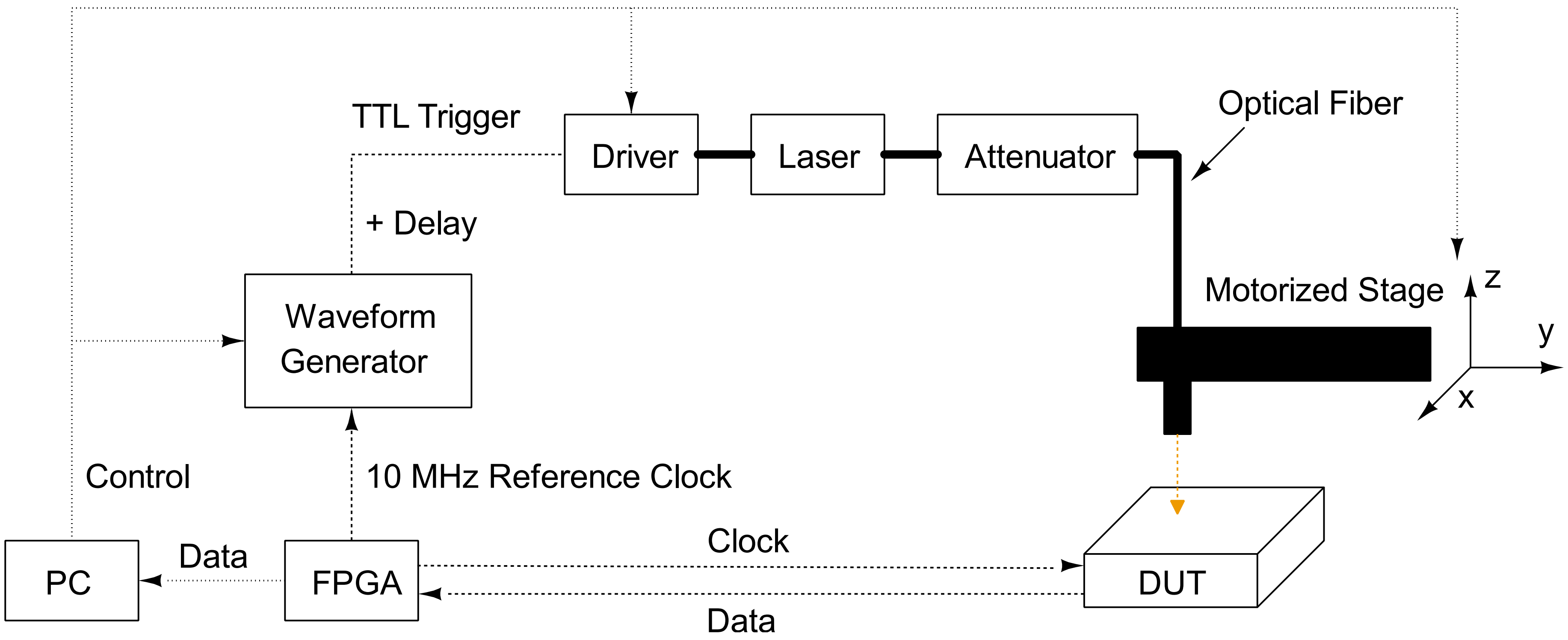


ANDESPix die glued and wirebonded on S4



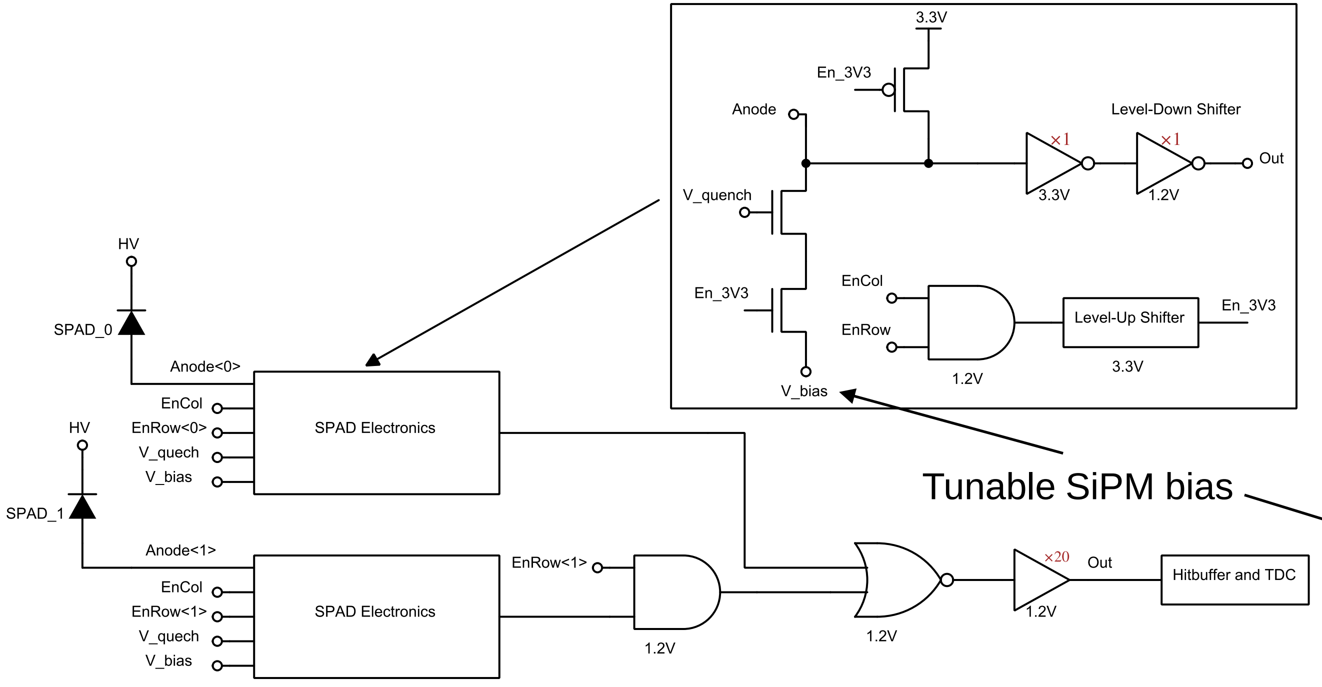
ANDESPix Carrier PCB

Laser Test Setup

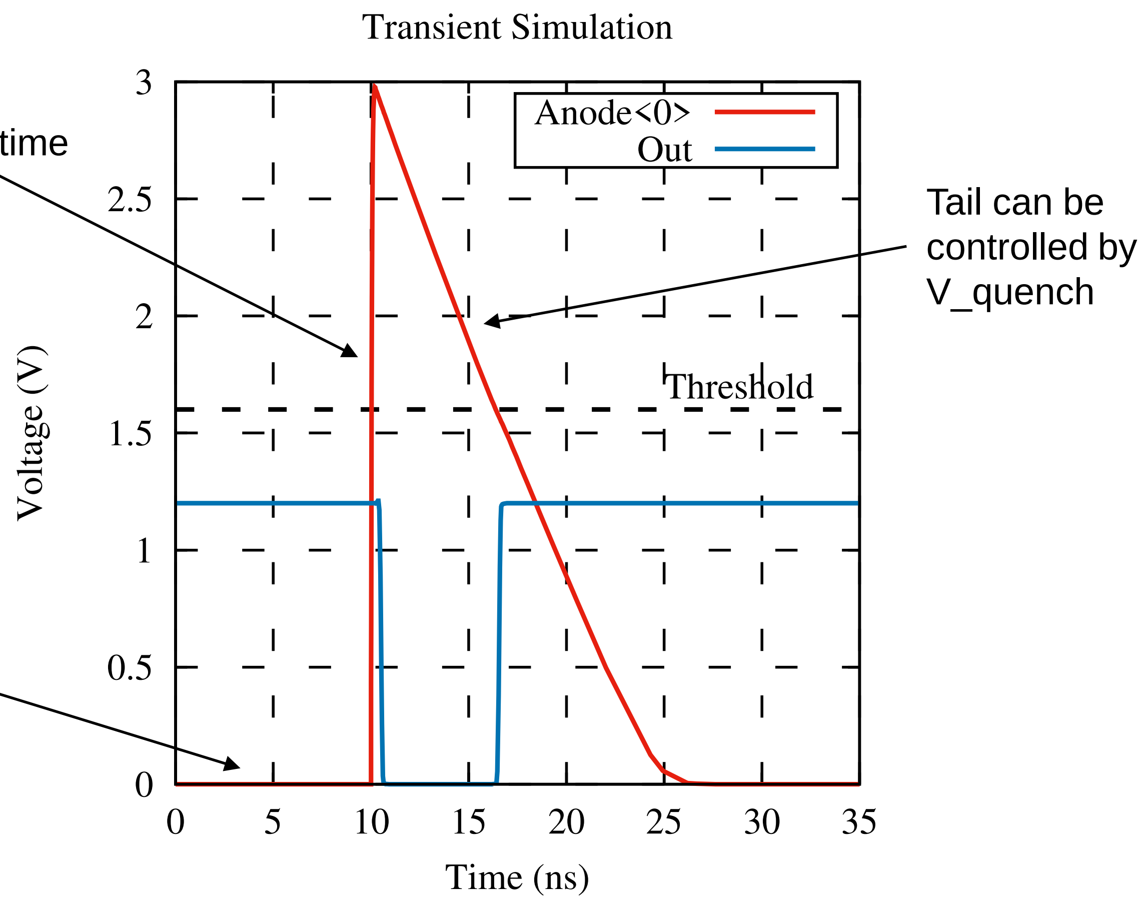


Measurement Setup for timing measurement of DUT (ANDESPix) with laser

Pixel and its Electronics

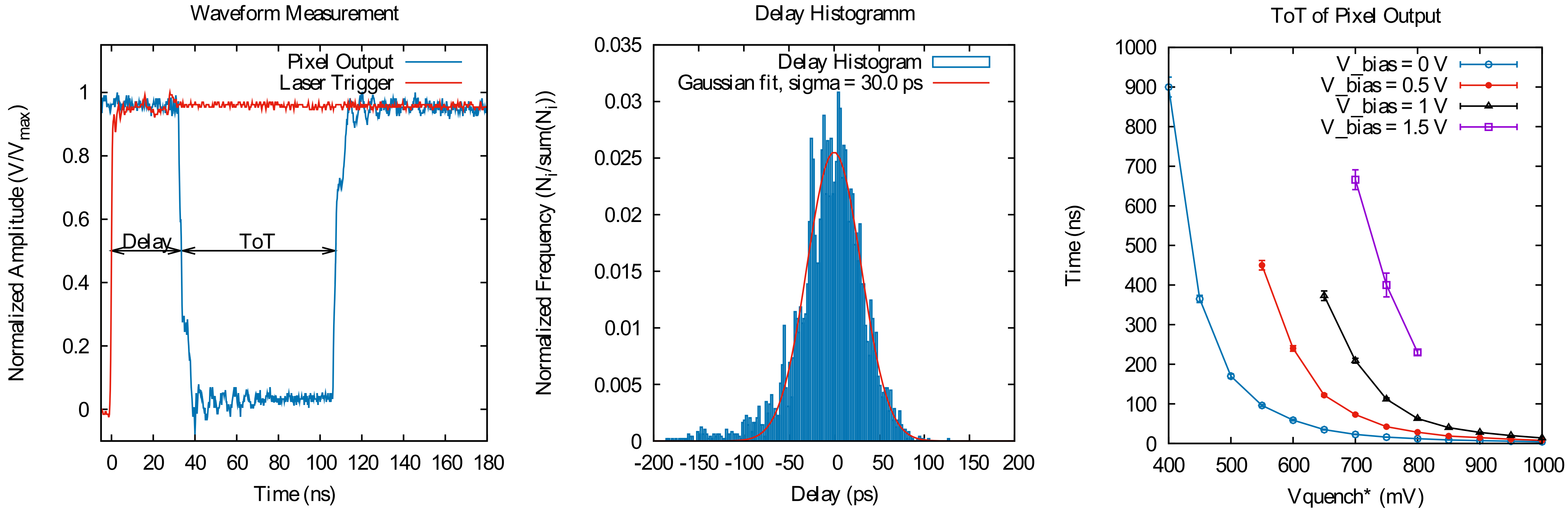


Pixel of ANDESPix



Waveforms when one photon hits SPAD_0

Timing Measurements of pixel



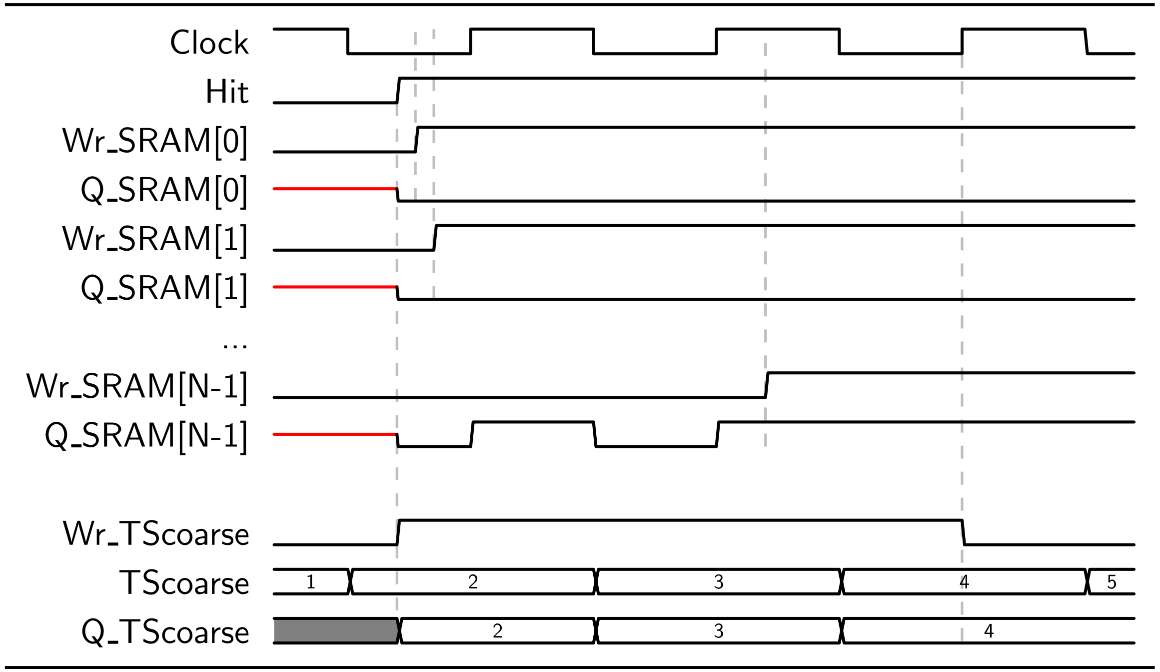
Waveform and time jitter of pixel output pulsed with 904 nm laser   *Time over threshold (ToT) of pixel output*

- Delay between laser trigger and pixel output was measured
  → Time jitter of single pixel << 100 ps

Time-to-Digital Converter (TDC)

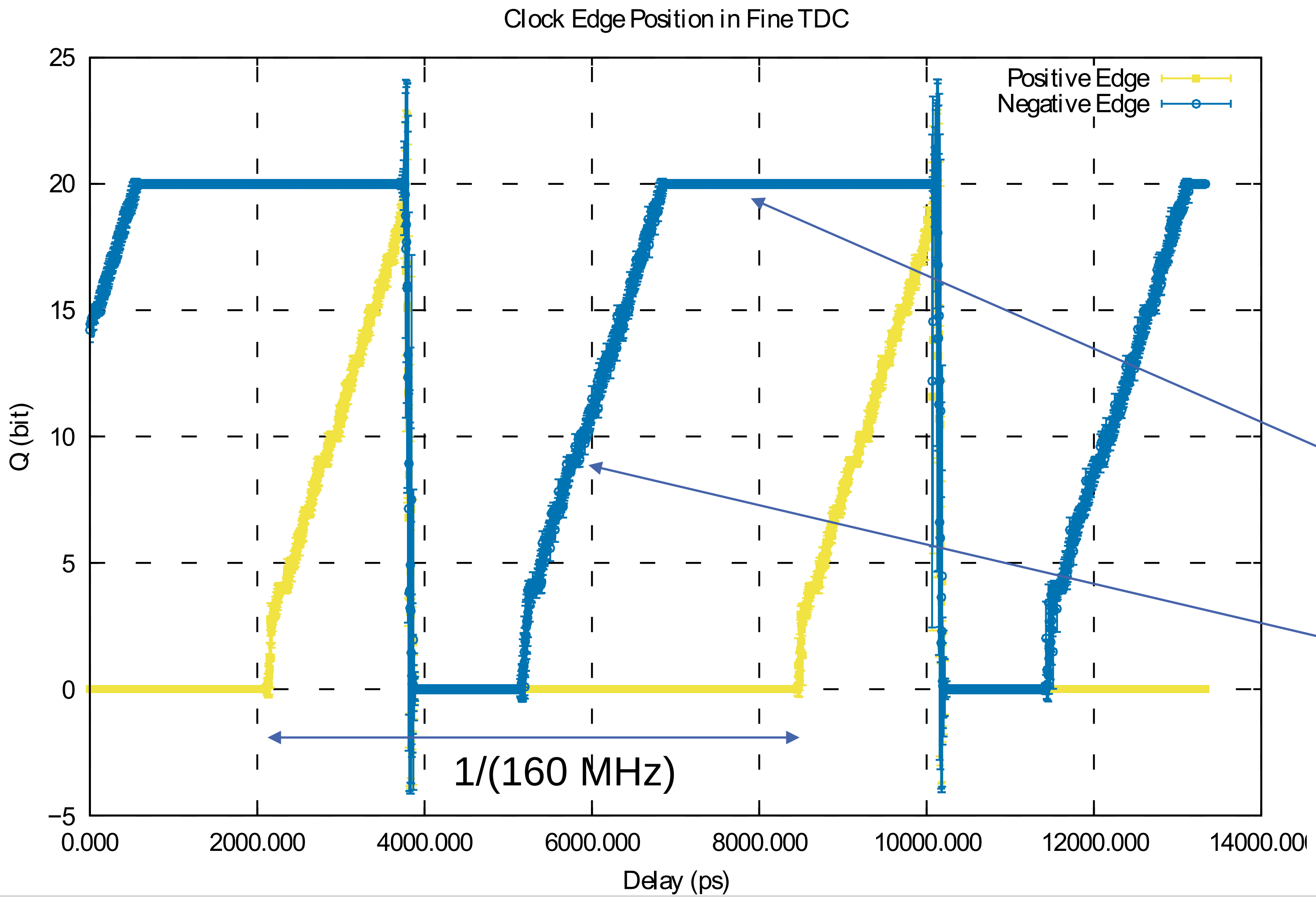
- 8 Transistor SRAM Cell based TDC
- TDC is split in 2 stages:
  - Coarse TDC by global gray-code timestamp counter
  - Fine TDC by delay line
    - Clock is sampled by equally distanced (<100ps) timepoints in phase to hit

    → Time between hit and clock edge can be detected
  - In case clock duty cycle is constant, TDC also works with half clock-cycle



Timing Diagram of TDC

Fine TDC Measurement



- ANDESPix clocked with 160 MHz and test input pulsed with signal generator
- Dead time between both clock edges visible
- Low jitter during clock edge in TDC

Conclusion and Outlook

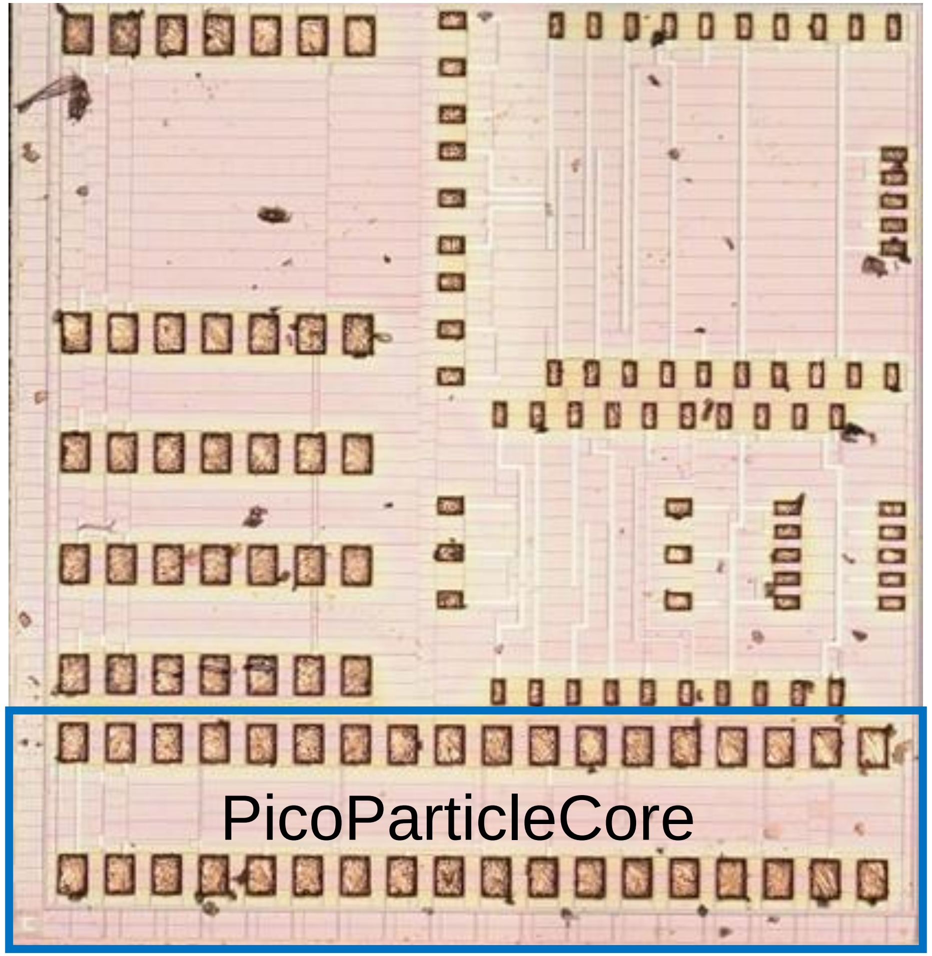
- ANDESPix is assembled on test system
- It is functional and sending data
- Time resolution of pixel is below 100 ps
- TDC Resolution is as excepted
- Further characterization ongoing

2023	2024			2025		2026
ANDESPix Tape Out	Test System Design	Assembly on PCB	First Measurements		Muon Telescope Measurements at ITeDA	
				Timing Measurements		

Today

Backup

The Future: Intel Callisto Test Chip

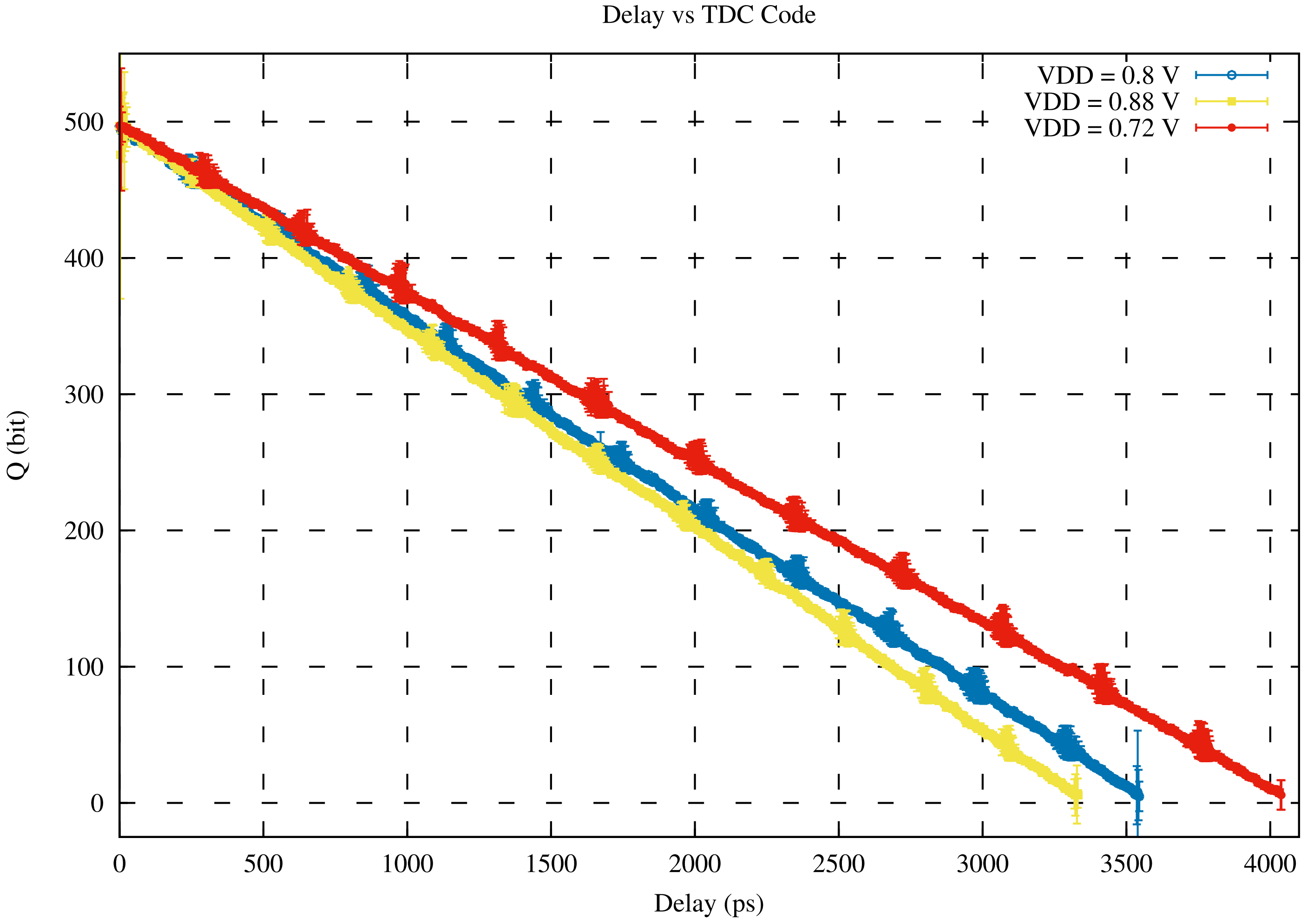


Microscope image of Callisto

- 16 nm Intel FinFET Technology
- University Shuttle Run Chip organized by KIT-INT with different test structures including PicoParticleCore
- TDC with resolution in ~ 10 ps
  - Gated Ring Oscillator based
  - Total Area: (only) 340 μm^2
  - Without Readout Logic: 220 μm^2
- 3D stacked SPAD Sensors with Cu-Cu bonding are becoming feasible
  - Top Tier: SPAD Array in Image Process
  - Bottom Tier: Readout Chip in Advanced Node Technology (e.g. FinFET)

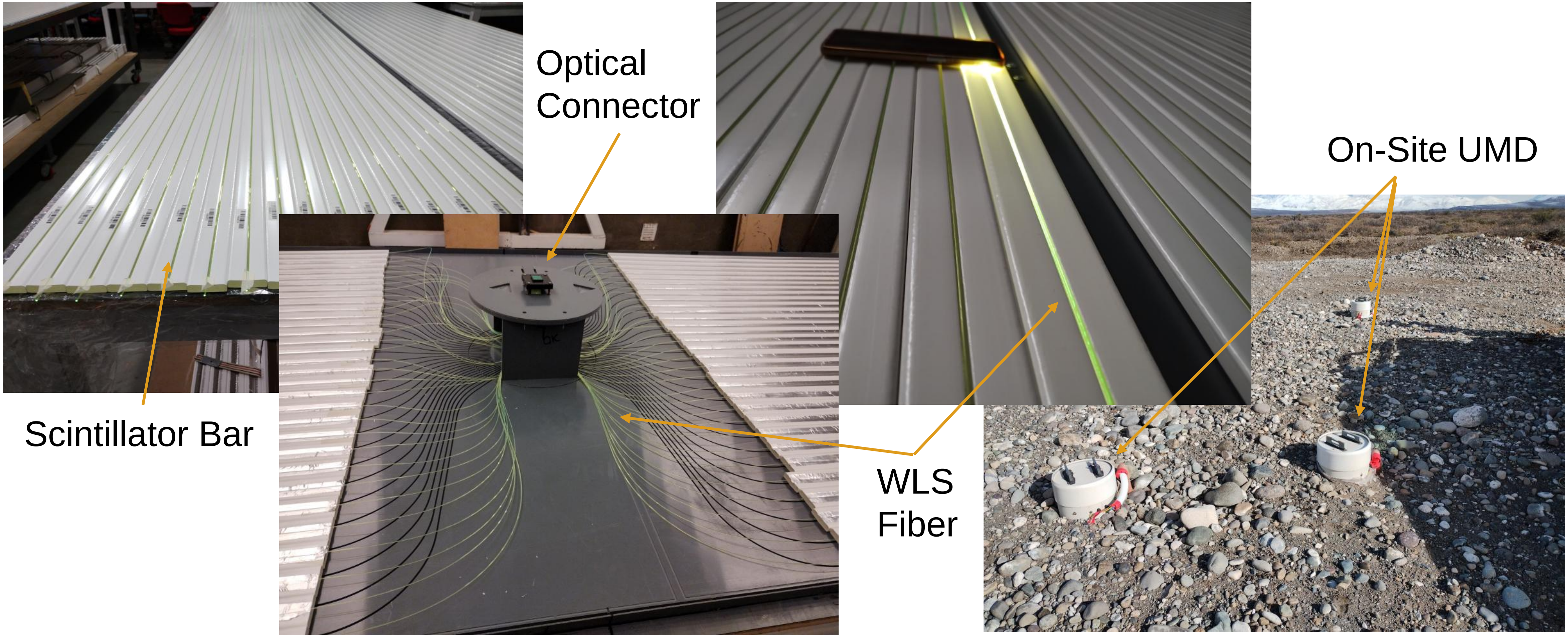
R. K. Henderson *et al.*, "5.7 A 256×256 40nm/90nm CMOS 3D-Stacked 120dB Dynamic-Range Reconfigurable Time-Resolved SPAD Imager," *2019 IEEE International Solid-State Circuits Conference - (ISSCC)*, San Francisco, CA, USA, 2019, pp. 106-108, doi: 10.1109/ISSCC.2019.8662355.

PicoParticleCore TDC Measurement



- LSB is 7.2 ps for VDD = 0.8 V
- Jitter is currently dominated by signal generator

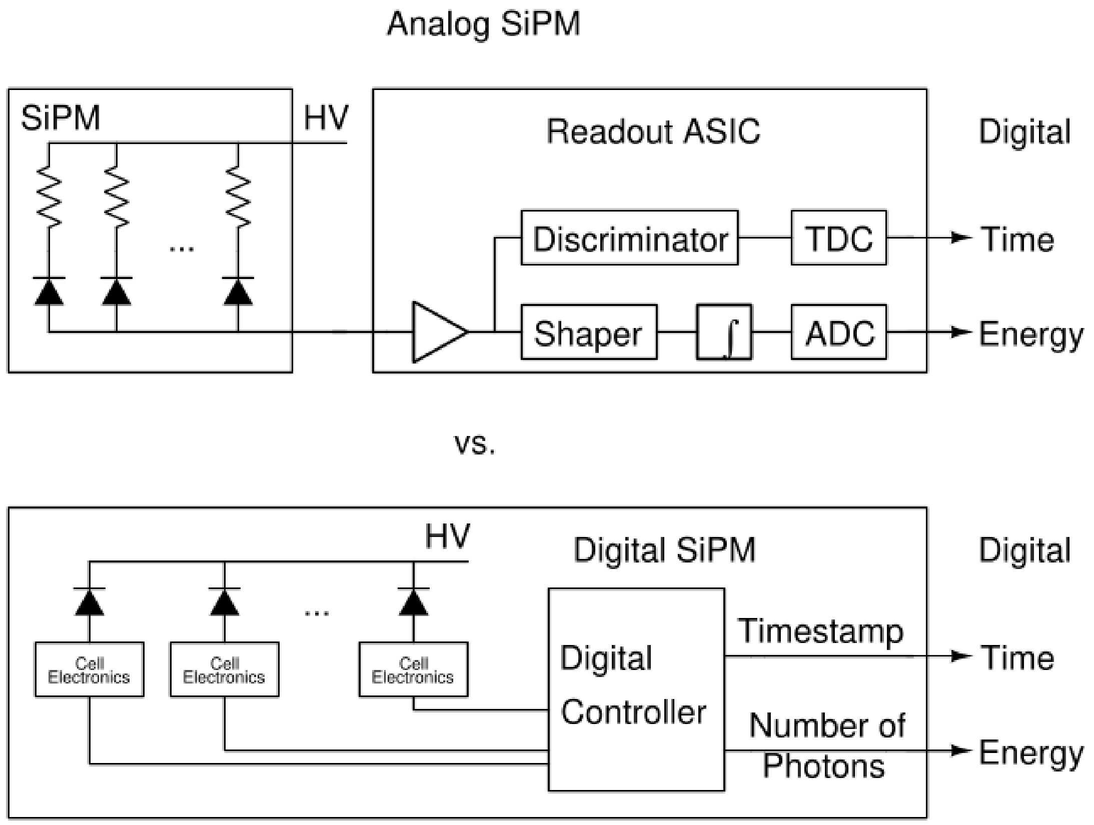
AMIGA Detector Assembly in Malargüe (Argentina)



Thanks to Nicolás Leal, Gustavo Ríos, Gabriel Morales, Agustin Morales, Maximiliano Maciel, Luciana Torres and Nicolás Sepúlveda for the detailed introduction to the detector assembly.

Analog vs. Digital SiPM

- SiPM is an array of Single Photon Avalanche Diodes (SPADs)
- Analog SiPM
  - All SPADs in parallel
  - Signal very small when only one SPAD fires
- Digital SiPM
  - Every SPAD has its own readout
  - Large Signal from firing SPAD
  - Noisy SPADs can be masked

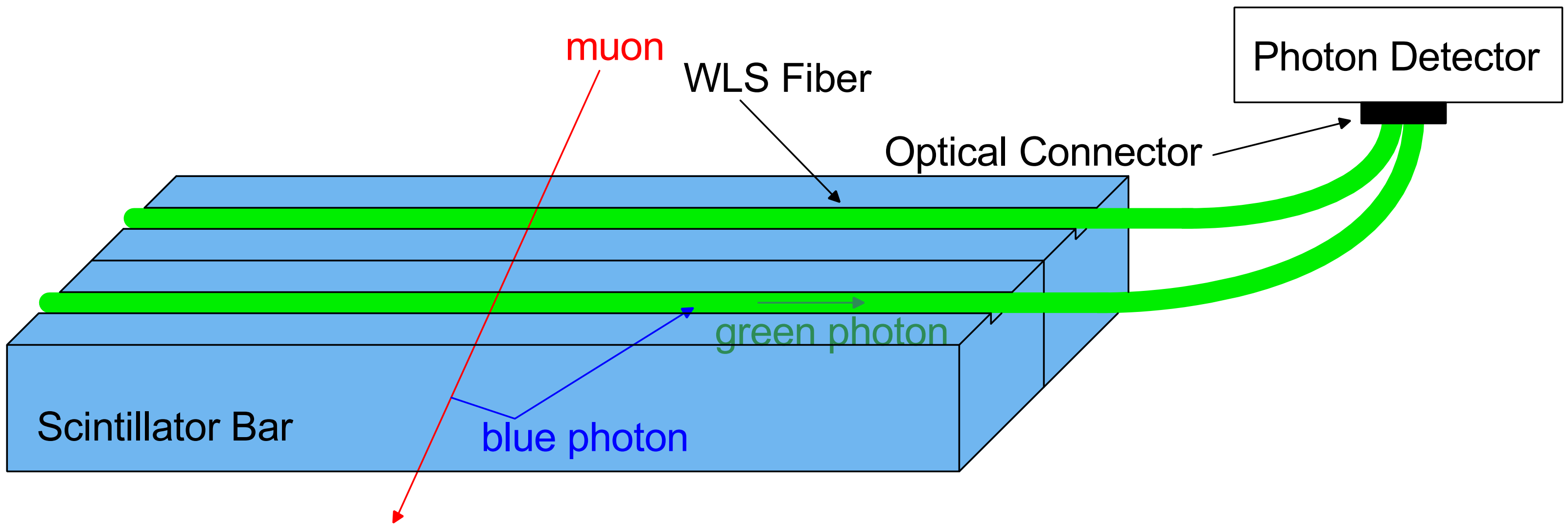


Analog (a) vs. Digital (b) SiPM

T. Frach, G. Prescher, C. Degenhardt, R. de Gruyter, A. Schmitz, and R. Ballizany, "The digital silicon photomultiplier — Principle of operation and intrinsic detector performance," in *2009 IEEE Nuclear Science Symposium Conference Record (NSS/MIC)*, Oct. 2009, pp. 1959–1965. doi: 10.1109/NSSMIC.2009.5402143.

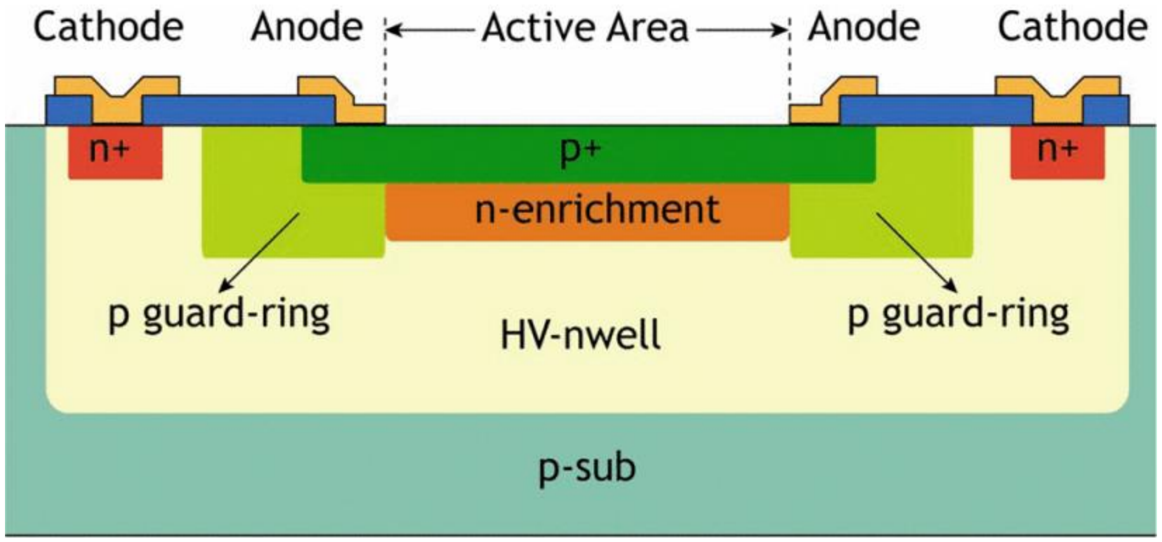
Scintillator Based Muon Detection (e.g. for Muon-Veto in ANDES or Muon Counting in AMIGA)

- Muon generates photons (410 nm/blue) in scintillator
- Photons are absorbed (+re-emitted at 485 nm (green)) by wavelength shifting (WLS) fiber
- Photon Detector (SiPM or PMT) to detect **<50 photons/muon** from fiber

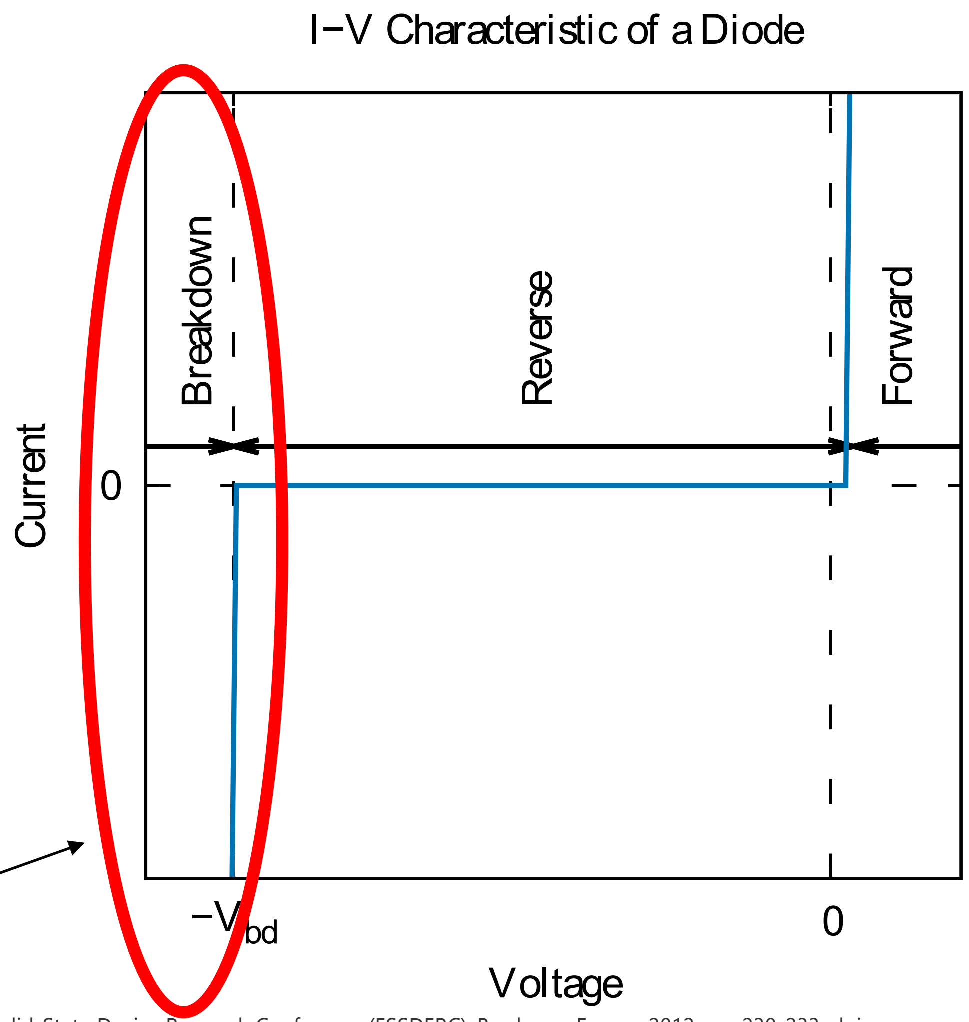


M. Platino et al., “AMIGA at the Auger Observatory: the scintillator module testing system,” J. Inst., vol. 6, no. 06, pp. P06006–P06006, Jun. 2011, doi: 10.1088/1748-0221/6/06/P06006.
A. Aab et al., “Muon counting using silicon photomultipliers in the AMIGA detector of the Pierre Auger observatory,” J. Inst., vol. 12, no.03, pp. P03002–P03002, Mar. 2017, doi: 10.1088/1748-0221/12/03/P03002

Single Photon Avalanche Diodes (SPAD)



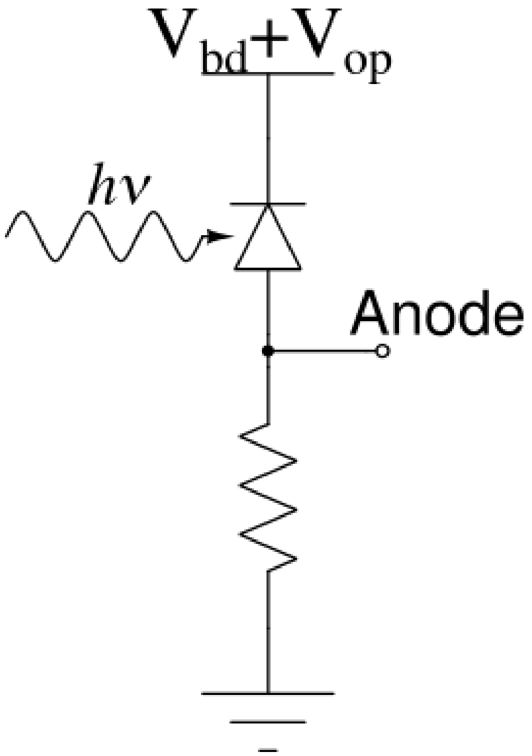
Exemplary Cross Section of a CMOS SPAD



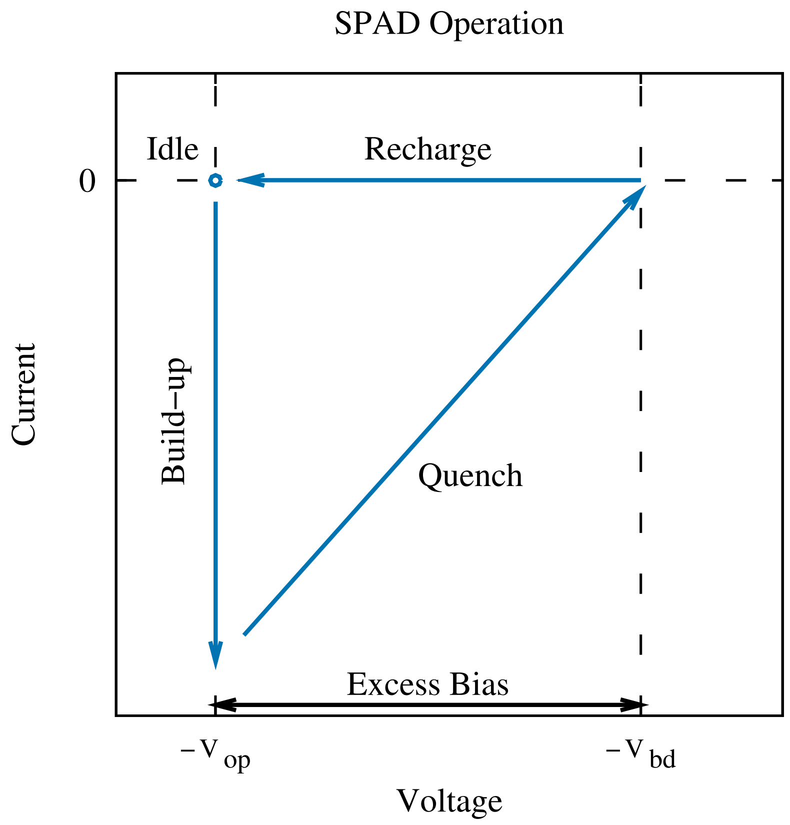
Operation Region

D. Bronzi et al., "Low-noise and large-area CMOS SPADs with timing response free from slow tails," 2012 Proceedings of the European Solid-State Device Research Conference (ESSDERC), Bordeaux, France, 2012, pp. 230-233, doi: 10.1109/ESSDERC.2012.6343375.

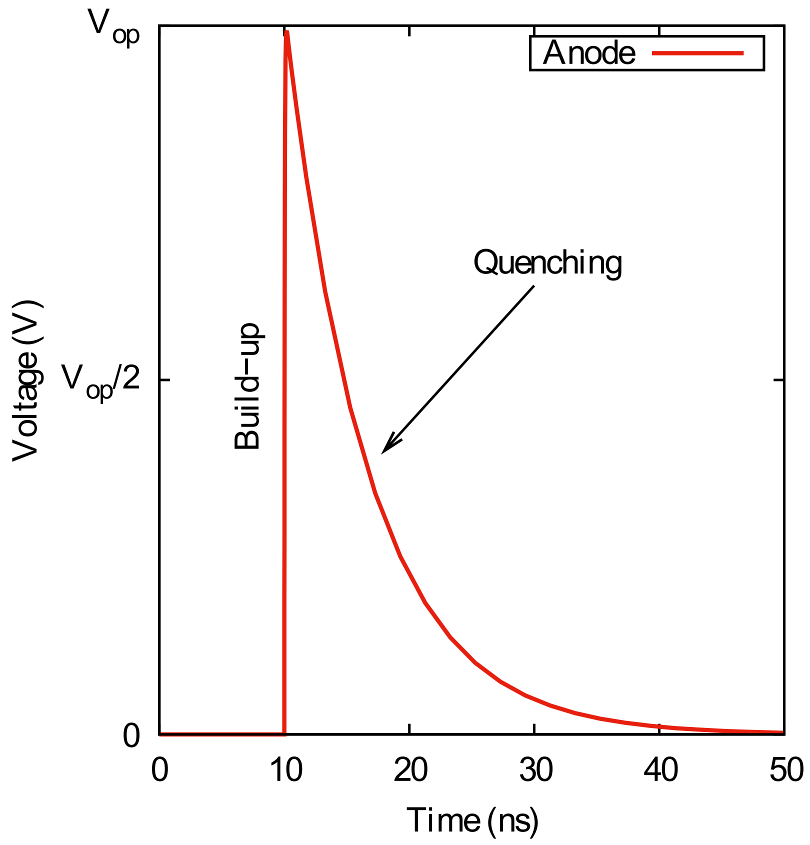
SPAD "Firing" and Quenching



Passive Quenching of SPAD



Operation Cycle



Anode Output

P. Seitz and Albert, Single-Photon Imaging. Springer, 2011.

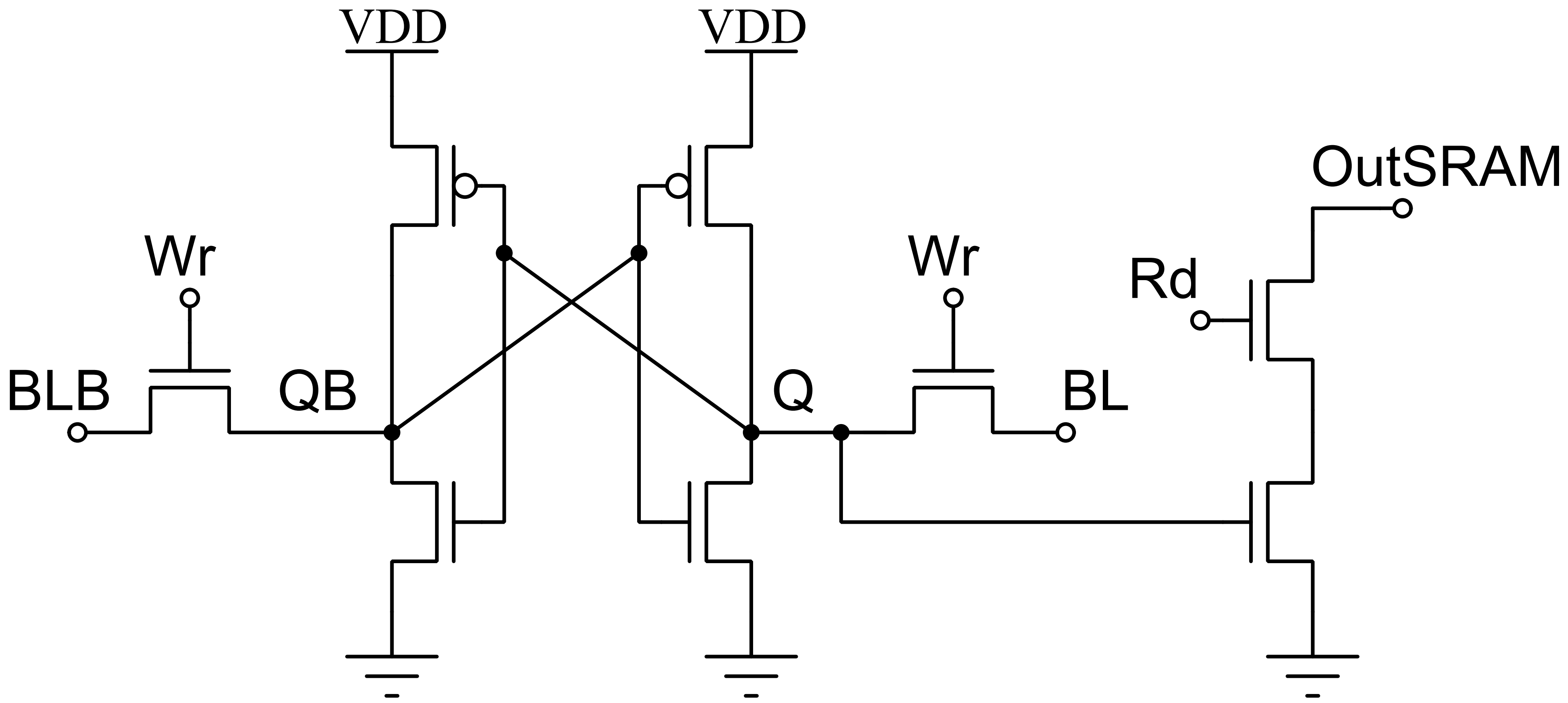
Pixel Data and Digital Readout

- Zero-suppressed priority logic readout with hitbuffers and end of column (EoC) buffers
- Different readout modes possible
  - Asynchronous mode: read all hits all the time
  - Synchronous mode: read a certain amount of hits in a certain time frame, discard remaining
  - Self-triggered mode: only read data if internal threshold number of columns with hits is passed

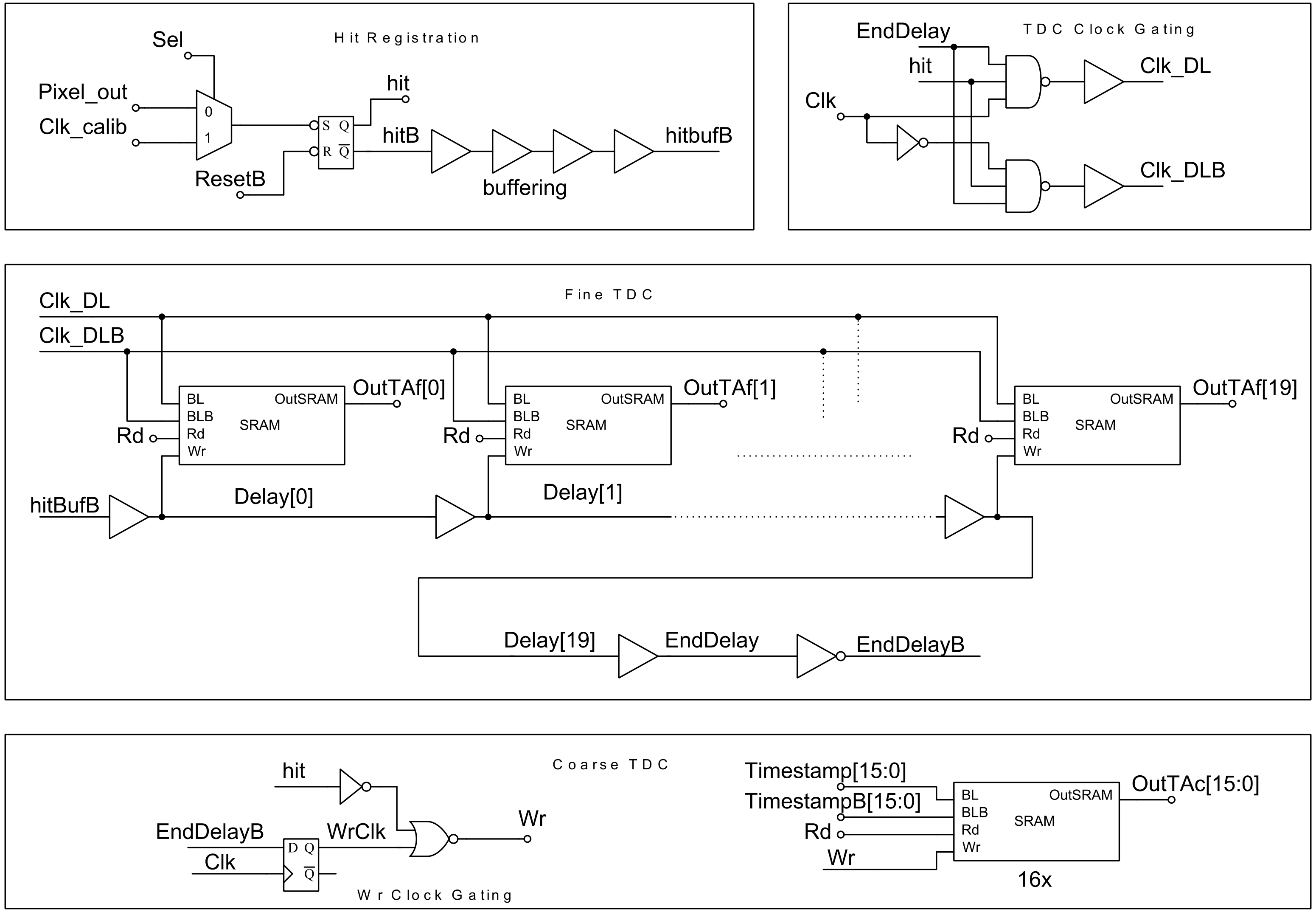
Name	Size (Bit)	Description
AddrCol	7	Column Address
AddrRow	6	Row Address
ToAc	16	Time of Arrival Coarse
ToAf	20	Time of Arrival Fine
Cnt	3	Hit Counter Value
ToT	6	Time over Threshold

Data per pixel (58 bit)

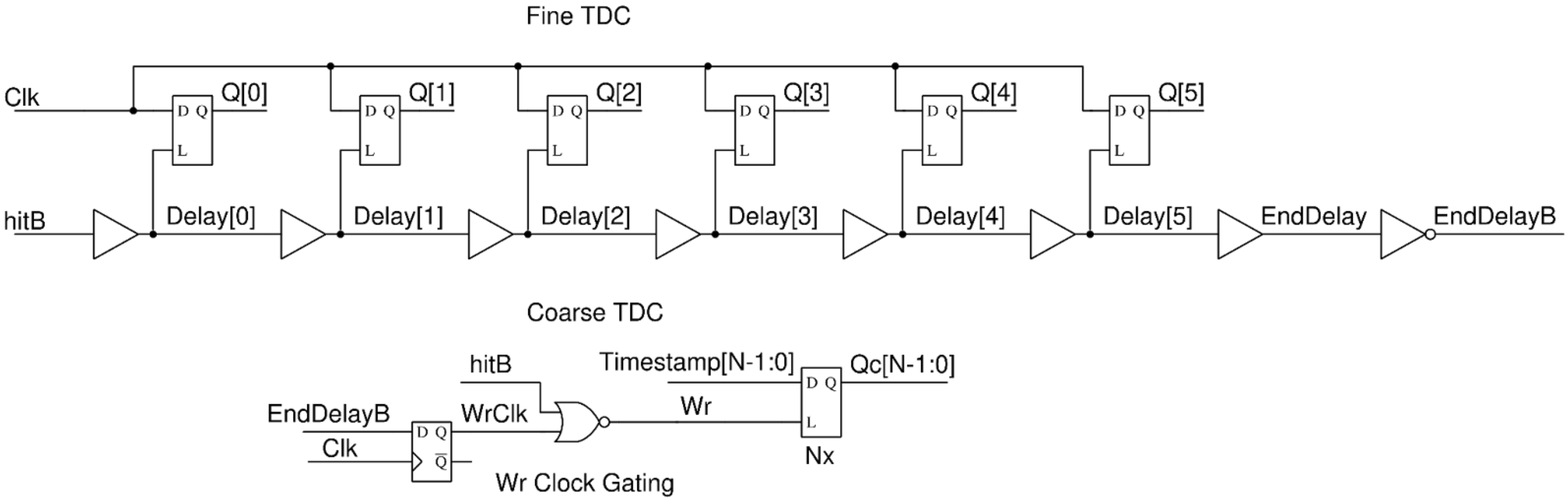
8T SRAM Cell



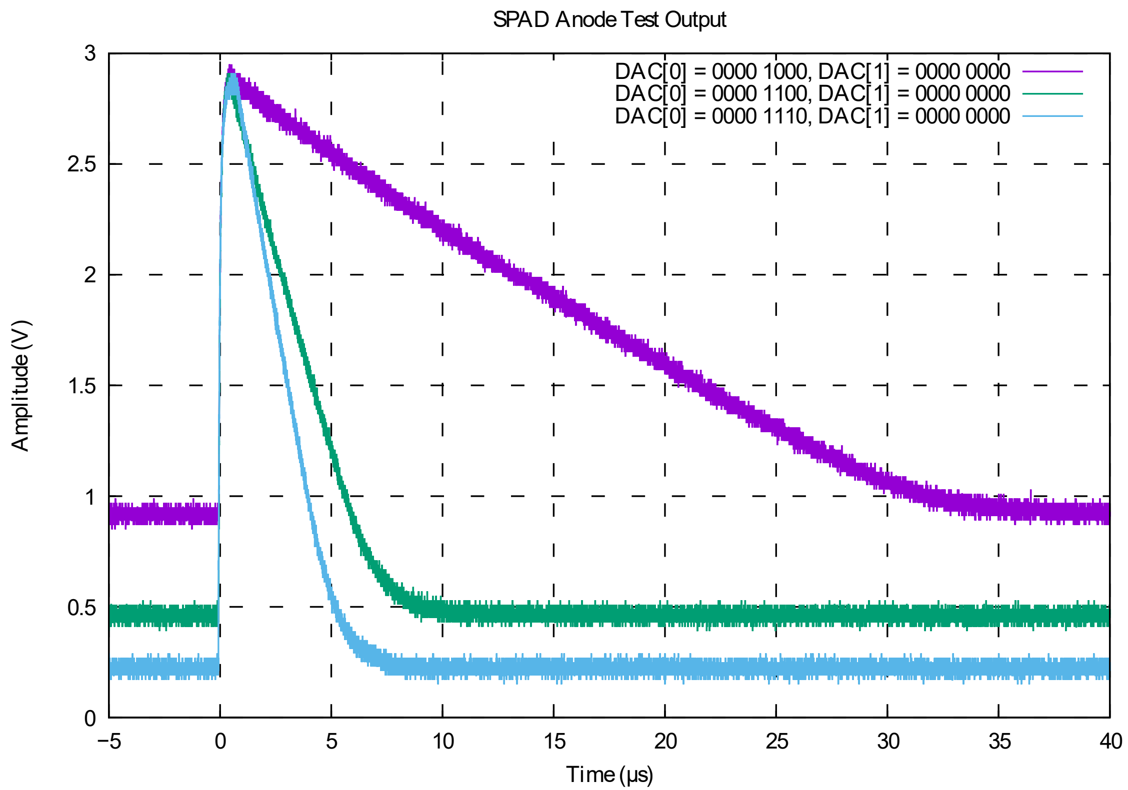
TDC

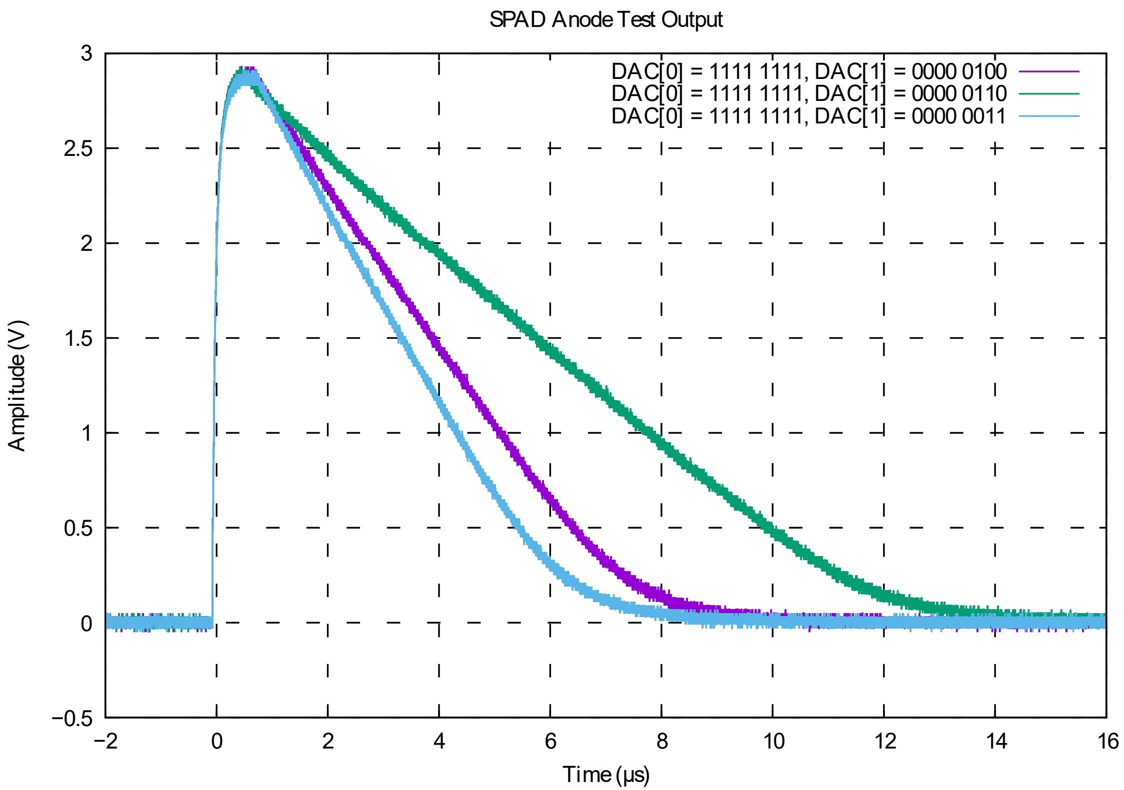

Hit Registration
Sel
Pixel_out
Clk_calib
0
1
S Q
R Q̄
hit
hitB
ResetB
buffering
hitbufB
TDC Clock Gating
EndDelay
hit
Clk
Clk_DL
Clk_DLB
Fine TDC
Clk_DL
Clk_DLB
BL
BLB
Rd
Wr
OutSRAM
SRAM
OutTAf[0]
OutTAf[1]
OutTAf[19]
Rd
hitBufB
Delay[0]
Delay[1]
Delay[19]
EndDelay
EndDelayB
Coarse TDC
hit
EndDelayB
Clk
D Q
Q̄
WrClk
Wr
Wr Clock Gating
Timestamp[15:0]
TimestampB[15:0]
Rd
Wr
OutTAc[15:0]
16x

TDC simplified



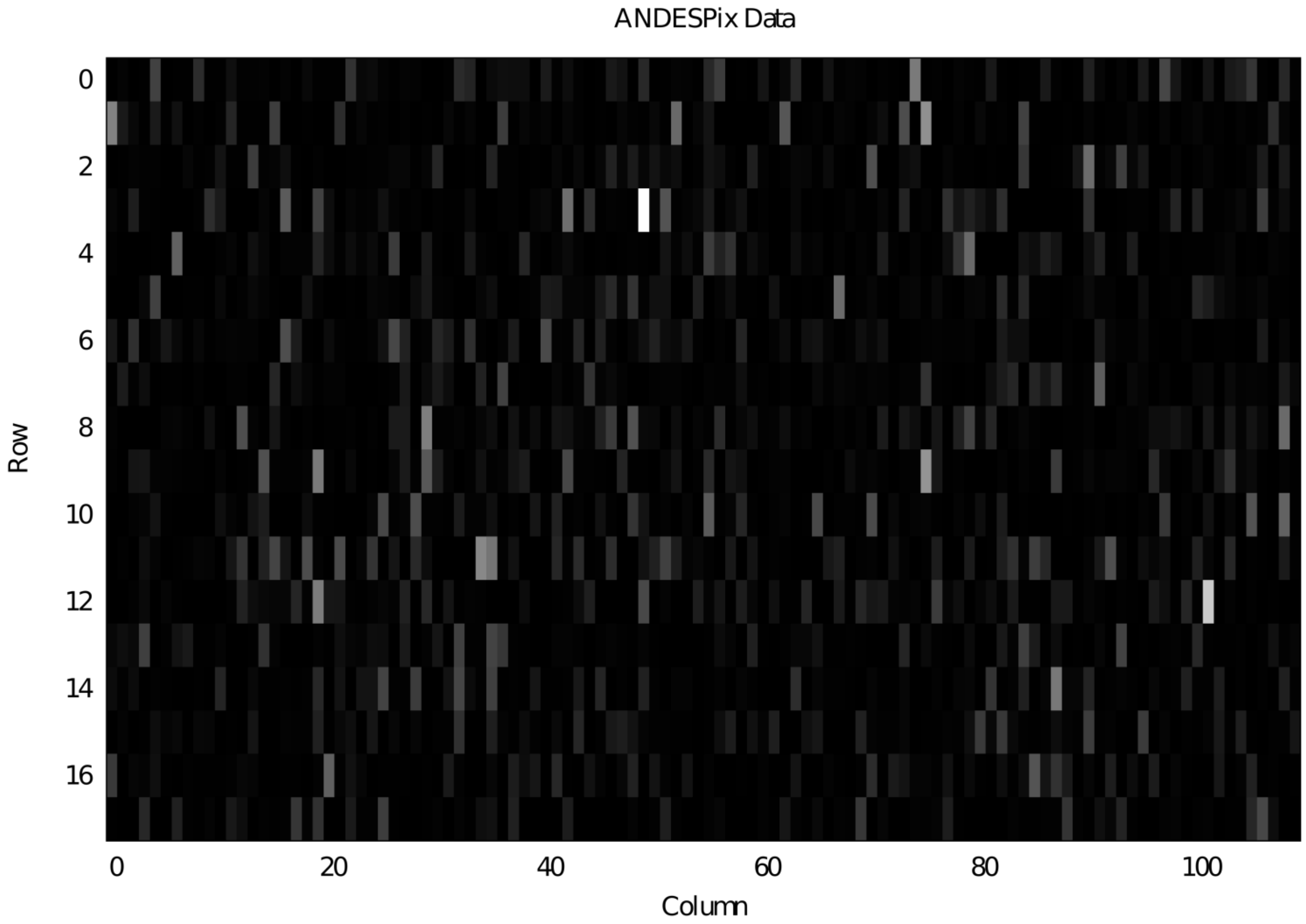
Test SPAD Waveforms





SPAD Anode Signal Measured by Oscilloscope with ~100 pF Load for Different DAC Settings

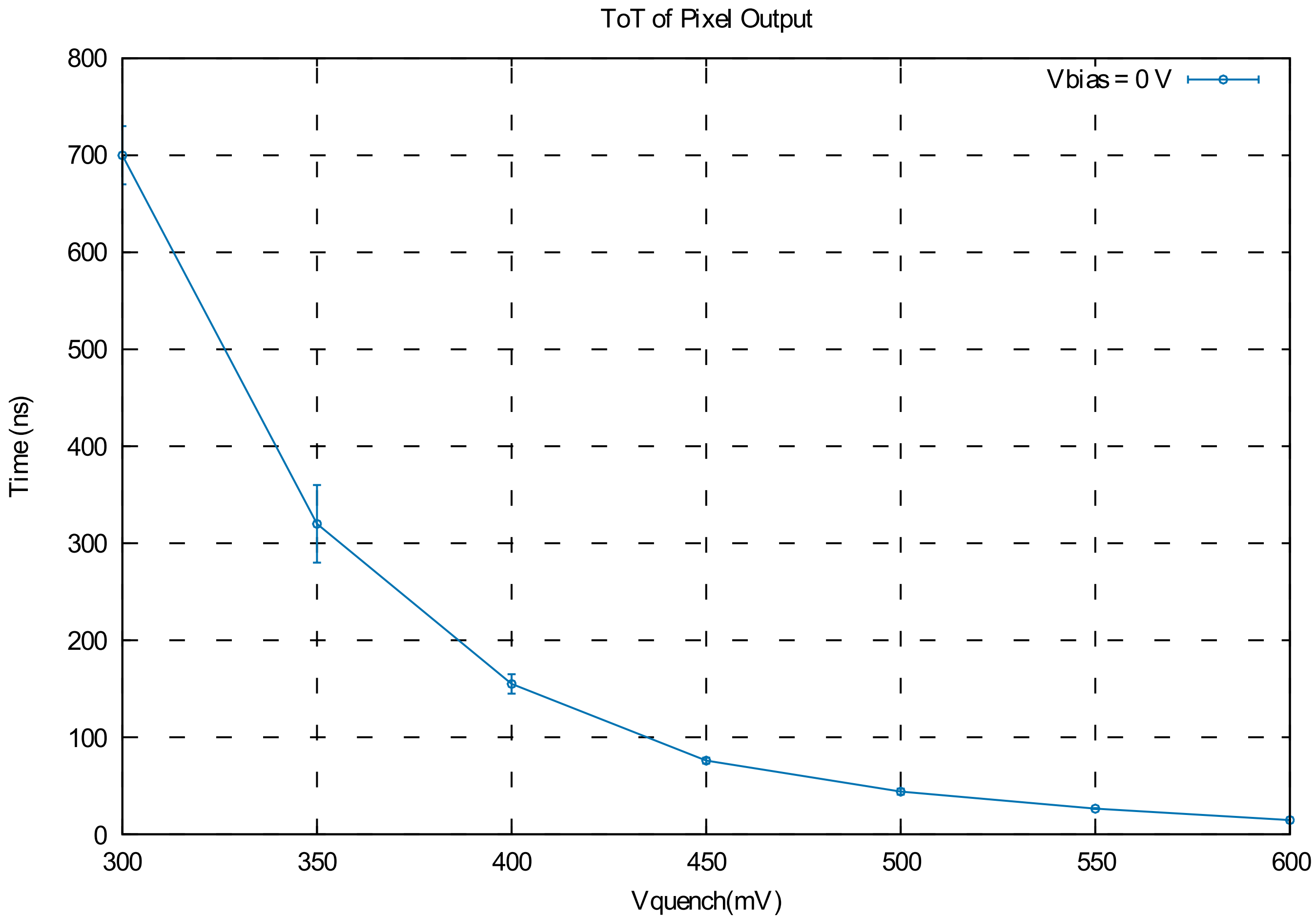
Relative Dark Count Rate (DCR) Measurement



Pixel by pixel DCR measurement of ANDESPix

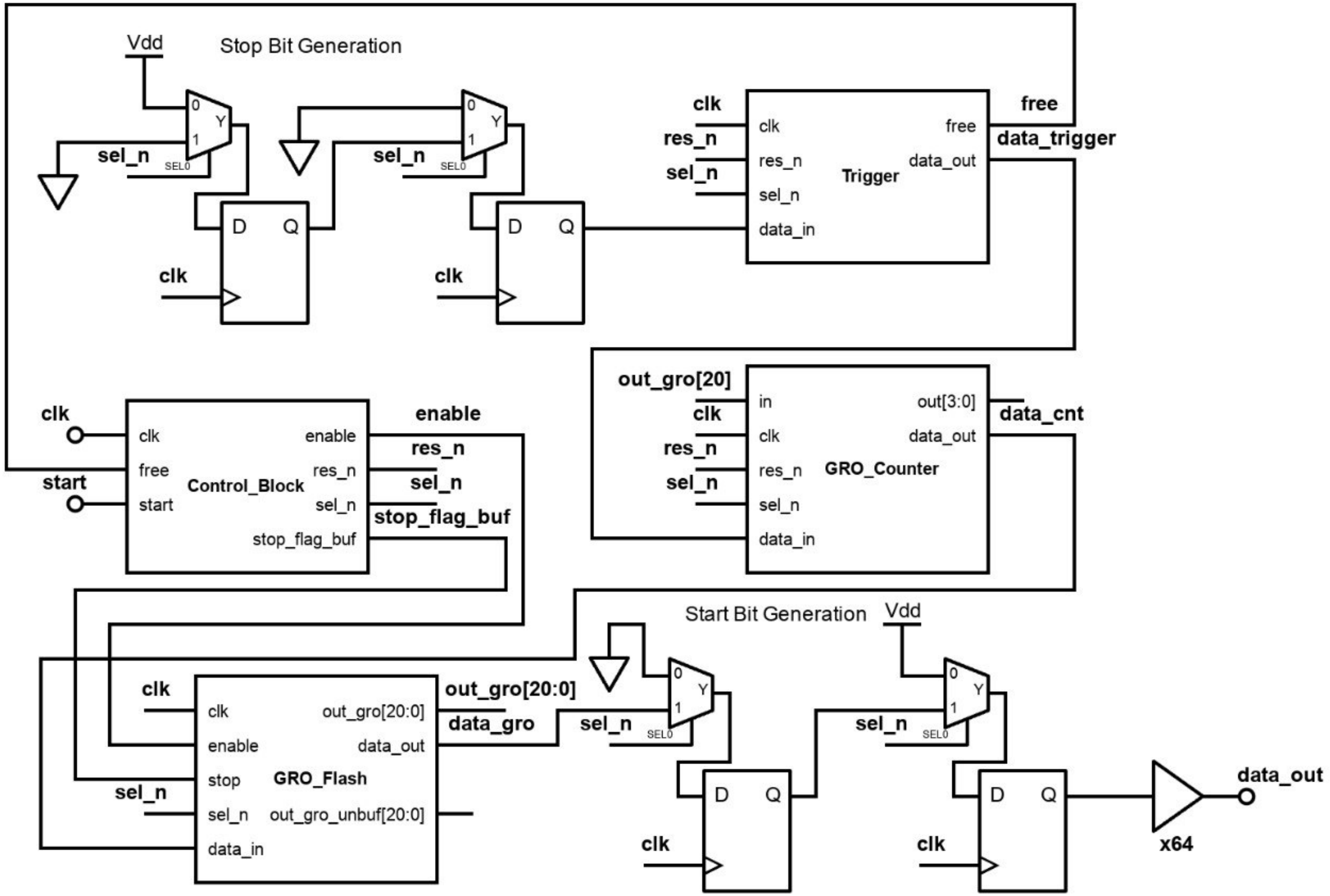
- Dark counts are avalanches that are not triggered by a photon
- Dark Count Rate
  - ~100 Hz per SPAD
  - varies between pixels
- Possibility to disable noisy pixels
  - Important for low detection threshold of muons

Time over Threshold



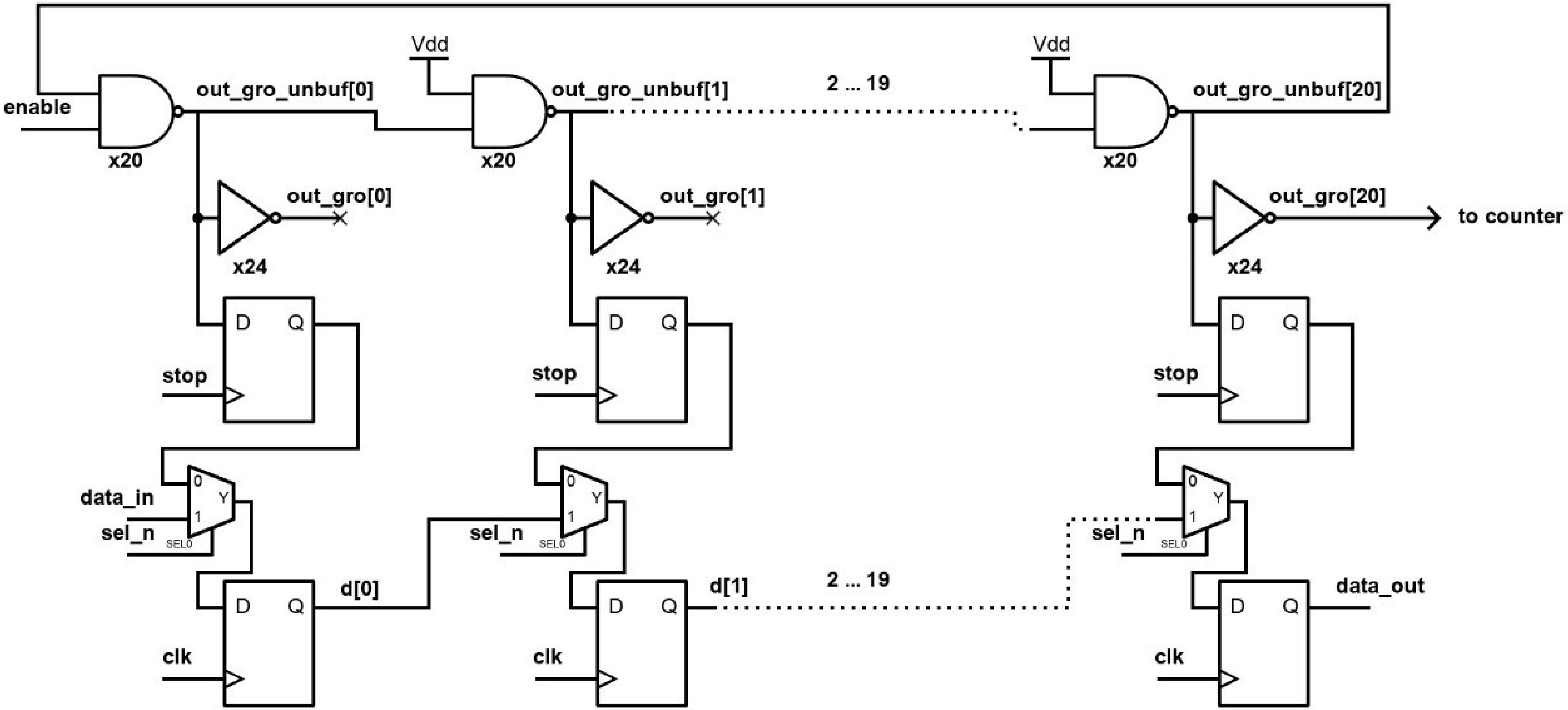
Test structure measurement for ToT, it saturates at roughly 15 ns

16 nm TDC



Stop Bit Generation
Vdd
sel_n
sel_n
clk
clk
clk
res_n
sel_n
clk
res_n
sel_n
data_in
free
data_out
Trigger
free
data_trigger
out_gro[20]
clk
res_n
sel_n
in
clk
res_n
sel_n
data_in
out[3:0]
data_out
GRO_Counter
data_cnt
clk
start
clk
free
start
Control_Block
enable
res_n
sel_n
stop_flag_buf
enable
res_n
sel_n
stop_flag_buf
Start Bit Generation
Vdd
clk
sel_n
clk
enable
stop
sel_n
data_in
GRO_Flash
out_gro[20:0]
data_out
out_gro_unbuf[20:0]
out_gro[20:0]
data_gro
sel_n
sel_n
clk
clk
x64
data_out

16 nm GRO



enable
x20
out_gro_unbuf[0]
Vdd
x20
out_gro_unbuf[1]
2 ... 19
Vdd
x20
out_gro_unbuf[20]
out_gro[0]
x24
out_gro[1]
x24
out_gro[20]
to counter
x24
D
Q
stop
D
Q
stop
D
Q
stop
data_in
0
1
Y
sel_n
SEL0
sel_n
sel_n
d[0]
d[1]
2 ... 19
data_out
clk
clk
clk

16 nm Counter