UNIVERSITAT DE BARCELONA

Geiger mode avalanche photodiodes in particle detection

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➢ Outline

➢ Introduction

- Our GAPDs timeline
- Available technologies
- Test beam program

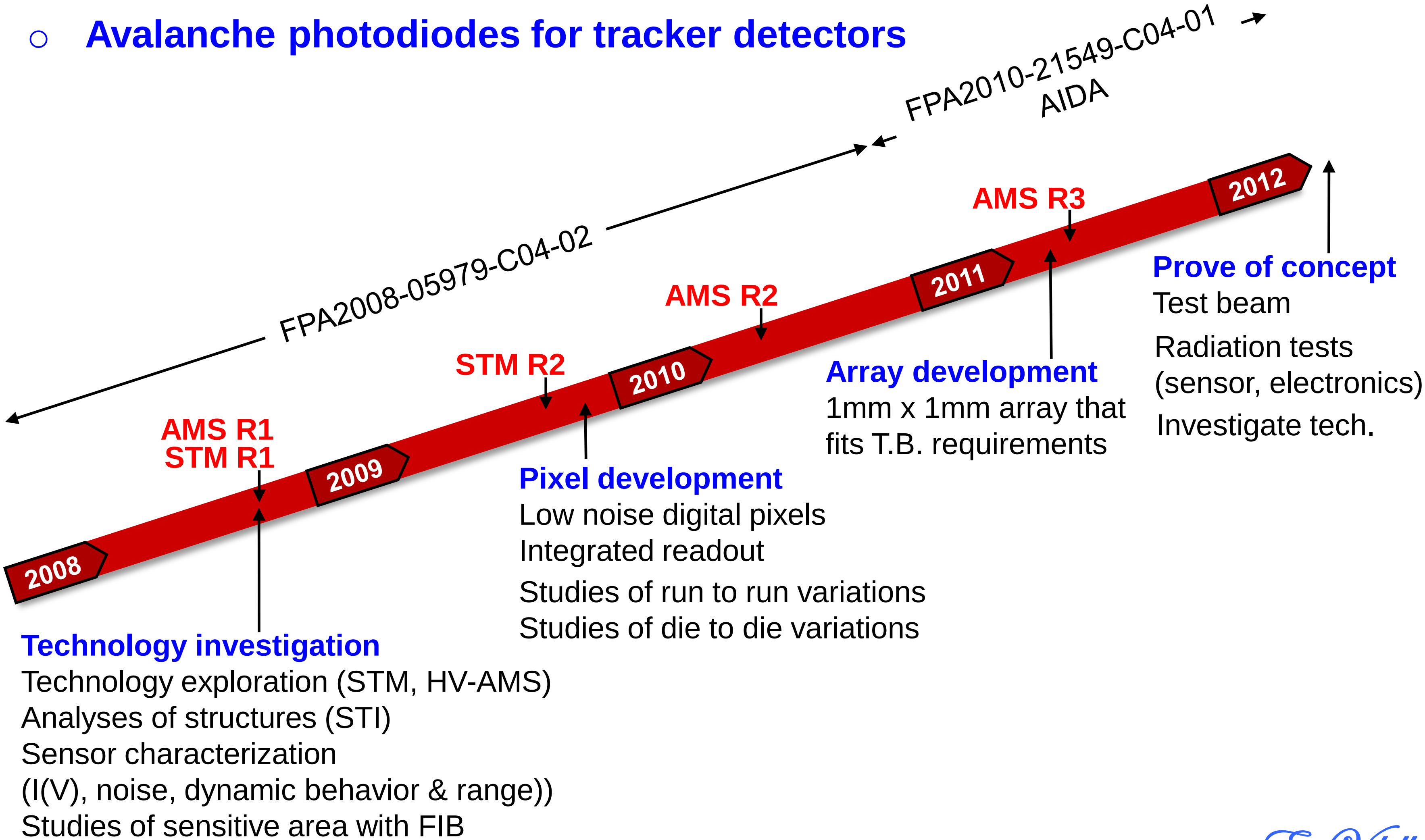
➢ 1mm x 1mm GAPD array

- FLC_APD_v1
- Pixel schematic
- Gated operation
- Results

➢ Conclusions

Our GAPDs timeline

- **Avalanche photodiodes for tracker detectors**



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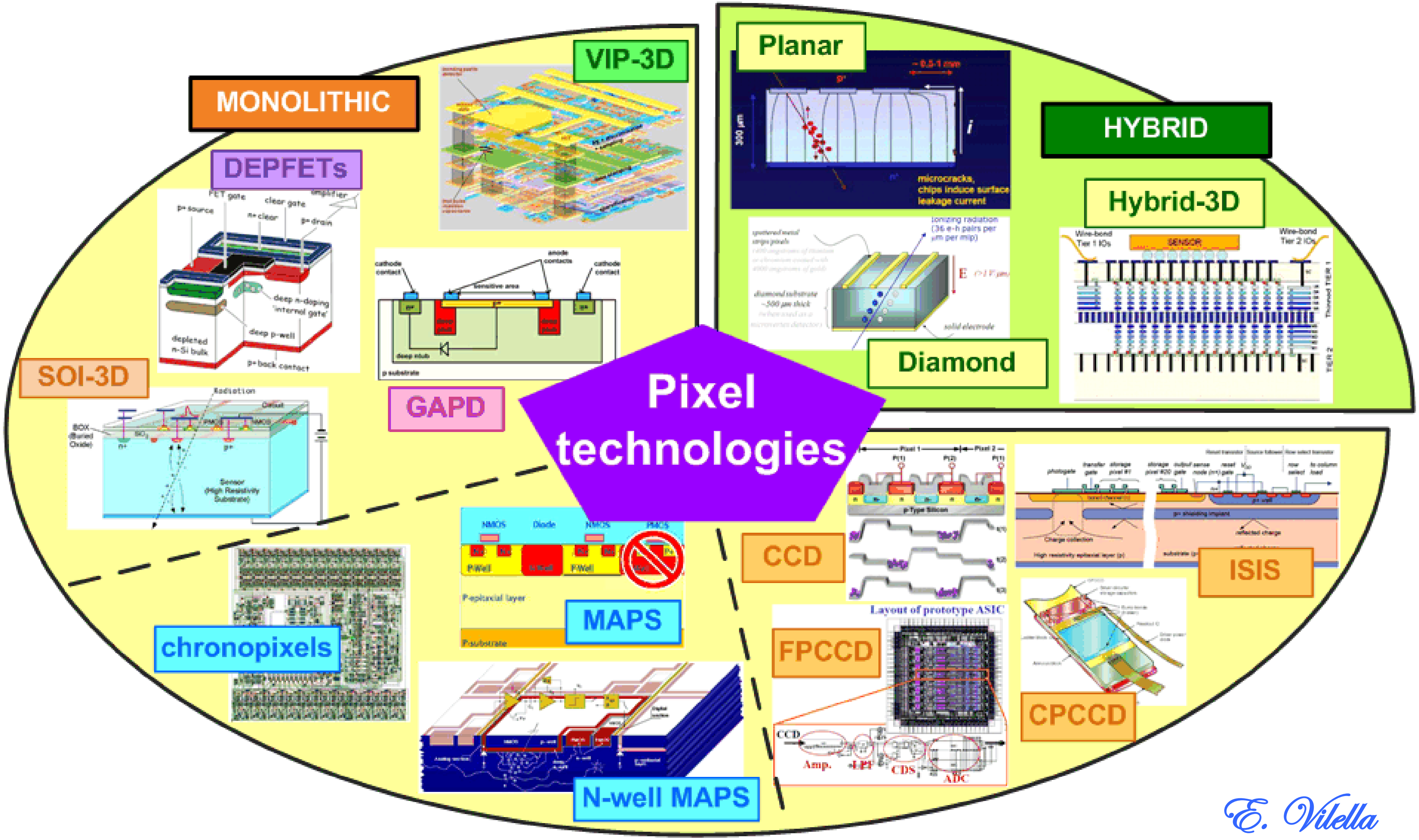
Available technologies



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Avalanche photodiode concept

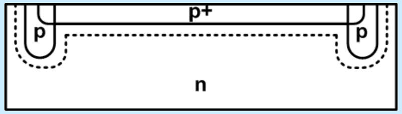
○ Geiger mode Avalanche Photodiodes (GAPDs)

- **Pros**
  - ✓ High intrinsic gain (no amplifier is needed)
  - ✓ Accurate time response (possible single BX detection)
  - ✓ Compatible with standard CMOS processes
- **Cons**
  - × Afterpulses
  - × Dark counts
  - × Crosstalk

  → Noise counts, indistinguishable from real **events**

  - × Reduction of detector performance
  - × Increase of memory area to store the total hits

Avalanche photodiodes in standard CMOS technologies



○ It is mandatory to reduce noise counts! How?

- Through technology
- Introducing readout electronics for low noise GAPD pixels

Avalanche photodiode concept

- **Intrinsic noise sources**
  - **Dark counts**
    - Spurious pulses due to thermal and tunneling carriers generated within the p-n juntion.
    - Depends on the doping profile (technology), quality of the process (sensor area), reverse bias overvoltage and temperature.
    - Measured in terms of frequency of generation or dark count rate (DCR). Typical values range from Hz to hundreds of kHz.
  - **Afterpulses**
    - Correlated pulses due to charge carriers trapped during a previous avalanche and released some time later.
    - Depends on the trap density, the number of carriers generated during an avalanche and the lifetime of these carriers.
  - **Crosstalk**
    - Spurious pulses caused by interactions among adjacent pixels (electrical) or photons generated during an avalanche in a neighbouring pixel (optical).
    - Depends on the sensor pitch, the number of carriers generated in an avalanche and the reverse bias overvoltage.

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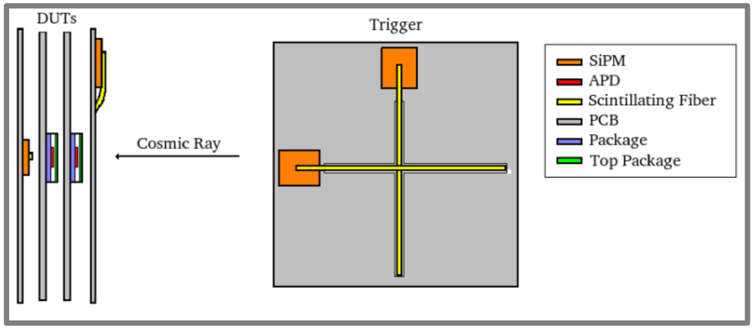
Test beam program (1)

We plan to go to 2 test beams

1) **DESY (2011)** - Initial test beam with 6GeV electrons
   We expect to distinguish detection between neighbour pixels
2) **CERN (2012)** - Final test beam with 120GeV pions
   We expect to distinguish detection in an specific region of the pixel

Test set-up

- DUT (1mm x 1mm GAPD array), PCB, scintillators and telescope (EUDET)



- A TLU is used to distribute the trigger
- Main worries → Hit density losses with distance and distortion in the particle path caused by test set-up materials
- Different ideas to reduce total material thickness
  - GAPD array with thin silicon wafer of 250µm
  - No chip package & wire bond the chip directly to the PCB
  - PCB perforated under the chip
- Running simulations with **Geant4**
  - Software to simulate the passage of particles through matter

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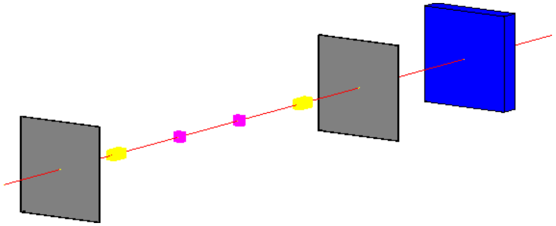
Test beam program (2)

○ Geant4 studies



- Performed using 2 silicon wafers, 2 aluminum layers and 2 or 4 scintillators (test beam set-up)
- Sources → electrons (6GeV) and pions (120GeV)

○ Results

	Detector at 2cm	X-Mean (μm)	X-Sigma (μm)	Y-Mean (μm)	Y-Sigma (μm)	Peak (μm)	R-Sigma (μm)
electrons	T.B. with 2 Sc.	-0.0801	16.2	0.008922	16.2	13	12.48
	T.B. with 4 Sc.	0.1474	17.6	0.07584	17.68	13	13.34
pions	T.B. with 2 Sc.	0.008092	0.7767	0.001725	0.7814	0.7	0.5769
	T.B. with 4 Sc.	0.0001457	0.8606	0.003204	0.8625	0.8	0.6955

	Detector at 10cm	X-Mean (μm)	X-Sigma (μm)	Y-Mean (μm)	Y-Sigma (μm)	Peak (μm)	R-Sigma (μm)
electrons	T.B. with 2 Sc.	-0.2033	16.91	0.18	46.88	35	39.25
	T.B. with 4 Sc.	0.3413	50.18	-0.06107	50.39	37	41.75
pions	T.B. with 2 Sc.	0.004929	2.092	0.00374	2.1	1.8	1.614
	T.B. with 4 Sc.	0.000984	2.301	0.00865	2.308	1.9	1.749

○ We need distortion lower than pixel width (20μm)!

- T.B. at DESY (electrons) → distortion is ~16μm
- Complicated to characterize (further studies are needed)
- T.B. at CERN (pions) → distortion is ~0.5μm
- To measure detector resolution and active regions we need 1-2μm precision

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AMS R3 - FLC_APD_v1 (1)

Aim of the chip

- **Characterize GAPDs response to MIPs in a test beam**
  - Measurements of efficiency depending on position and time
  - Study the areas of sensitivity
  - Crosstalk characterization

Requirements

- Minimum sensitive area is 1mm x 1mm
- Sensor area is 20µm x 100µm (optimized for ILC forward tracking)

Not taken into account (by now)

- Fill factor (FF)
- Radiation tolerance
- Use the best technology in terms of FF, speed, noise and cost

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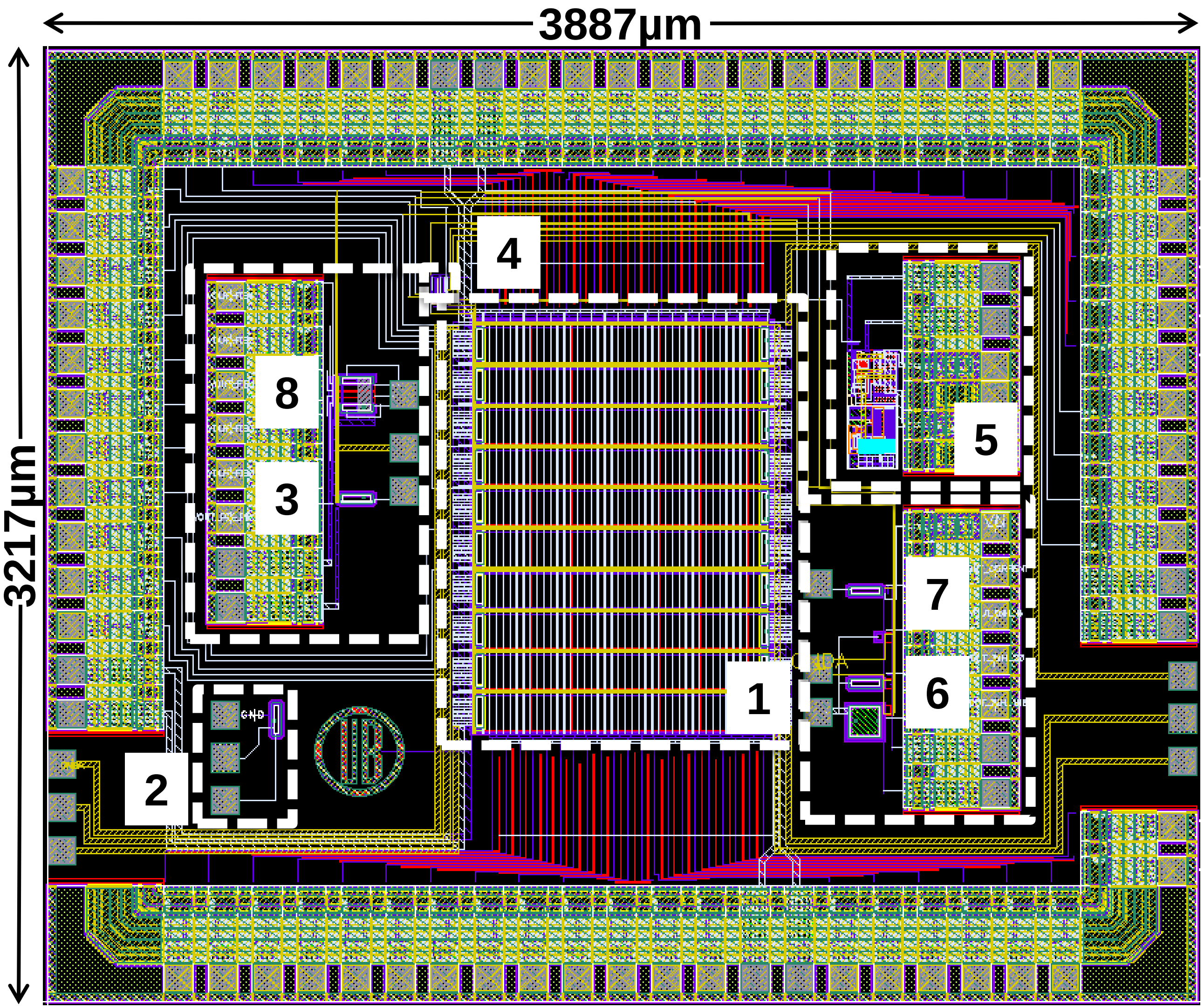
AMS R3 - FLC_APD_v1 (2)



1. 10 x 43 GAPD array
2. Test photodiode
3. Test pixel
4. Control signal generation circuit
5. Pad LVDS
6. Active inhibit pixel
7. Current mode pixel
8. 1 x 5 GAPD array with PAD layer

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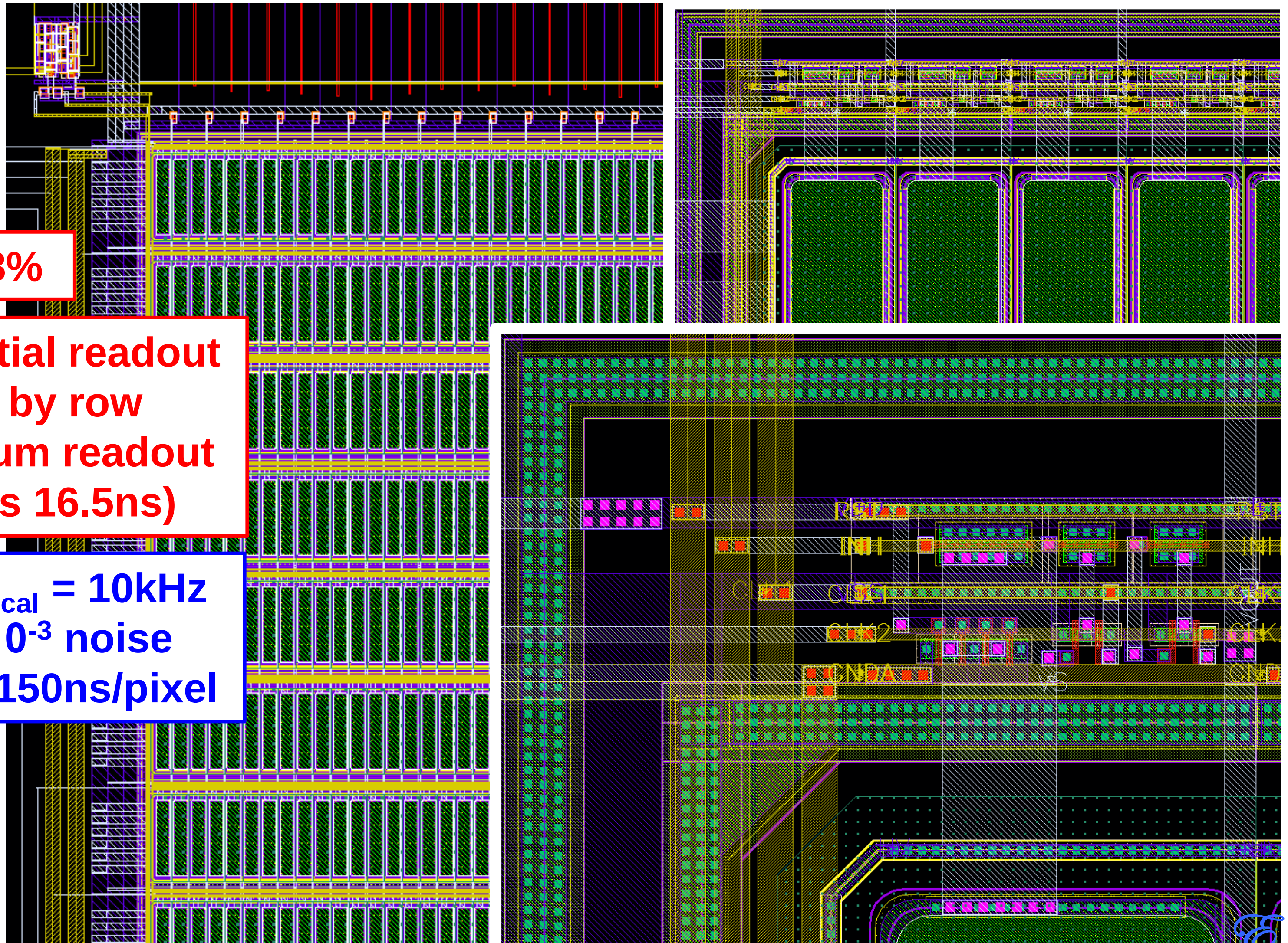
AMS R3 - FLC_APD_v1 (3)



FF is 88%

Sequential readout row by row (minimum readout time is 16.5ns)

$DCR_{Typical}$ = 10kHz → $1 \cdot 10^{-3}$ noise counts/150ns/pixel

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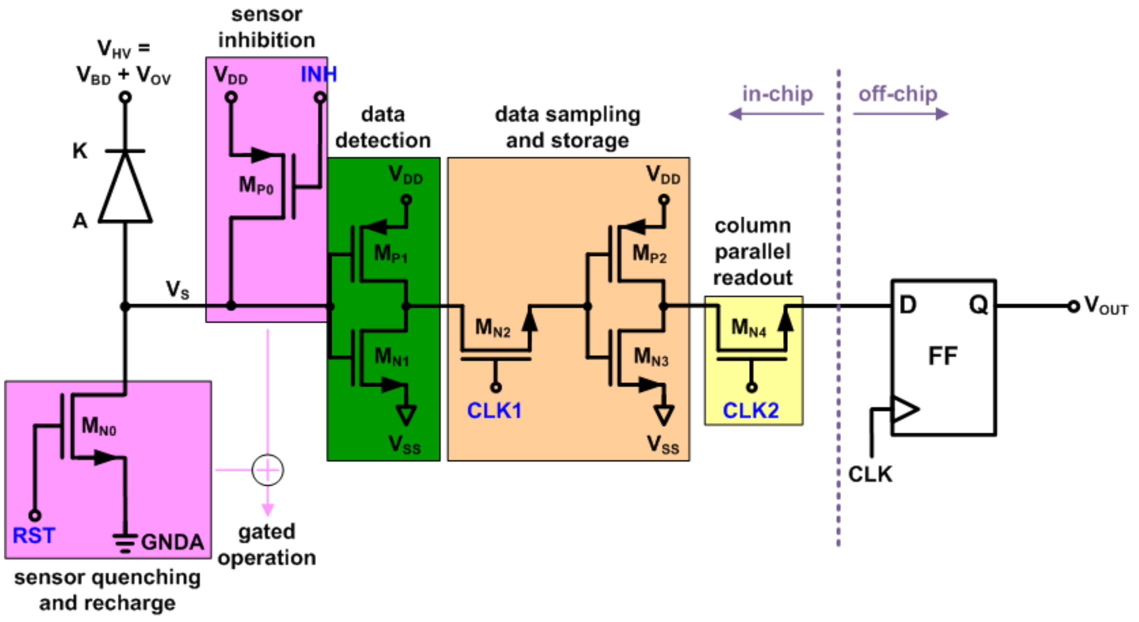
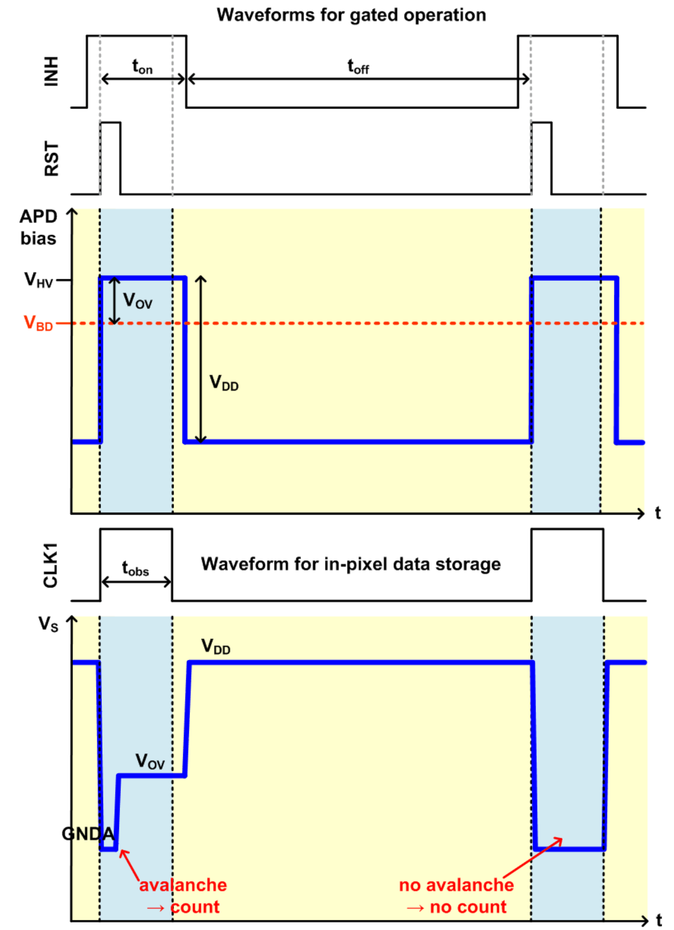
Pixel schematic and mode of operation

- Sensor and readout electronics monolithically integrated in the same die.
- Noise reduction through readout electronics (readout circuit for low overvoltage and gated operation).
- Digital output.





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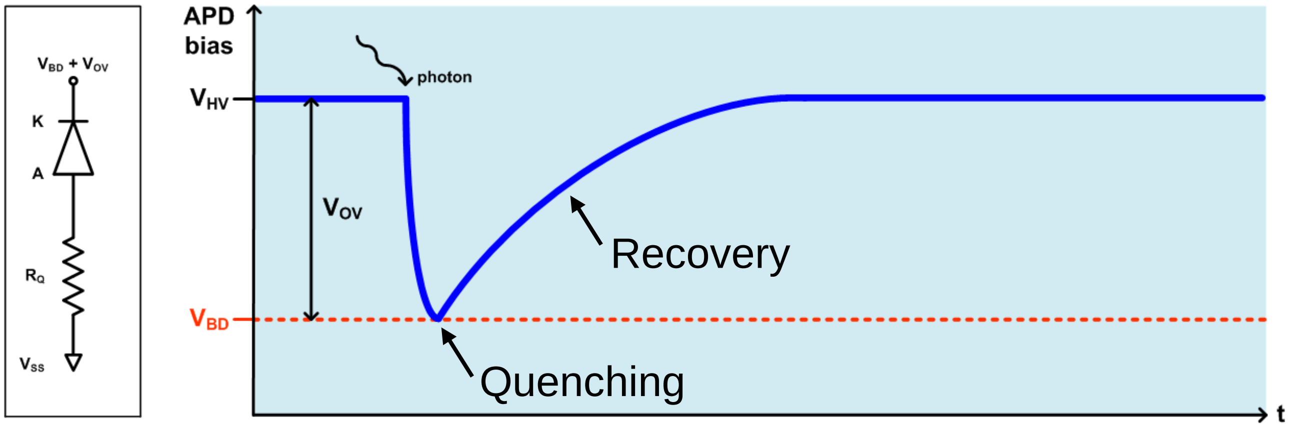
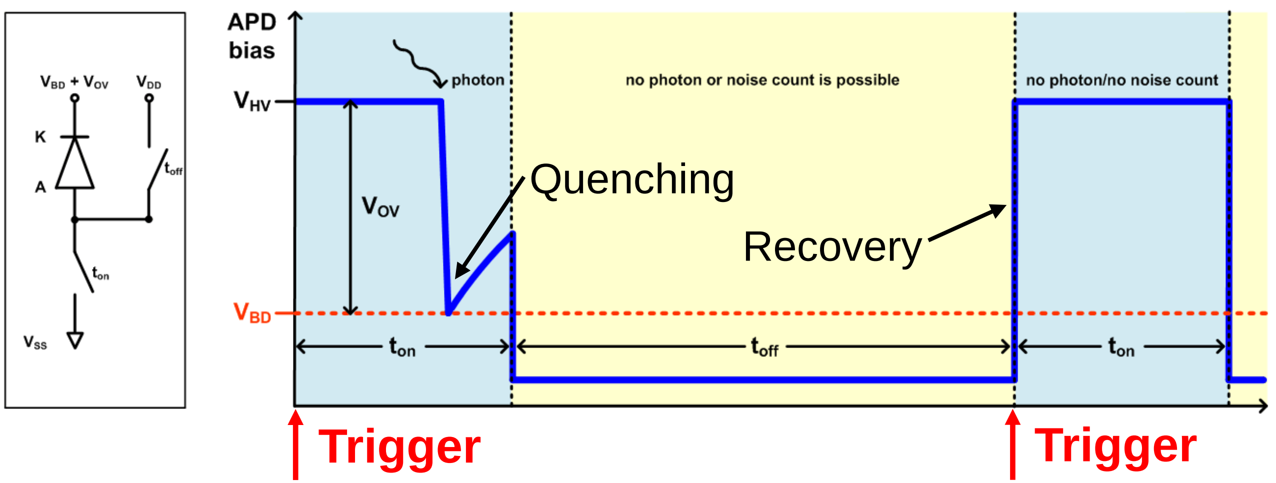
Free running vs. gated operation

- **Free running**



The APD is always active.

- **Gated operation**



The APD is active for short t_{on} by using a triggering signal.

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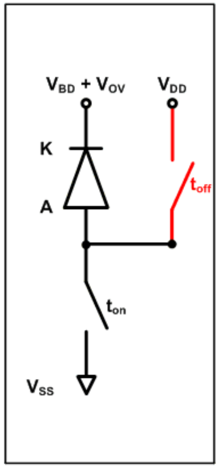
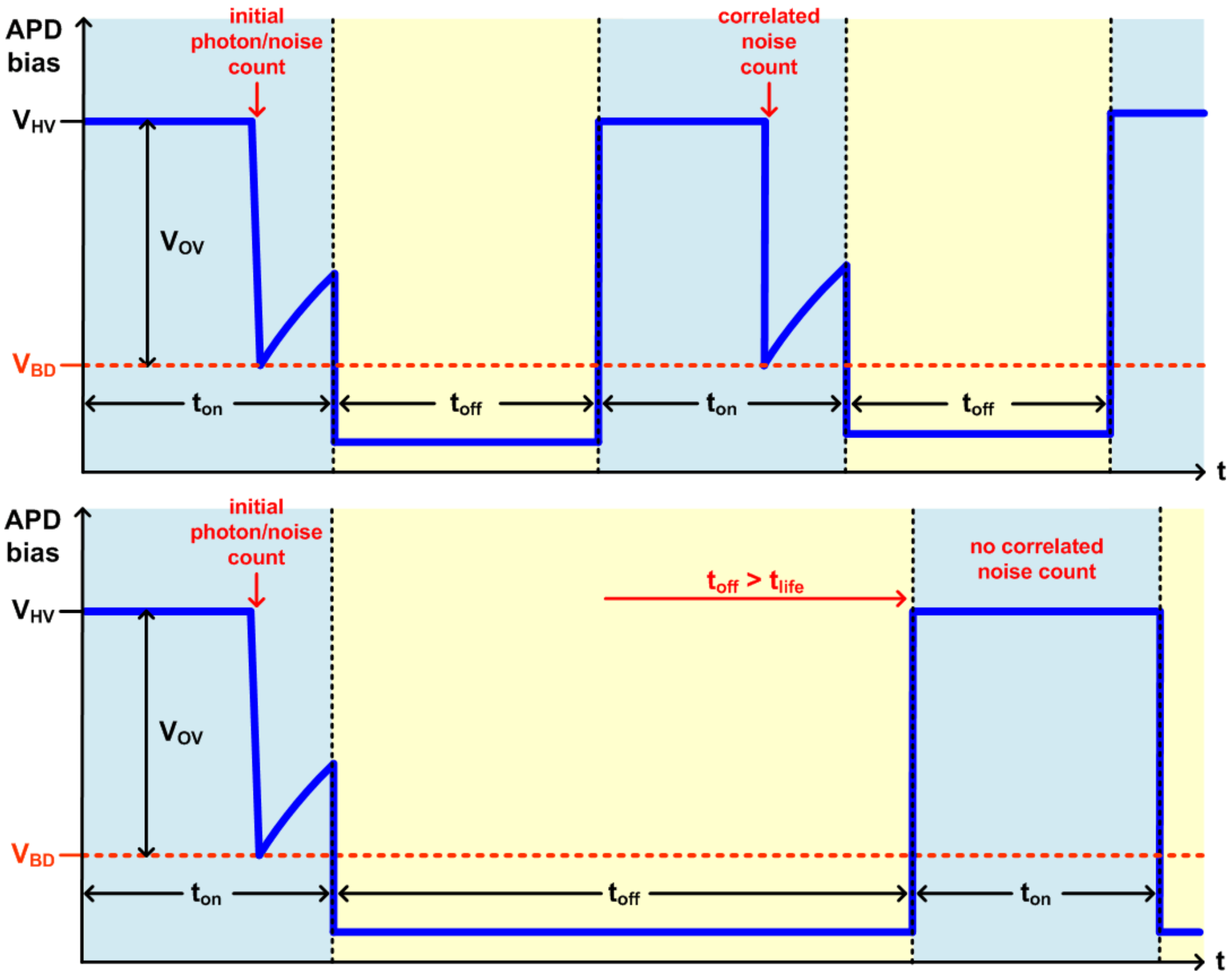
Advantages of gated operation

- **Gated operation**





Avoids afterpulses with $t_{off} > t_{life}$ of trap carriers

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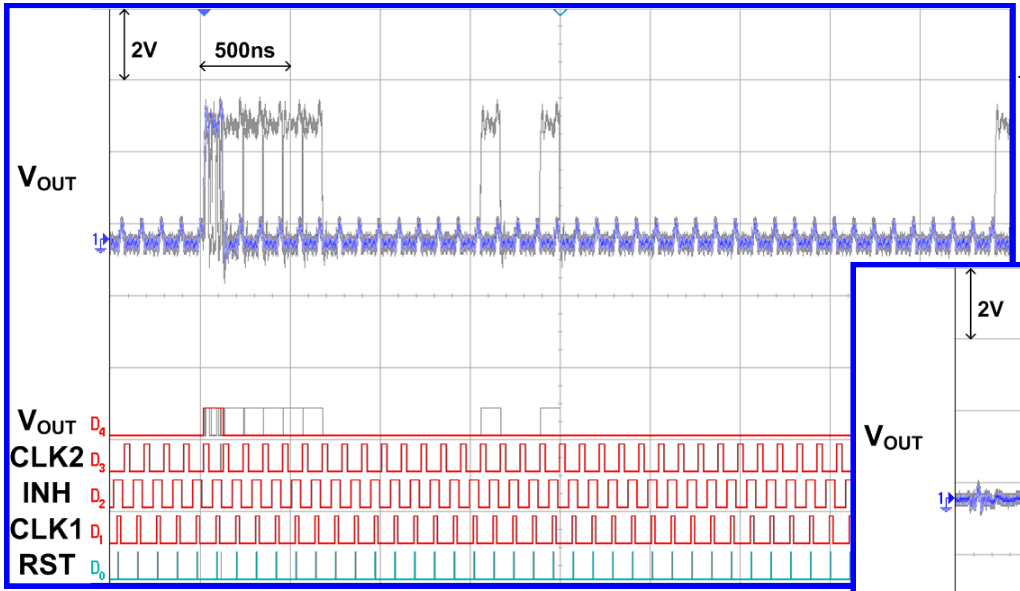
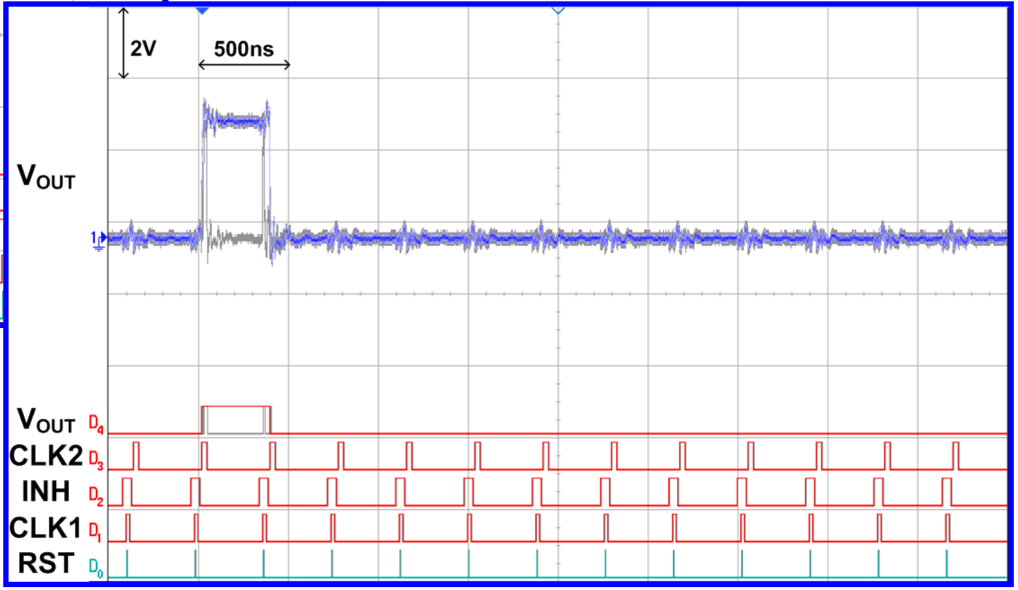
AMS R2 - Results (1)

- **It is possible to eliminate the afterpulsing probability by means of the gated operation.**
  - Leaving long enough t_{off} periods of 300ns.



t_{off} = 80ns

t_{off} = 300ns



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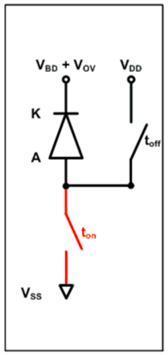
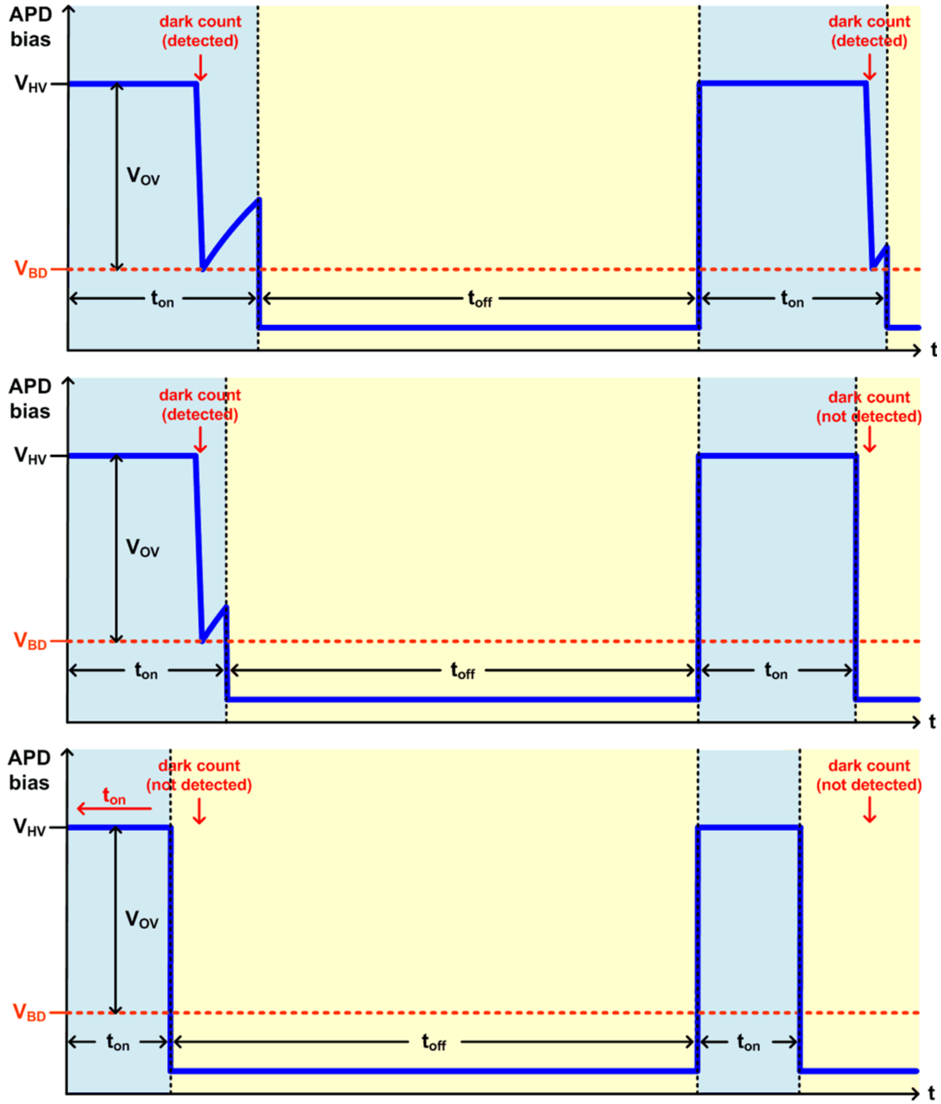
Advantages of gated operation

- **Gated operation**





Reduces the probability to detect a dark count with short t_{on}.

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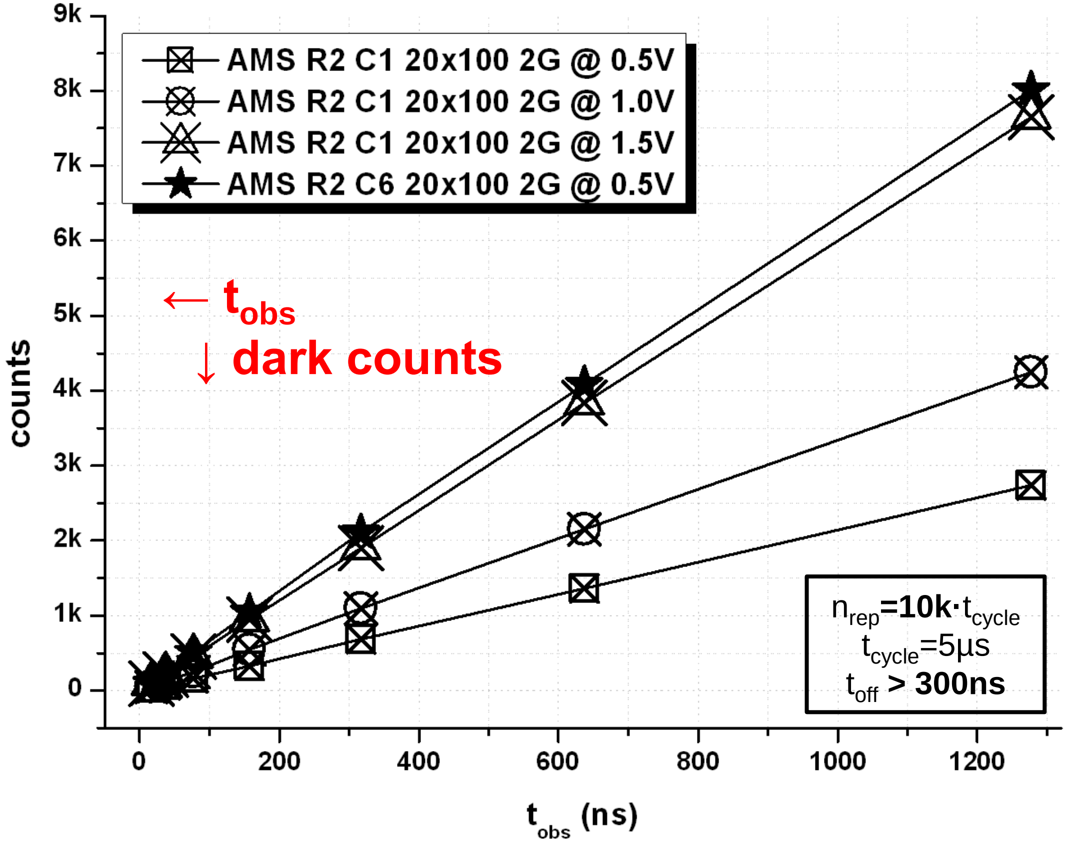
AMS R2 - Results (2)

- The probability to detect a dark count is reduced by using short $t_{obs.}$



DCR = dark counts · t_{obs}

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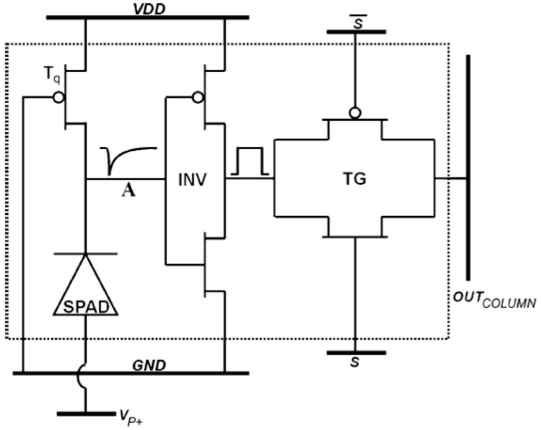
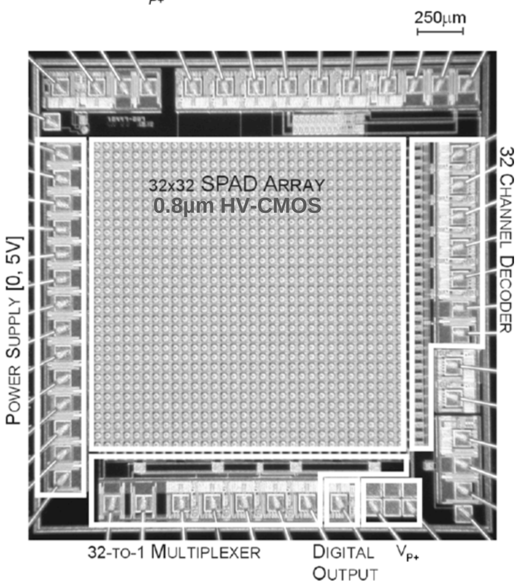
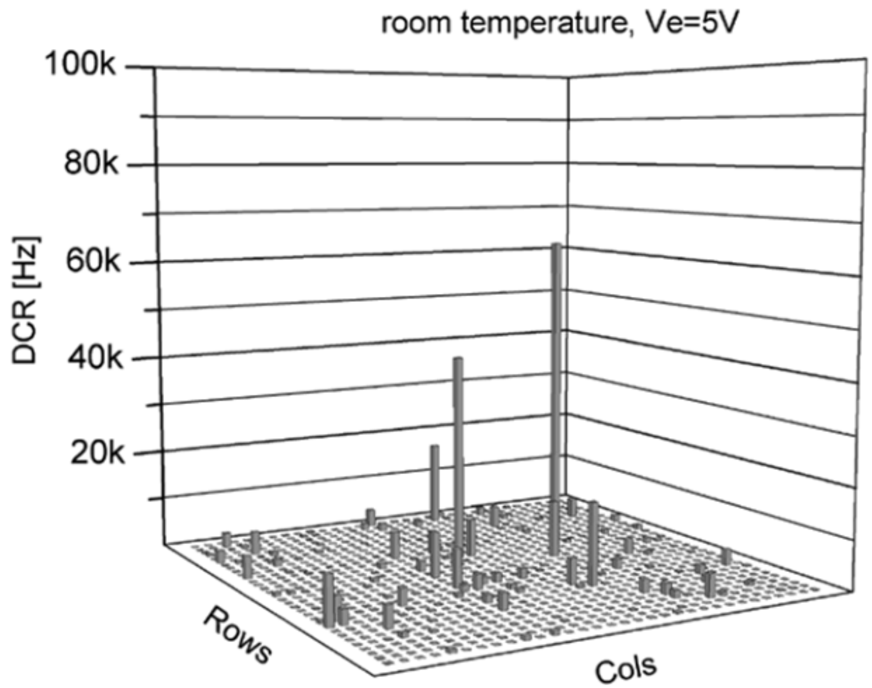
Dead pixels in GAPD arrays

- **Presence of dead pixels in GAPD arrays.**



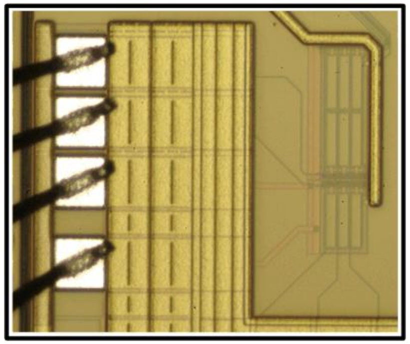


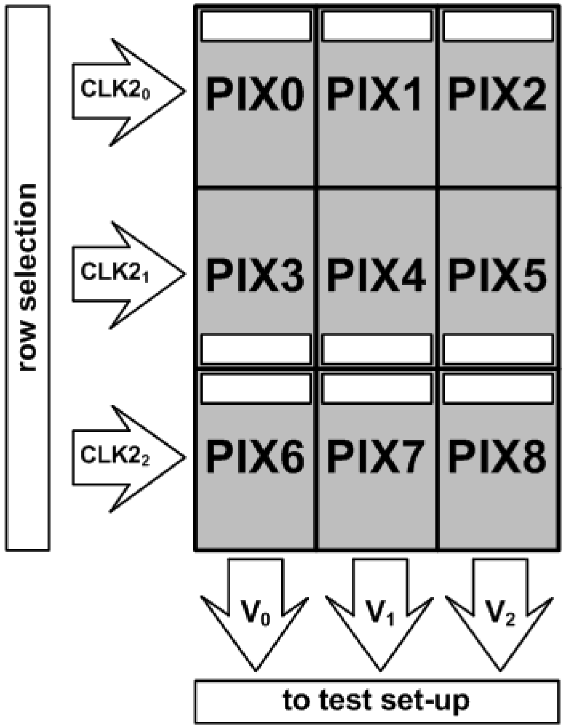


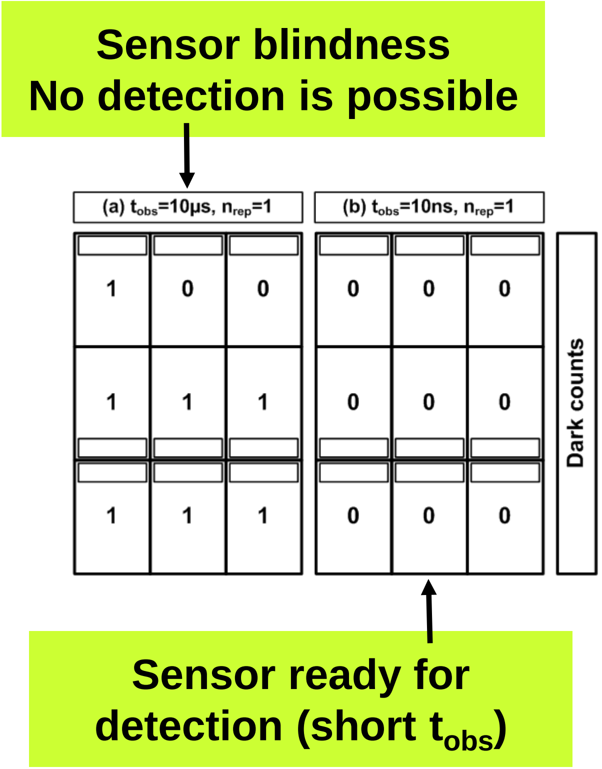
C. Niclass et al., "Design and characterization of a CMOS 3-D image sensor based on single photon avalanche diodes", IEEE Journal of Solid-State Circuits, vol. 40, no. 9, 2005.

AMS R2 - Results (3)

- **The gated operation is also effective in avoiding sensor blindness around a triggering signal in GAPD arrays.**
  - 3 x 3 GAPD array.
  - Colunn parallel readout (CLK2 acts as a row selector).







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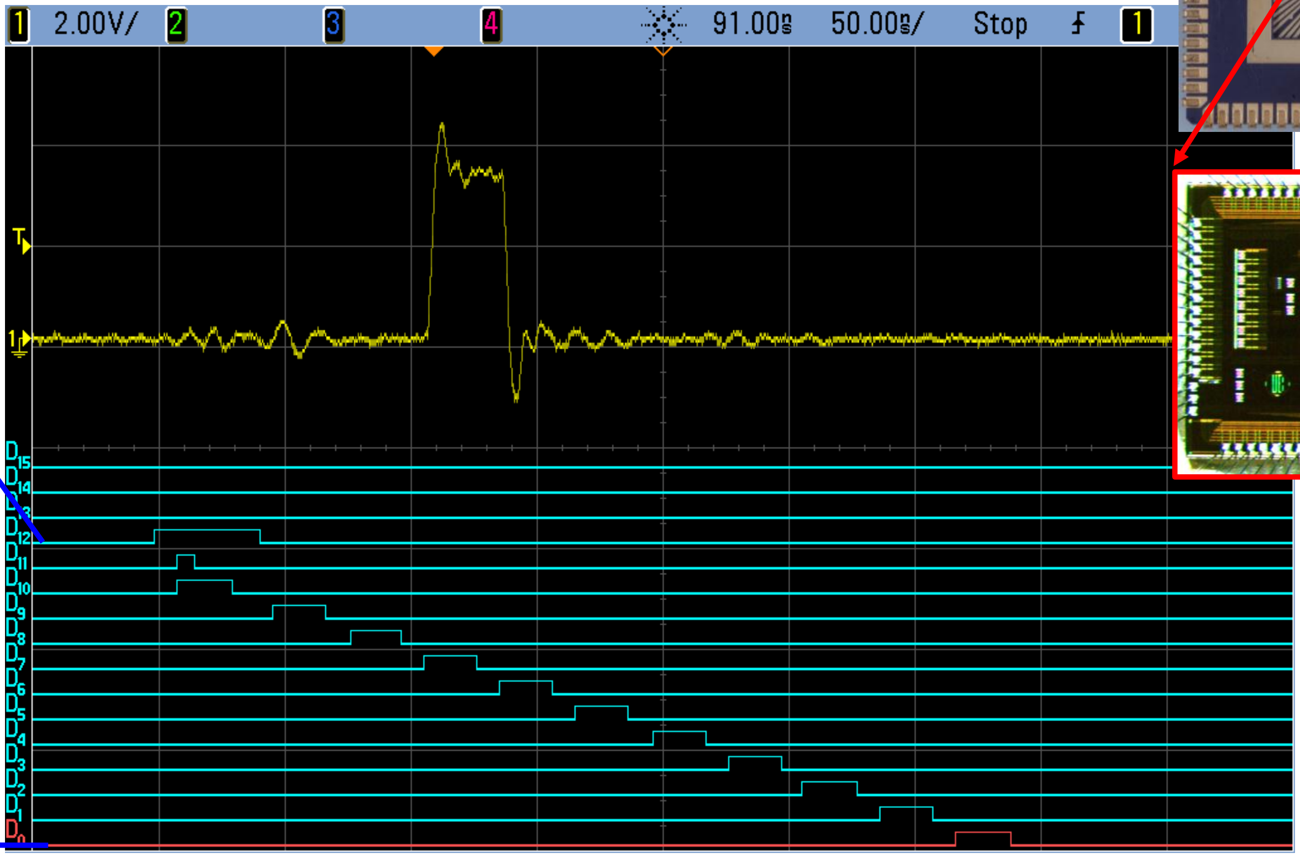
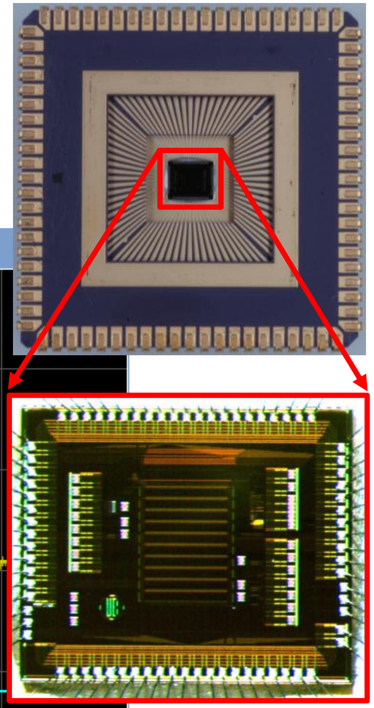
Preliminary results

- The GAPD array has shown signs of life… Observation of noise counts for one output channel.





INH
RST
CLK1
CLK2_0
CLK2_1
CLK2_2
CLK2_3
CLK2_4
CLK2_5
CLK2_6
CLK2_7
CLK2_8
CLK2_9

t_{obs} = 7ns
V_{HV} = 20.7V

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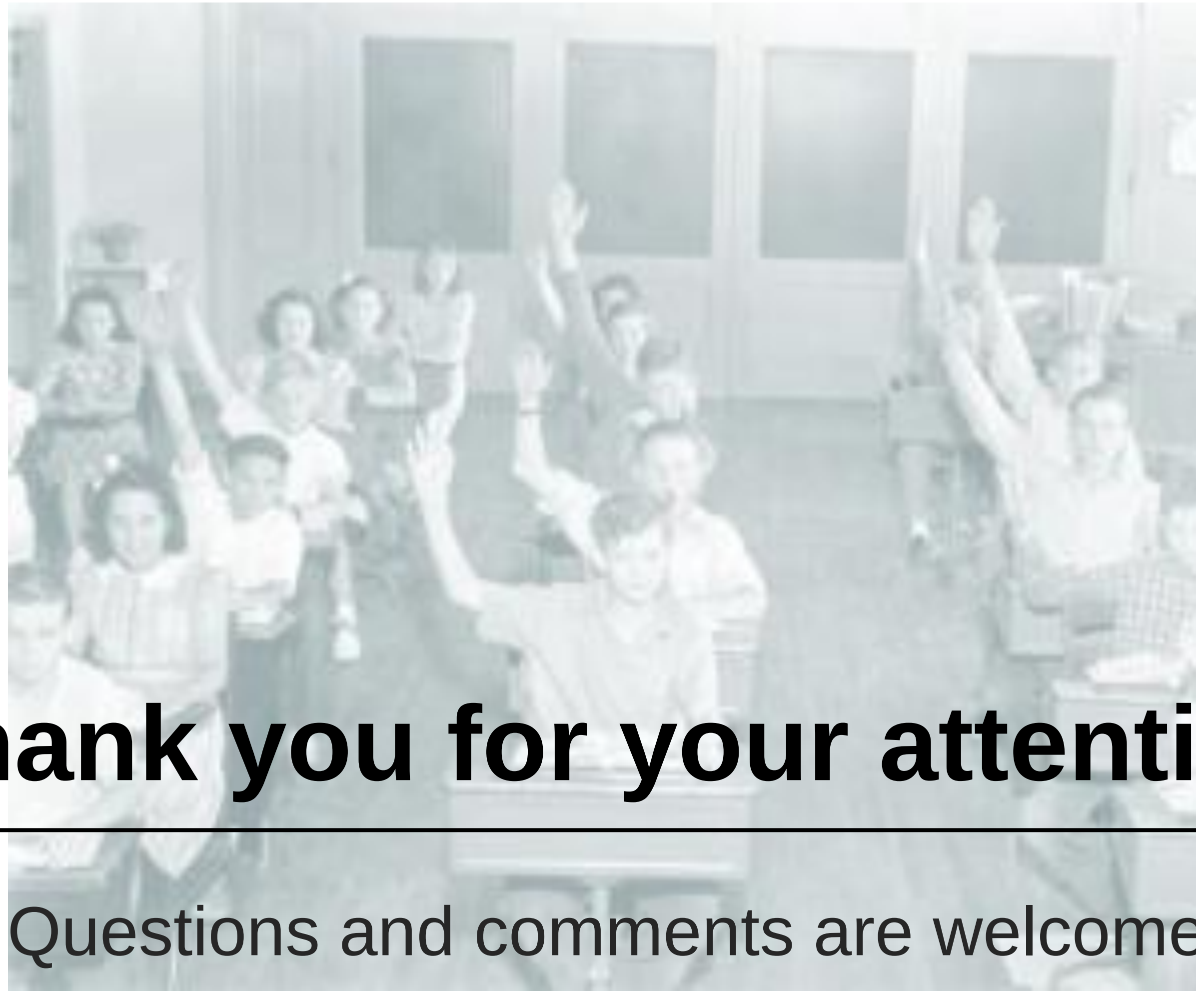
Conclusions

- We plan to test the efficiency of GAPDs fabricated with 0.35µm HV-AMS technology in particle detection at 2 test beams very soon.
  - We expect to distinguish detection between neighbour pixels (DESY) and within one pixel (CERN).
- Given that we want to prove the efficiency of the sensor, some aspects have not been taken into account (fill-factor, radiation tolerance, best technology).
- The test set-up will be comprised of…
  - 1mm x 1mm GAPD array, satellite electronics, scintillators, EUDET telescope and TLU.
- The GAPD array consists of…
  - Digital pixels with integrated readout.
  - 20µm x 100µm sensors.
- The sensors are operated in the gated acquisition because…
  - Avoids afterpulses and reduces observed dark count.
  - Eliminates dead pixels.
  - Avoids sensor blindness.



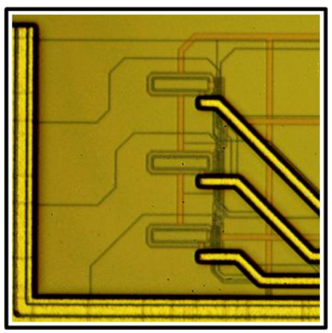
Thank you for your attention

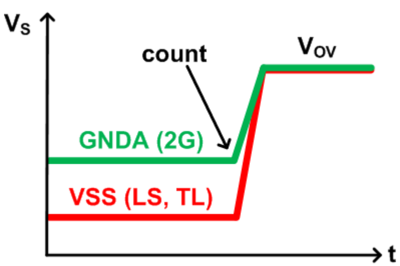
Questions and comments are welcome

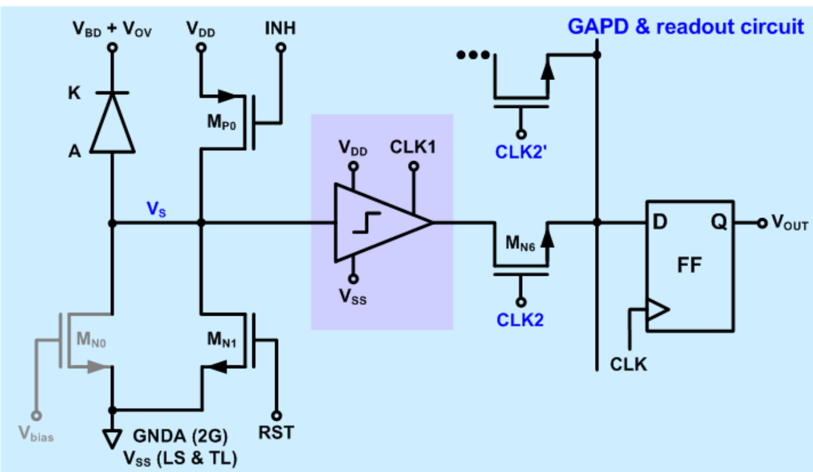
Back-up slides

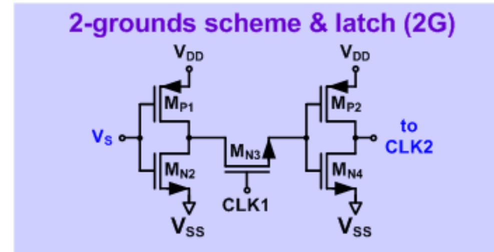
AMS R2 - GAPD pixels

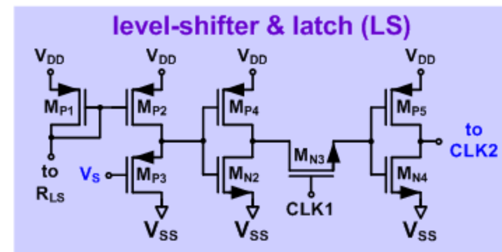
- **We developed readout circuits for low noise GAPD pixels**
  - Monolithically integrated with the sensor
  - Comprised of electronics for gated operation **and 3 different readout circuits**
  - Digital output

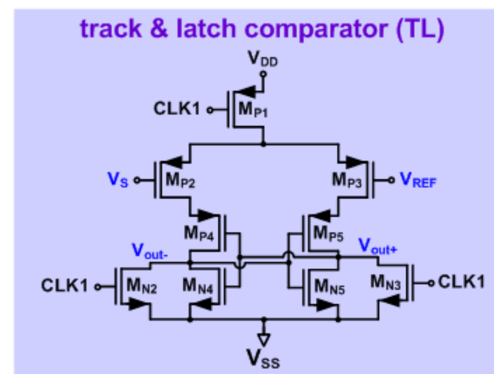












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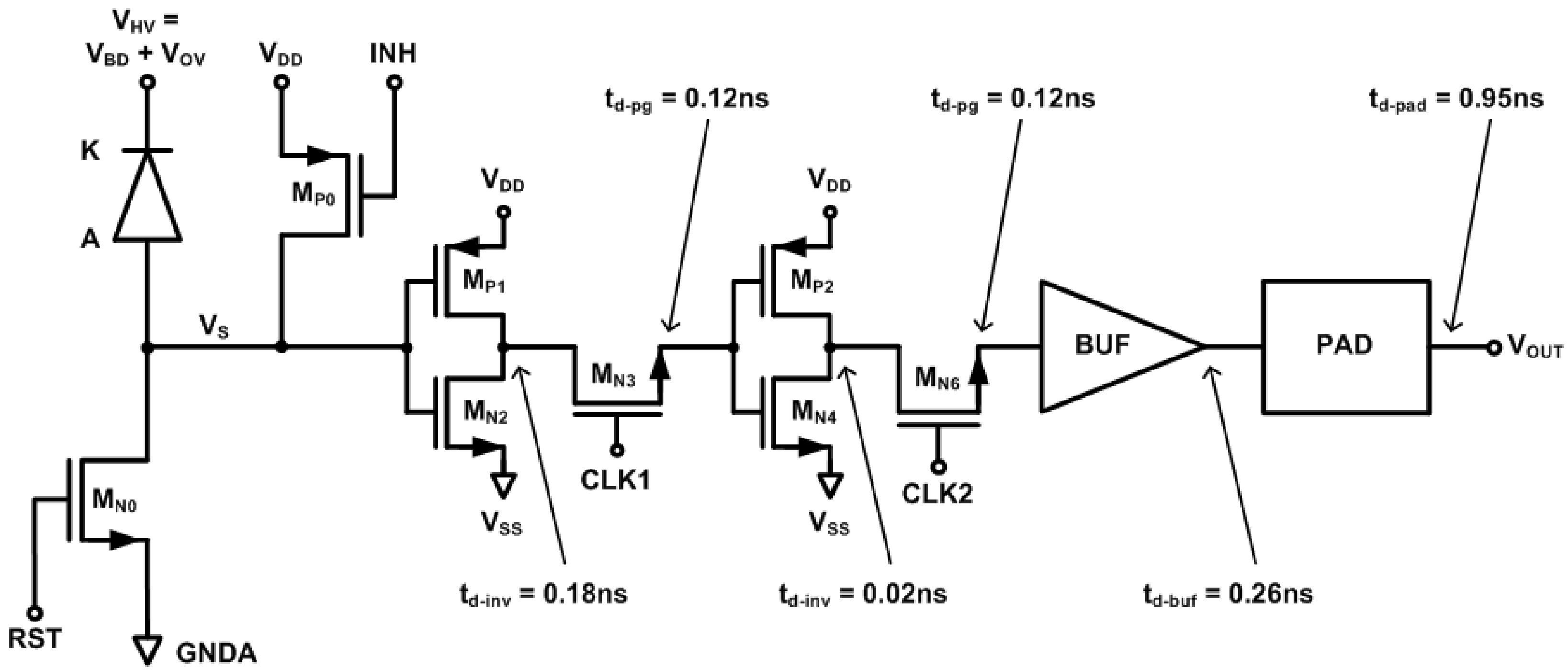
Delay introduced by the electronics

- Total delay introduced by electronics is 1.65ns.



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