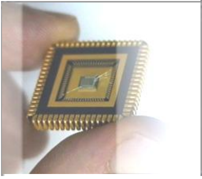

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3D integration of Geiger-mode avalanche photodiodes for future linear colliders

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➢ <u>Outline</u>

➢ Introduction

- Avalanche photodiodes in CMOS
- The noise issue
- The low fill-factor issue

➢ Options to increase the fill-factor

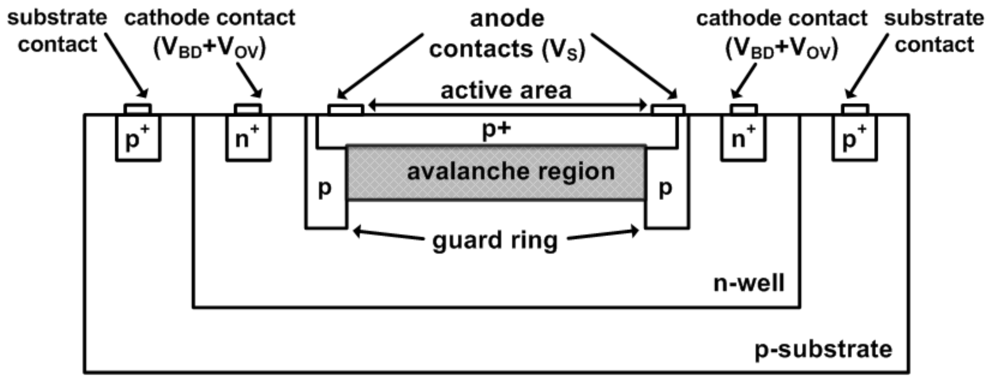
- 3D GAPD array with Chartered 130nm/Tezzaron 3D
- Pixel schematics and mode of operation to reduce the noise
- Functional diagram
- Structures and layout
- Alternative solutions (HV-AMS)

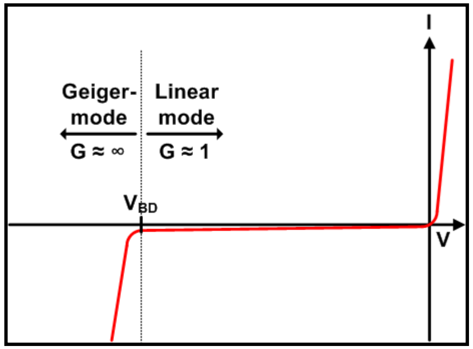
➢ Conclusion

Avalanche photodiodes in CMOS (1)

○ Geiger-mode Avalanche Photodiodes (GAPDs)

- p-n junction in reverse bias





- avalanche generation
  - Linear mode → limited gain, self-quenched
  - Geiger-mode → gain ≈ ∞, self-sustained

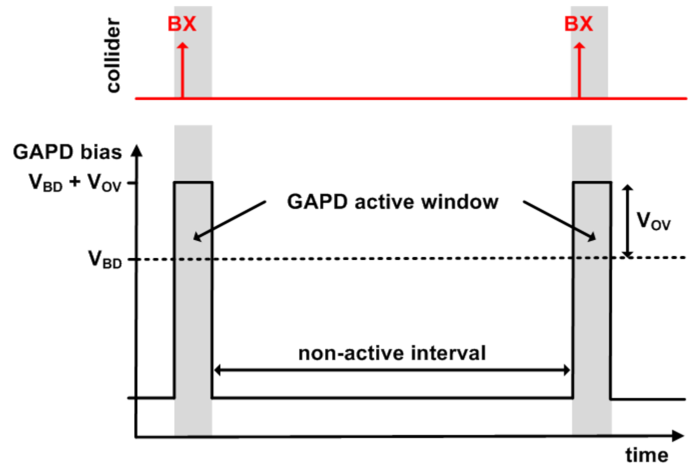
- macroscopic current pulse detected by the readout electronics

Avalanche photodiodes in CMOS (2)

- GAPDs offer **excellent qualities** to meet the requirements of the next generation of particle colliders
    - high sensitivity
    - fast timing response (ps rise times)
    - virtually infinite gain (10^5-10^6)
    - compatibility with standard CMOS processes
    - simple readout
    - possibility of single hit detection at each bunch crossing (BX).
- but they also present **some drawbacks**
    - generation of noise pulses (some kHz) that cannot be distinguished from radiation-triggered events
        - erroneous results
        - limited range of detectable signals
    - low fill-factor (usually <50%)
        - low detection efficiency.
- **Fortunately, this situation can be improved!**

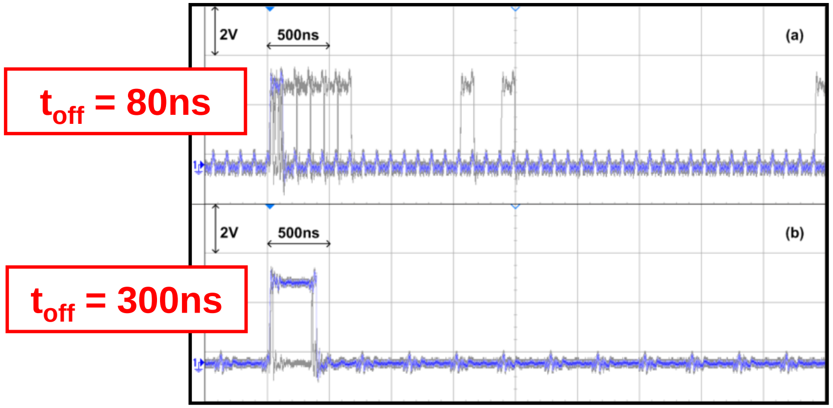
The noise issue (1)

- The noise in GAPDs is due to
  - afterpulses (carriers trapped by cristal deffects)
  - dark counts (thermal/tunnel carriers)
  - crosstalks (avalanche generated photon/carriers trigger GAPD)
- It can be coped with advanced techniques
  - particle sampling at various layers
  - **the time-gated operation**



  - the GAPD is periodically activated and deactivated to reduce the probability to detect the noise pulses

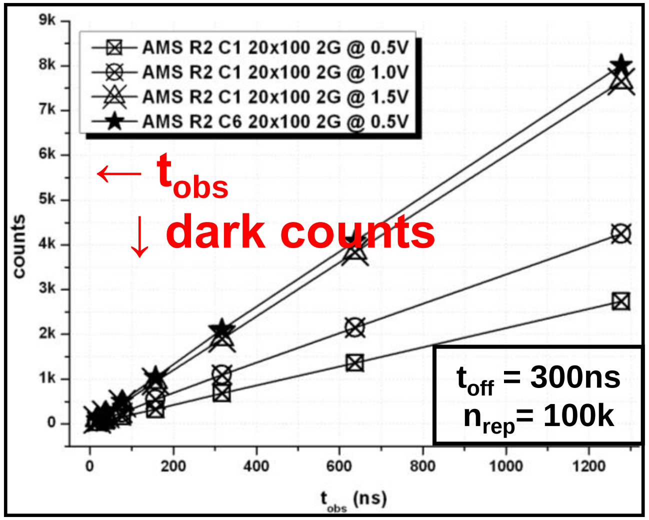
- From our experience with time-gated pixels (HV-AMS 0.35µm)



• elimination of afterpulses with non-active periods around 300ns

• reduction of the detected dark counts with short active periods (down to 10^{-4} noise counts per frame with a 10ns active period)

DCR (kHz) = (noise counts)·$(t_{obs} \cdot n_{rep})^{-1}$



• elimination of crosstalks with short active periods

The low fill-factor issue

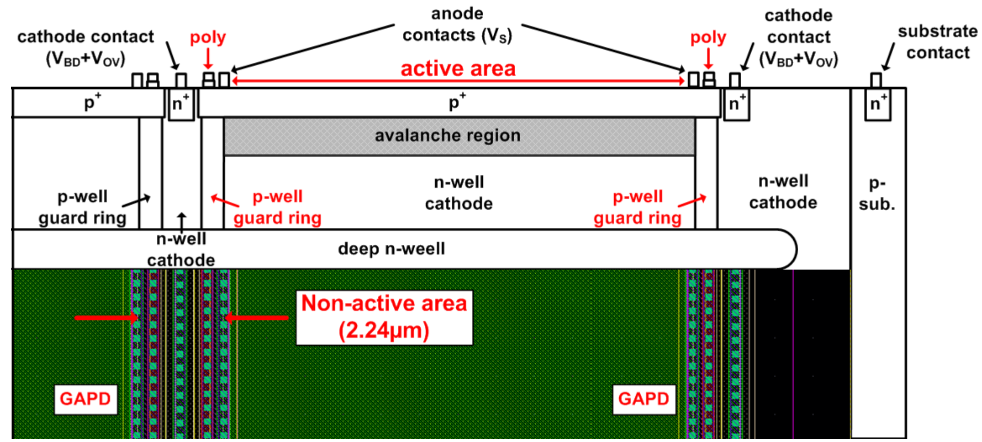
- Why such a low fill-factor?

Sensor design

• a **p-well guard ring** is used to prevent premature edge breakdown

• for technologies < 0.250µm:

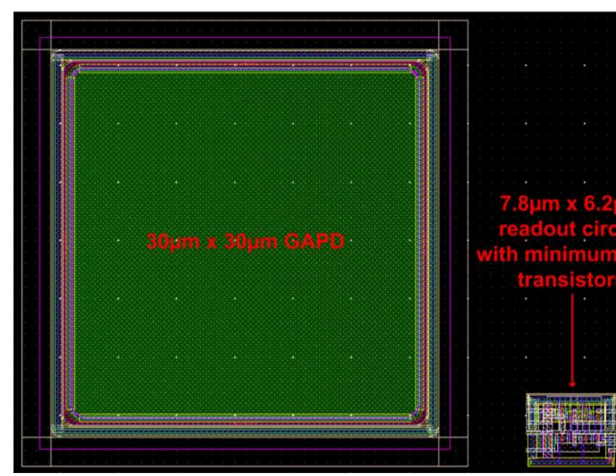
a **polysilicon gate** is used to force the physical separation between the STI interface from the GAPD avalanche region and avoid an increase of the dark count (1)



Readout electronics

• monolithically integrated with the sensor

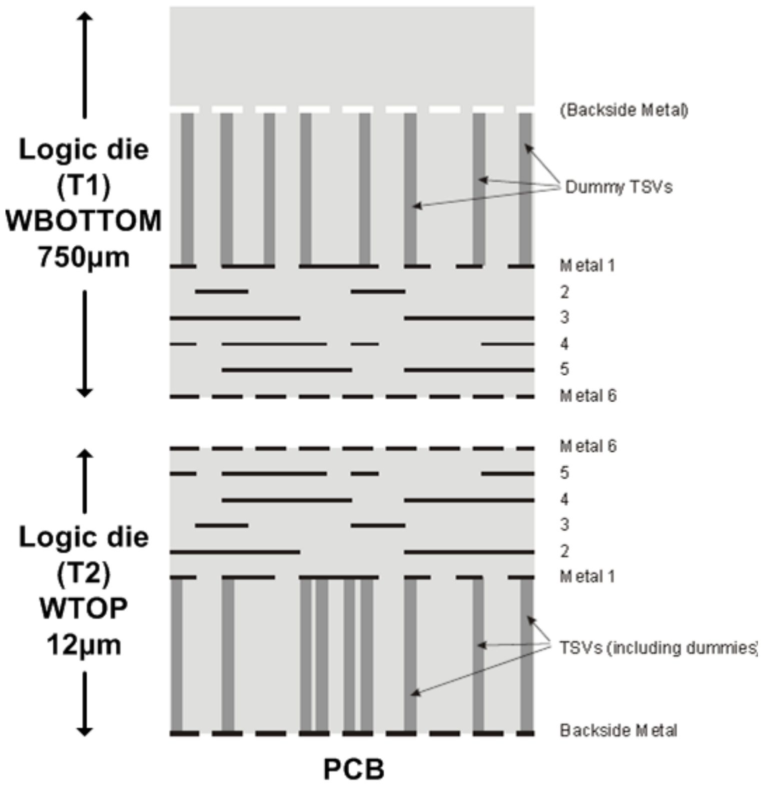
• based on a simple comparator and a memory cell → still too much



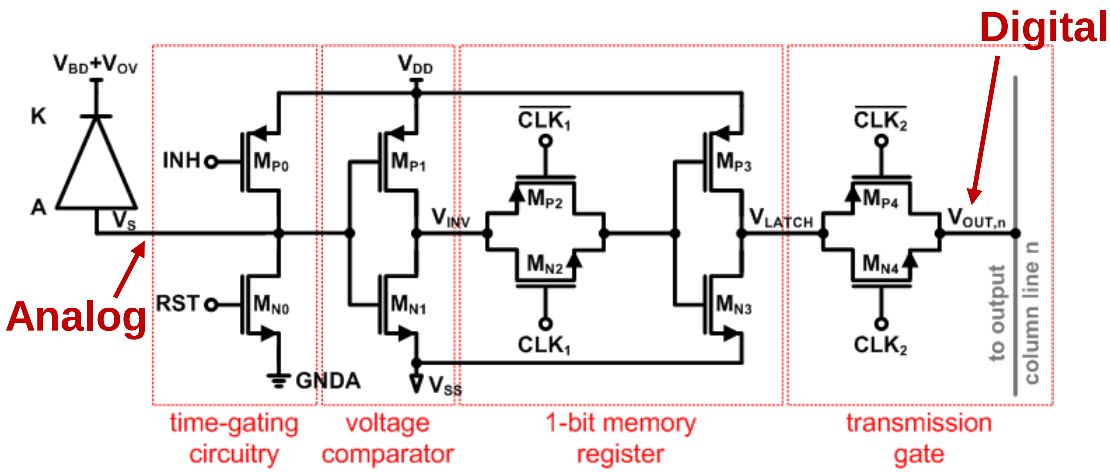
(1) C. Niclass, A Single Photon Avalanche Diode Implemented in130-nm CMOS Technology, IEEE J. Quantum Electron. (2007).

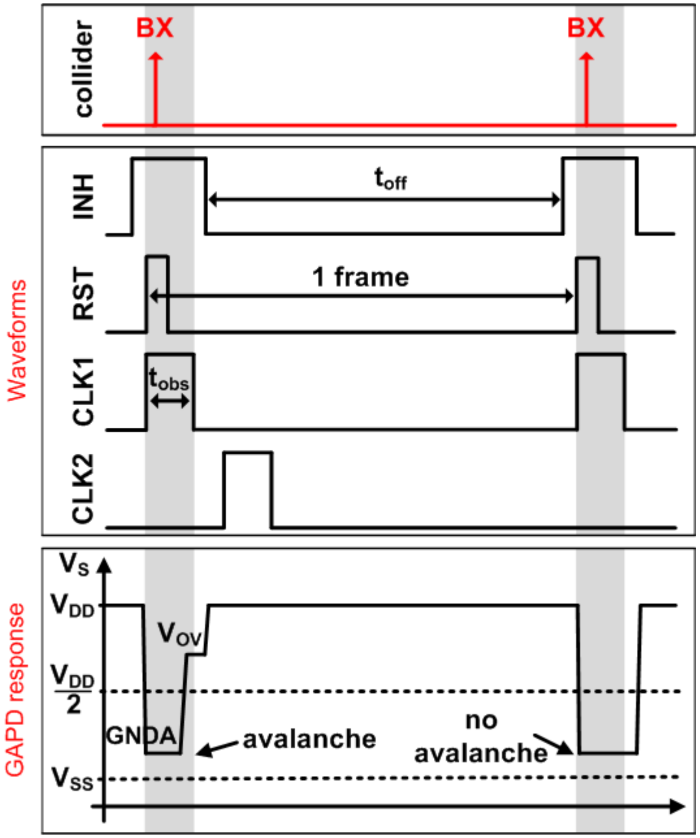
3D-IC GAPD array

- 3D-IC technologies as a solution to increase the fill-factor in GAPD arrays
  - Process → Chartered 130nm/Tezzaron 3D
  - 2-layer stack with TSVs (Through Silicon Vias) in a via first process
  - TSVs → SuperContacts with a recommended spacing of 100µm (dummy TSVs)
  - The 2 dies are connected face-to-face
  - I/O pads on the back of WTOP
- Our design
  - Array size → 48 rows x 48 columns
  - 2 different structures
    1) T1 → electronics; T2 → sensors
    2) T1 → sensors; T2 → sensors & electronics (the dead areas of one tier are overlapped by the active areas of the other tier)
  - Sensor size → 18µm x 18µm, 30µm x 30µm
  - Time-gated operation
  - Passive quenching, active recharge/inhibit



- Pixel schematics implemented in this work
  - Based on a GAPD sensor and a 10-transistors circuit

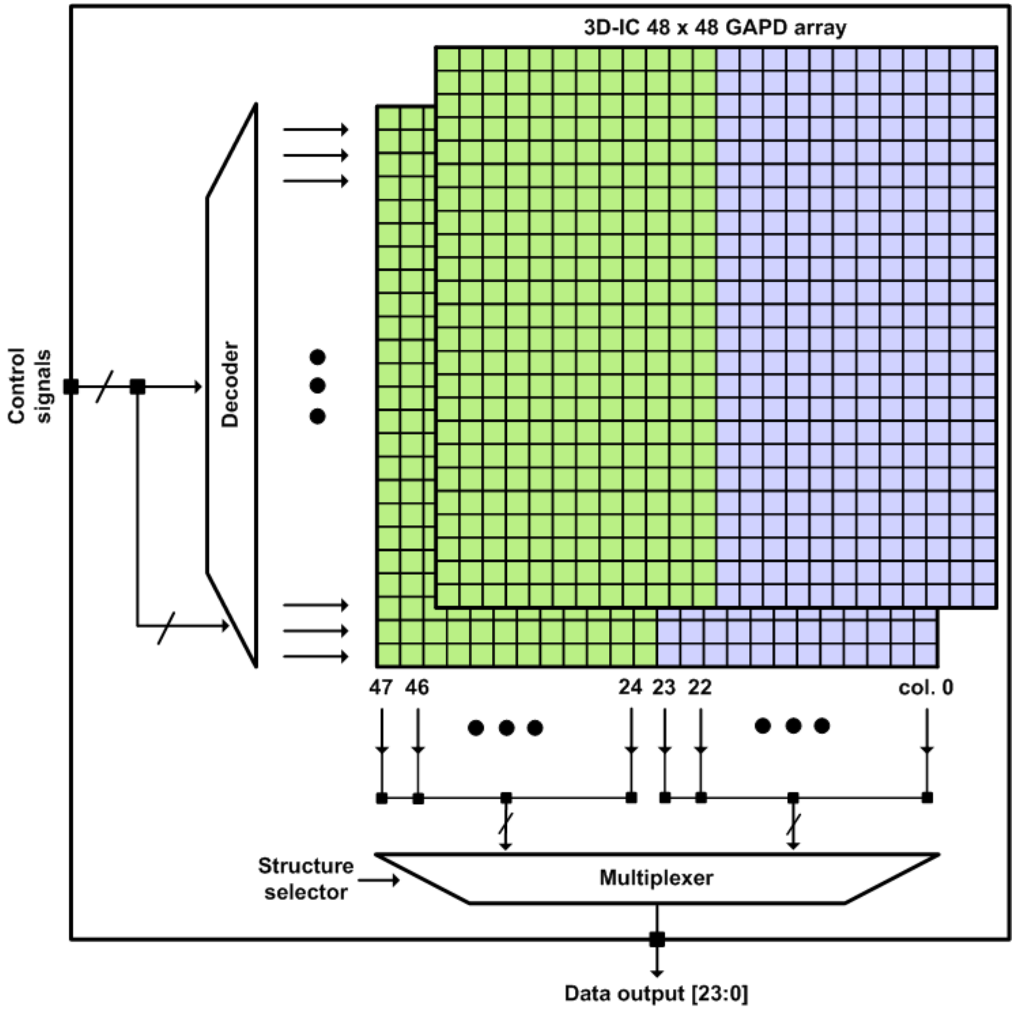




- The GAPD is activated before the BX
- It is deactivated during the interBXs
- The GAPD's ground GNDA allows to use low V_{OV} and further reduce the noise
- The array is read row by row during the interBXs

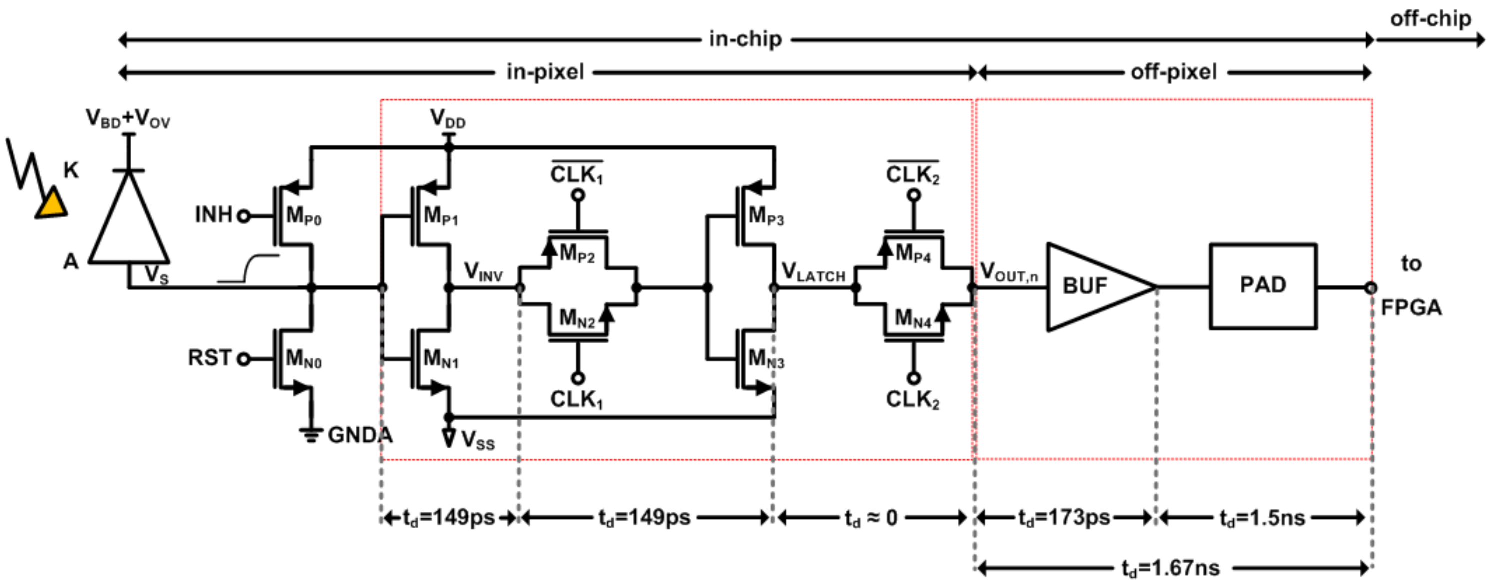
Functional diagram

- Control signals (external generation)
  - INH
  - RST
  - CLK1, /CLK1
  - CLK2, /CLK2 (per row)
- Readout
  - Sequential by structures
  - Sequential by rows



Propagation delay

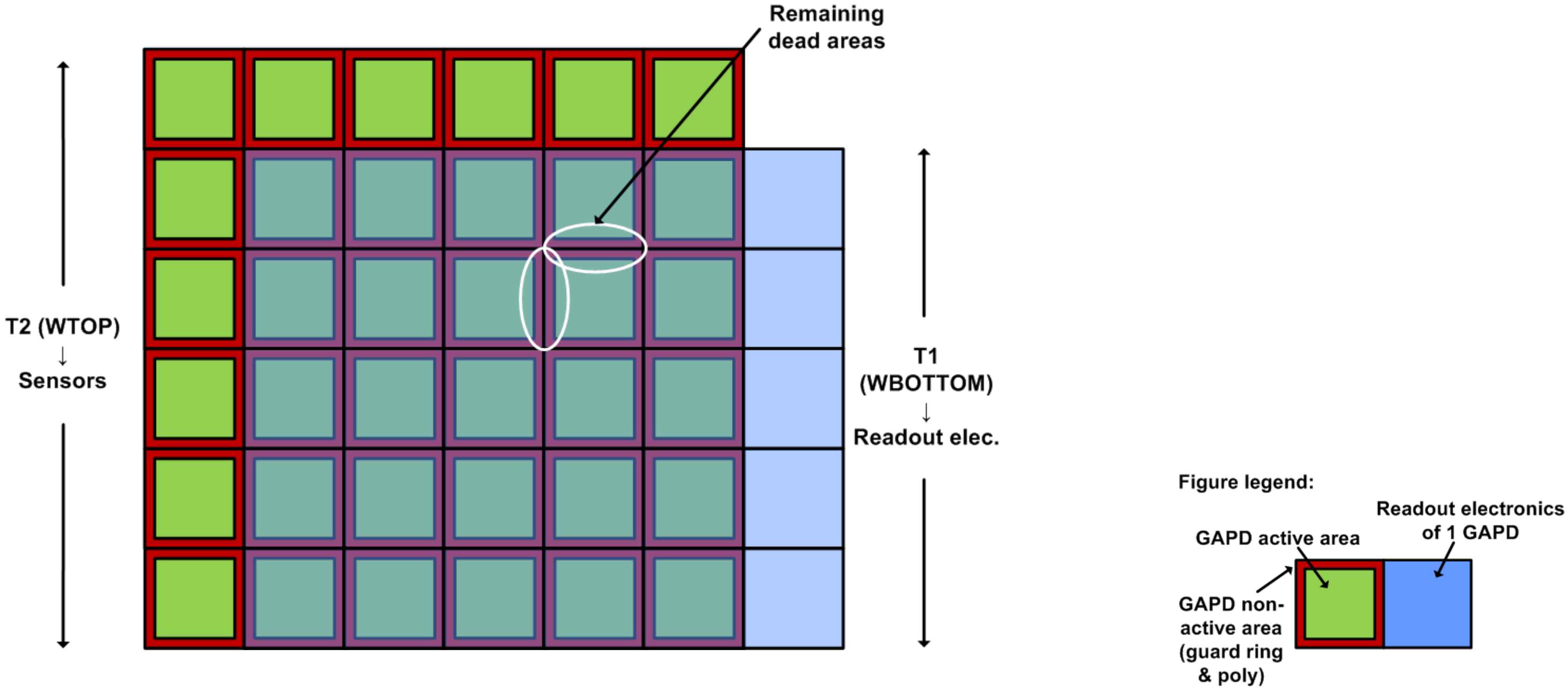
○ Delay introduced by the electronics



- The delay introduced by the inverters is 300ps.
- The 48 x 48 array could be read in less than 200ns.
  - $t_{read\text{-}array}$ = 1.67ns x 48 rows x 2 structures = 160ns

Structures (1)

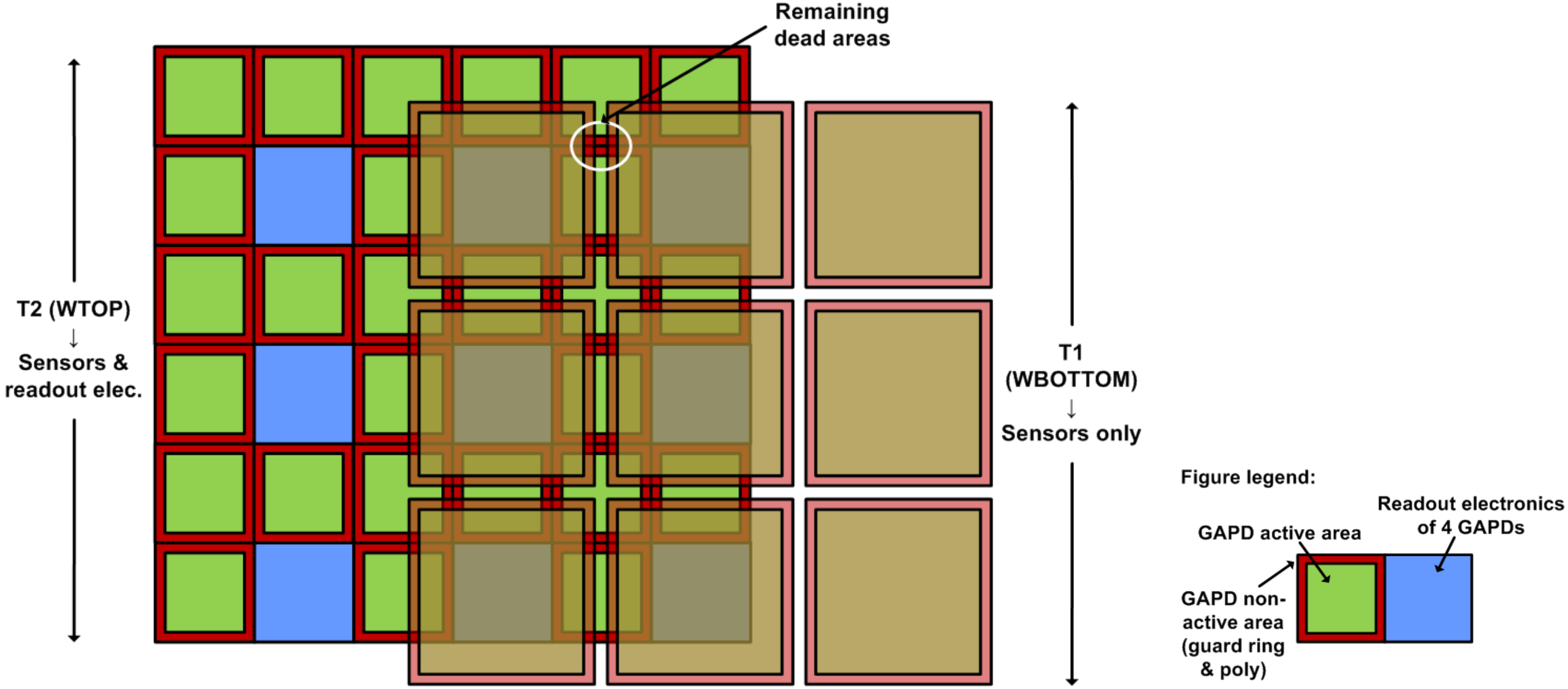
- T1 → electronics; T2 → sensors



- Array size → 48 rows x 24 columns
- Sensor size → 18µm x 18µm (T2)
- Interconnection between tiers → Each GAPD to its readout circuit
- Fill-factor → 66%

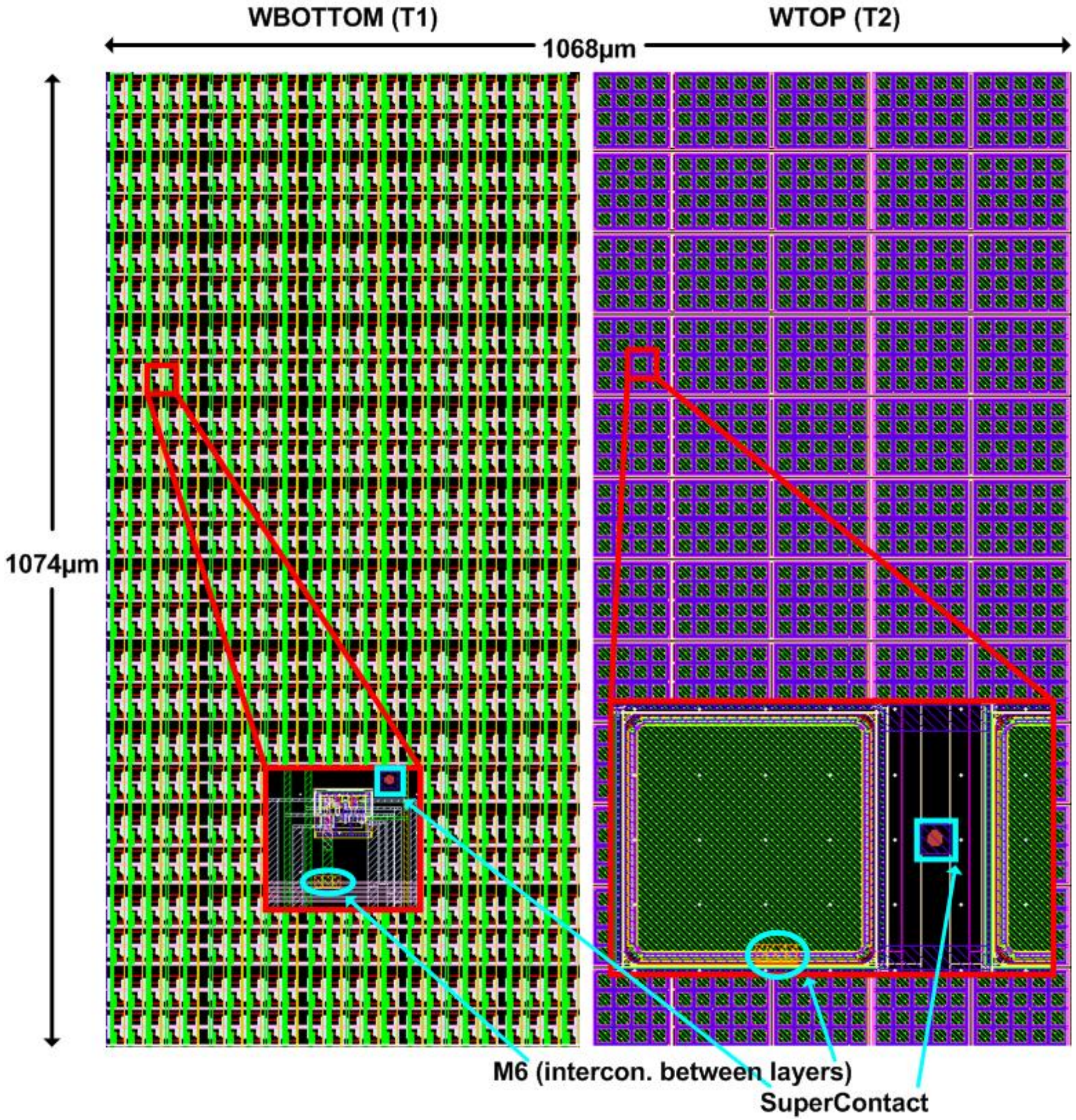
Structures (2)

- T1 → sensors; T2 → sensors & electronics

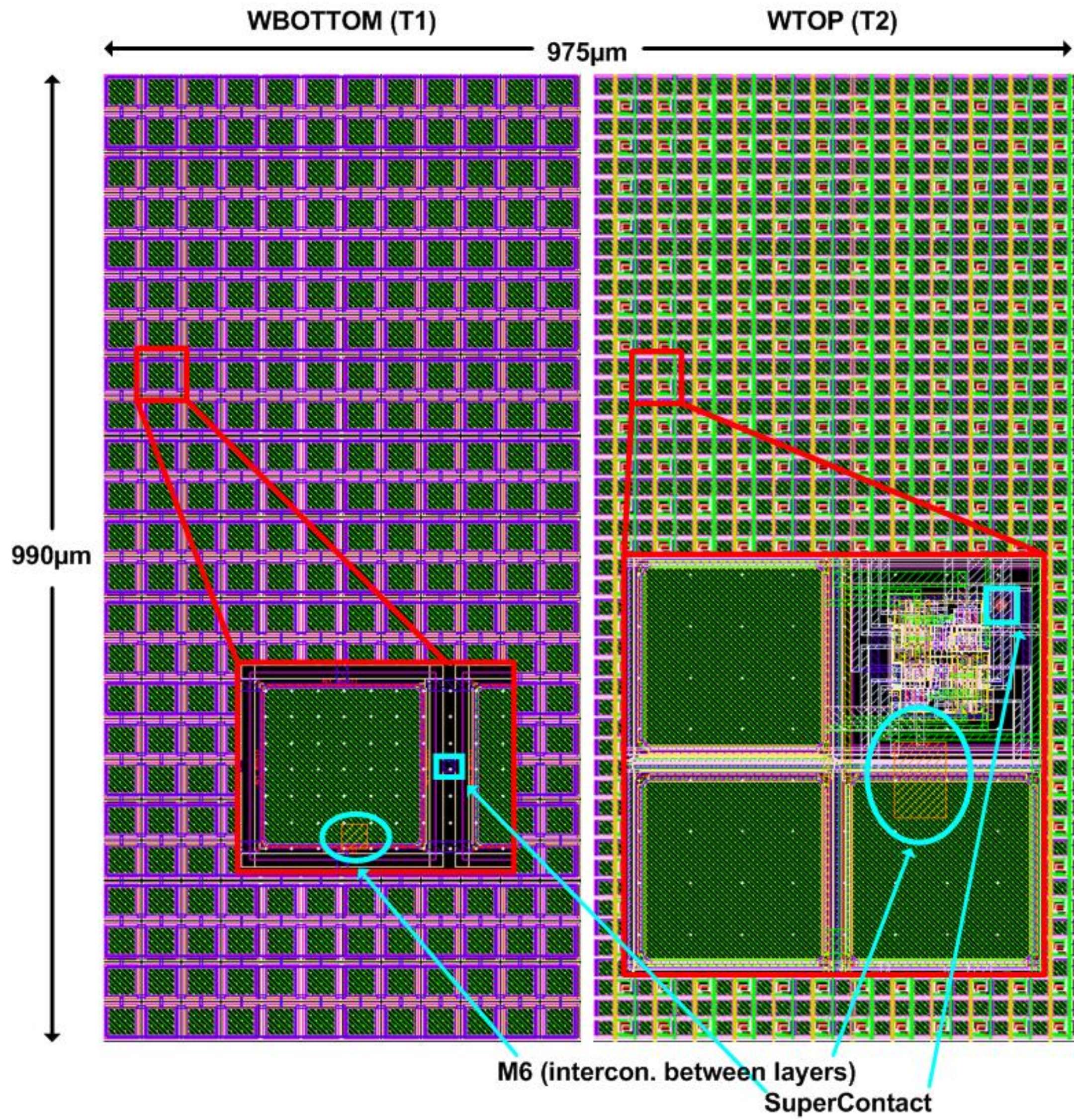


- Array size → 48 rows x 24 columns
- Sensor size → 30µm x 30µm (T1), 18µm x 18µm (T2)
- Interconnection between tiers → 30µm x 30µm GAPD to its readout circuit
- Fill-factor → 92%

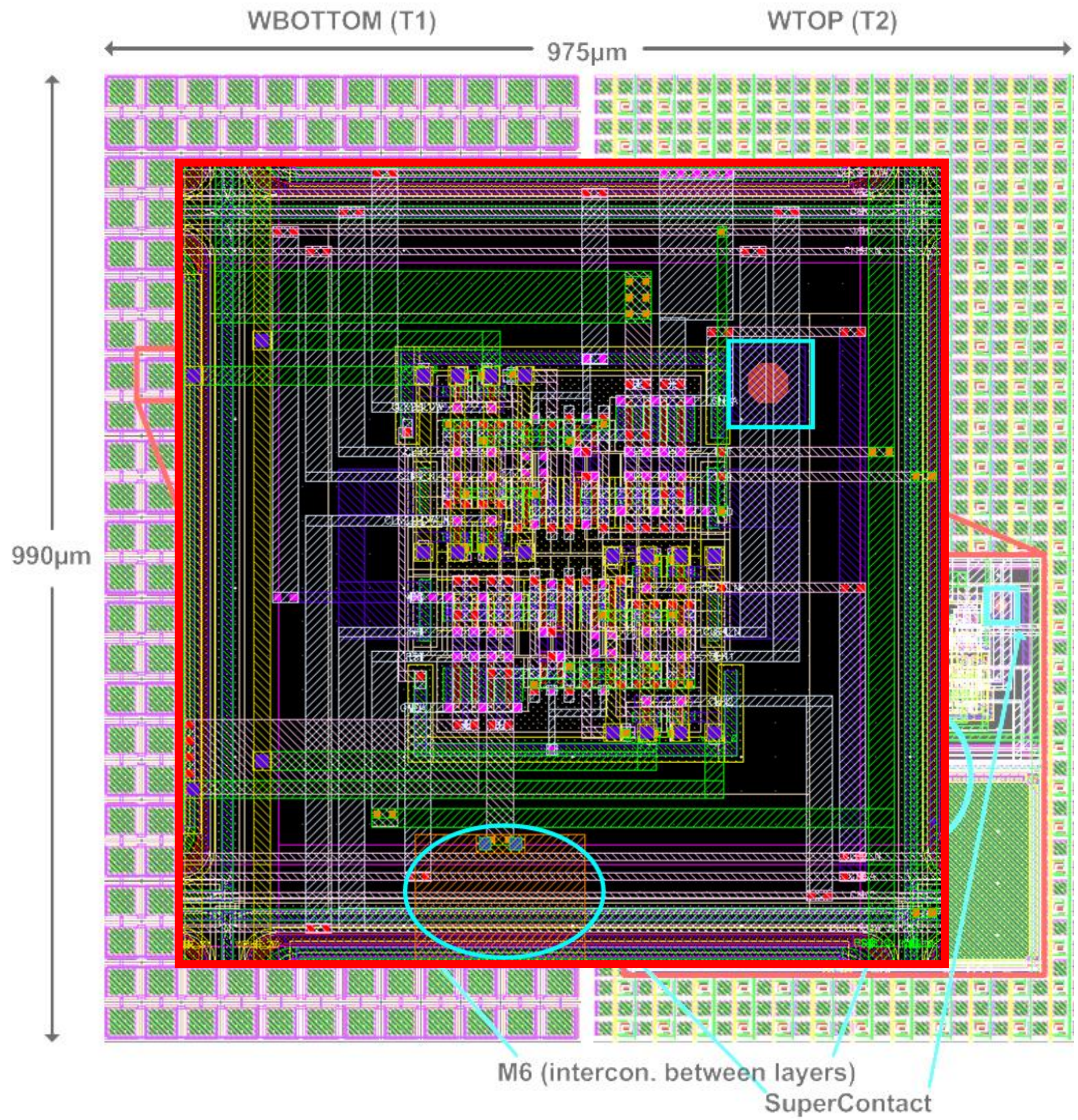
Layout (1)


WBOTTOM (T1)
WTOP (T2)
1068µm
1074µm
M6 (intercon. between layers)
SuperContact

Layout (2)


WBOTTOM (T1)
WTOP (T2)
975µm
990µm
M6 (intercon. between layers)
SuperContact

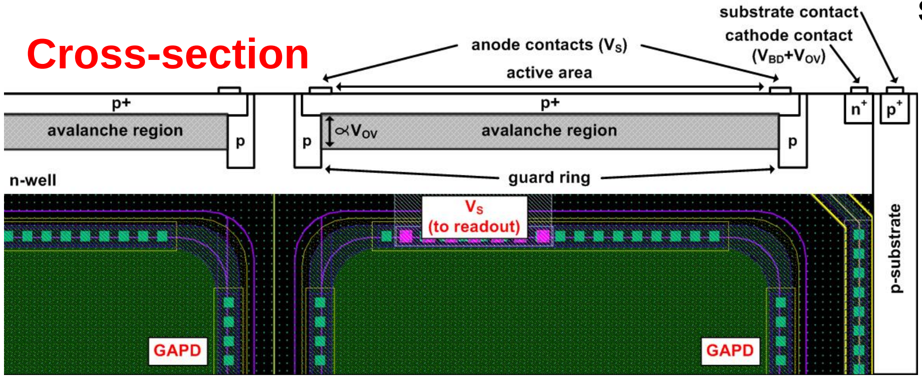
Layout (2)


WBOTTOM (T1)
WTOP (T2)
975µm
990µm
M6 (intercon. between layers)
SuperContact

Alternative solutions (HV-AMS)

- **Standard technology HV-AMS 0.35µm**

Cross-section



No STI !

In this particular technology, and with our structure, the guard ring is sensitive → ≈ 100% fill-factor seems feasible (2)

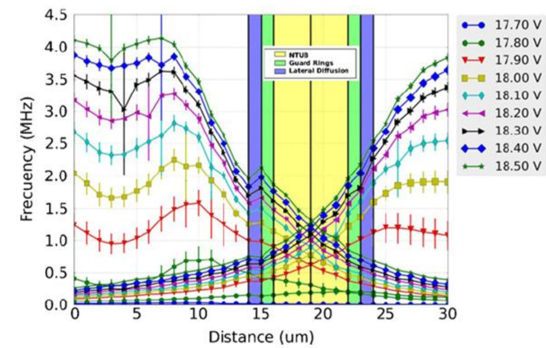
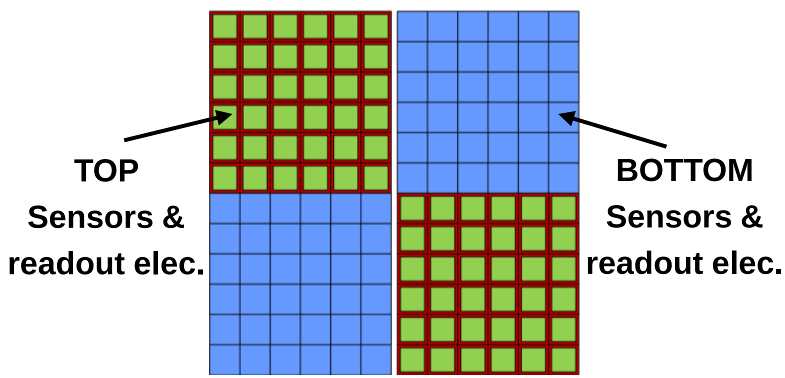
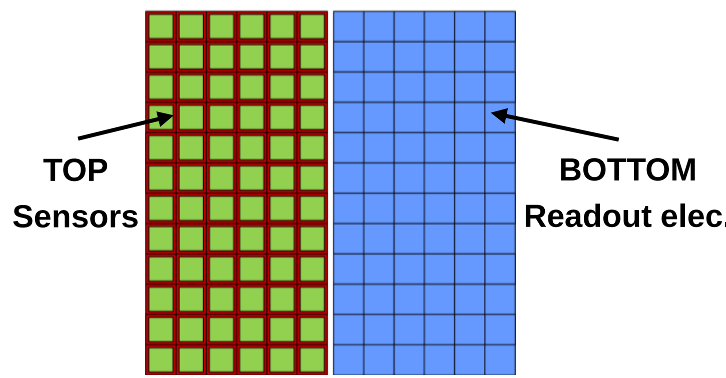


Fig. 16. Detection frequencies measured by scanning a 30 keV electron beam onto two neighbouring pixels in the array.

- **2-layer stack → Possible structures**





(2) A. Vilà, Characterization and simulation of avalanche photodiodes for next-generation colliders, Sens. Actuators A (2011).

Conclusion

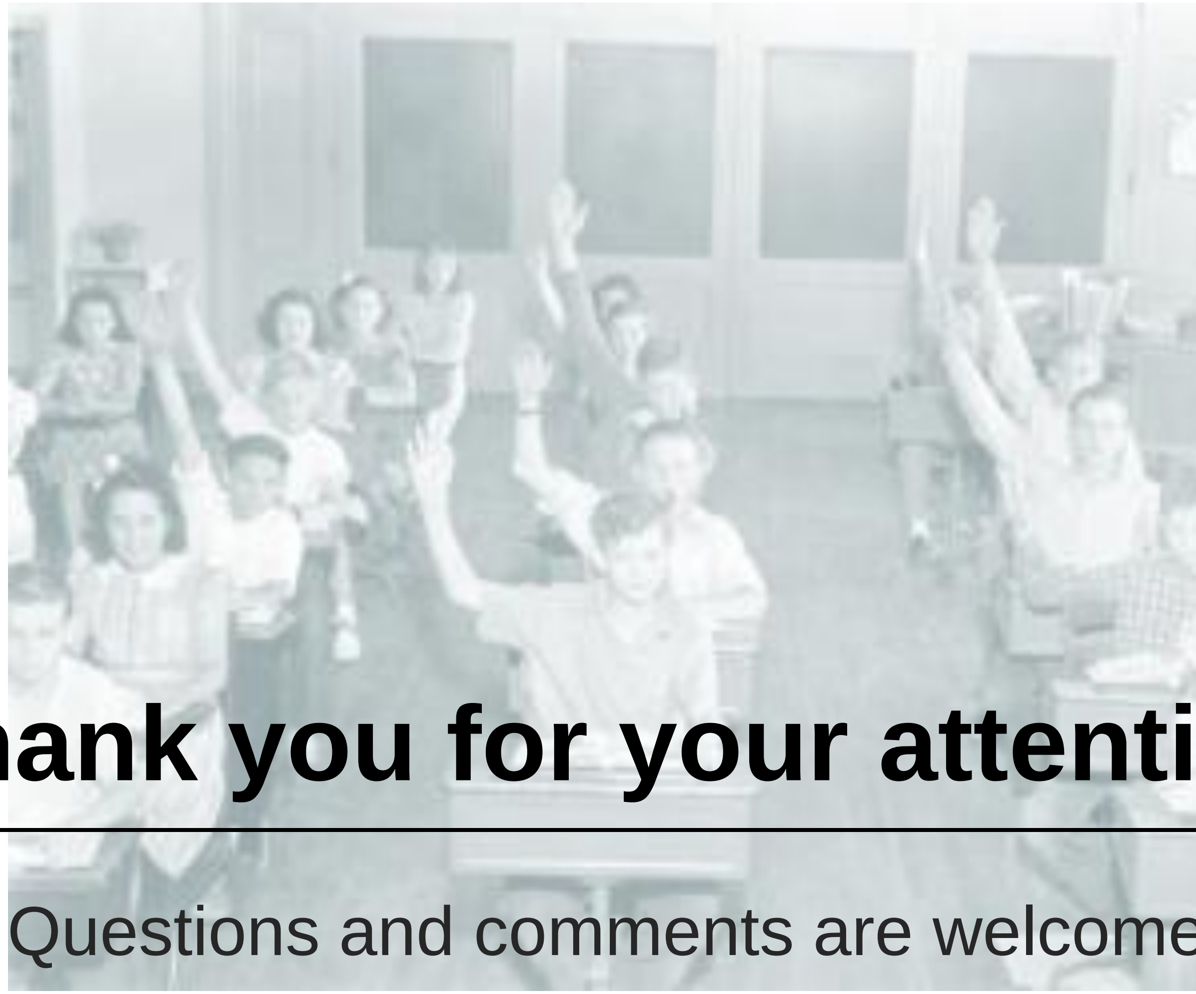
✓ A 3D-IC GAPD array

- Chartered 130nm/Tezzaron 3D (2-layer stack option)
- Array size → 48 rows x 48 columns (≈ 1mm x 1mm)
- 2 different structures with the same pixel schematics
  1) WBOTTOM → electronics; WTOP → sensors (48 rows x 24 cols)
  2) WBOTTOM → sensors; WTOP → sensors & electronics (48 rows x 24 cols)
- Sensor size → 18µm x 18µm, 30µm x 30µm
- Time-gated operation
- Passive quenching, active recharge/inhibit
- Sequential readout by structures and rows

✓ Achievements

- The fill-factor is increased up to 66% (1) and 92% (2) with this 3D-IC process
- We expect to reduce the noise down to 10^{-4} fake pulses per frame with the time-gated operation

✓ Our plan is to send the design for the next Tezzaron run via CMP (20th Sep. 2012?)



Thank you for your attention

Questions and comments are welcome