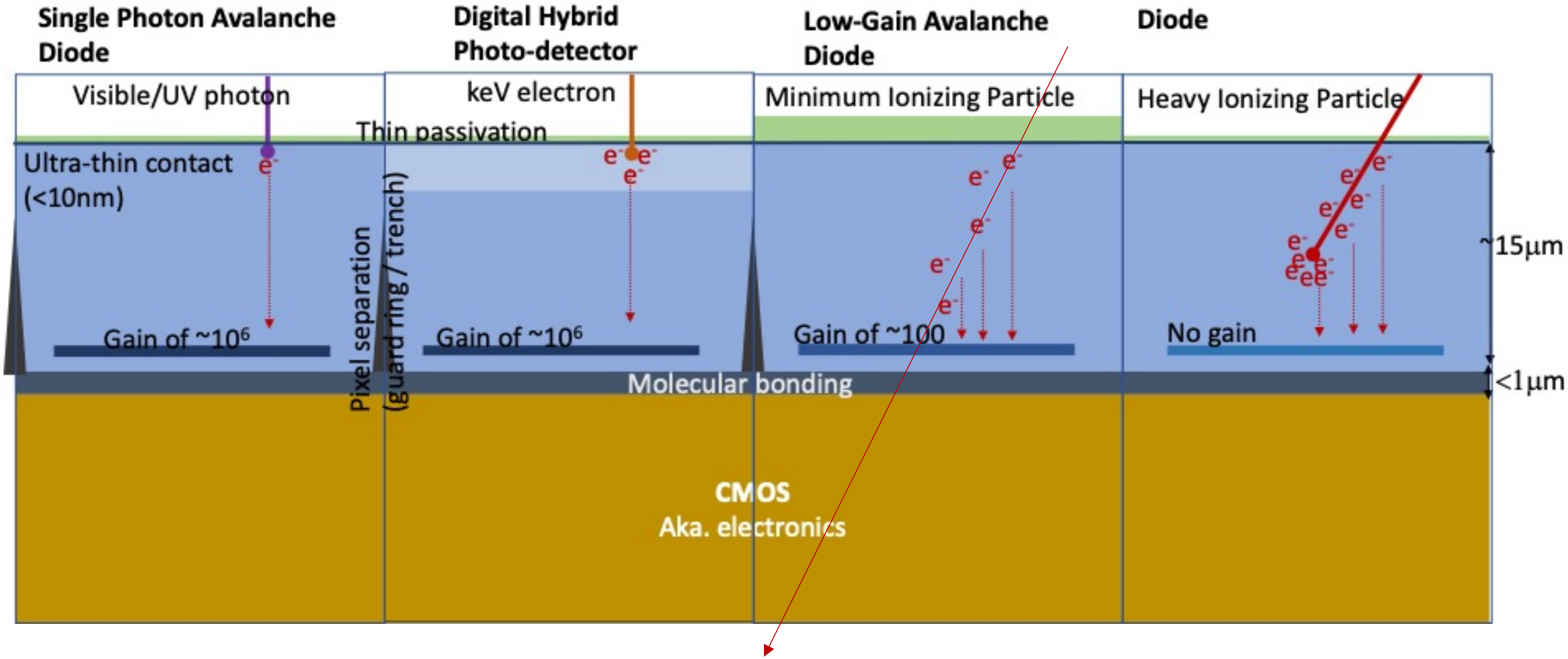
Particle/Photon to Digital Converter
Harnessing the power of 3D integration

Fabrice Retière (TRIUMF)

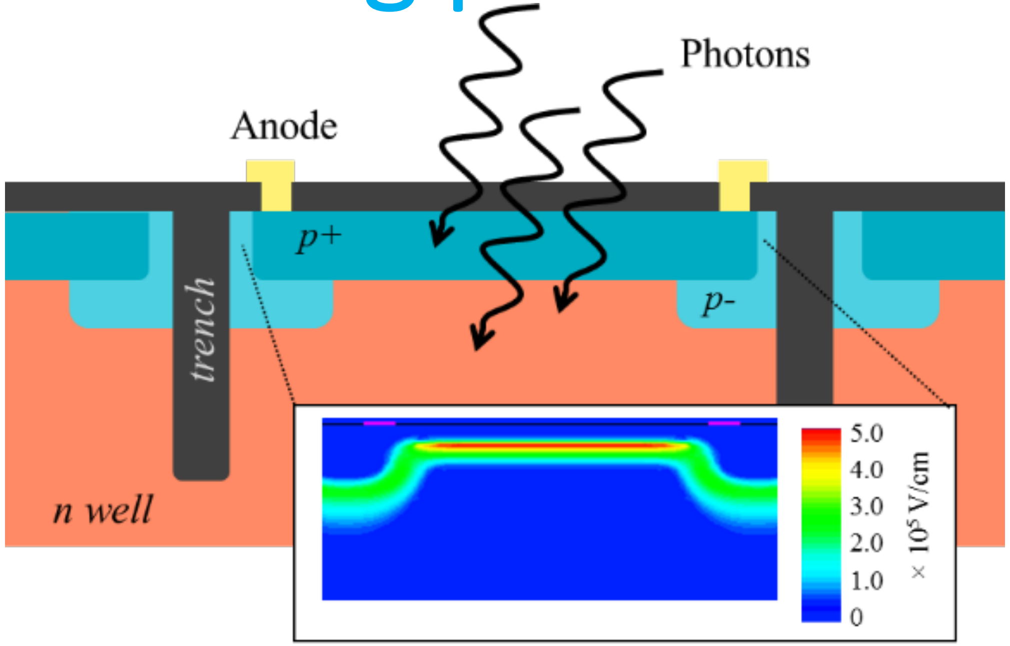
Part of the PDC group but not all ideas have been discussed

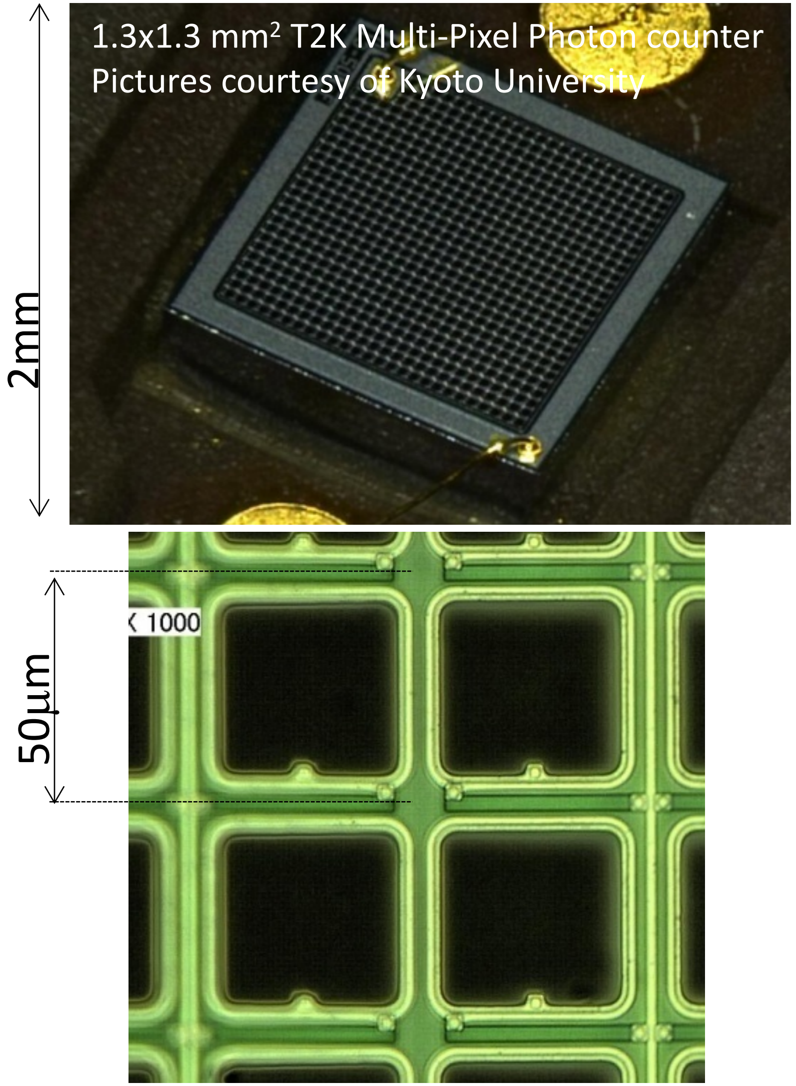
Discovery, accelerated

This talk in one slide



Starting point- SiPM





- Avalanche gain ~10^6
- Avalanche evolution jitter <100ps

K. Yamamoto et al. PD07(04)

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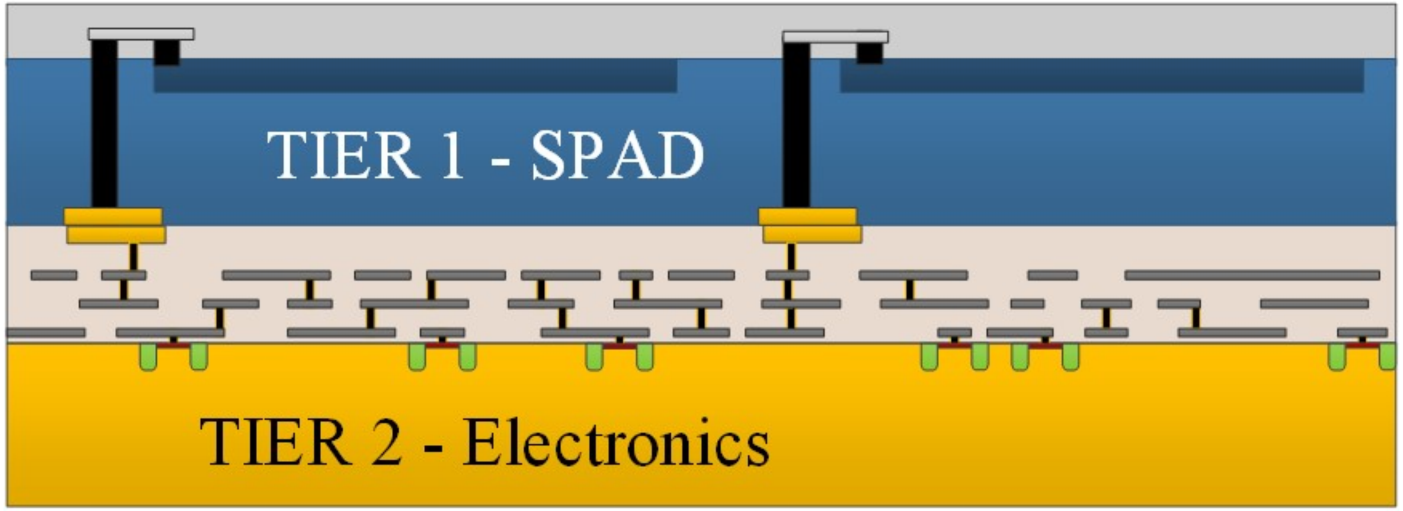
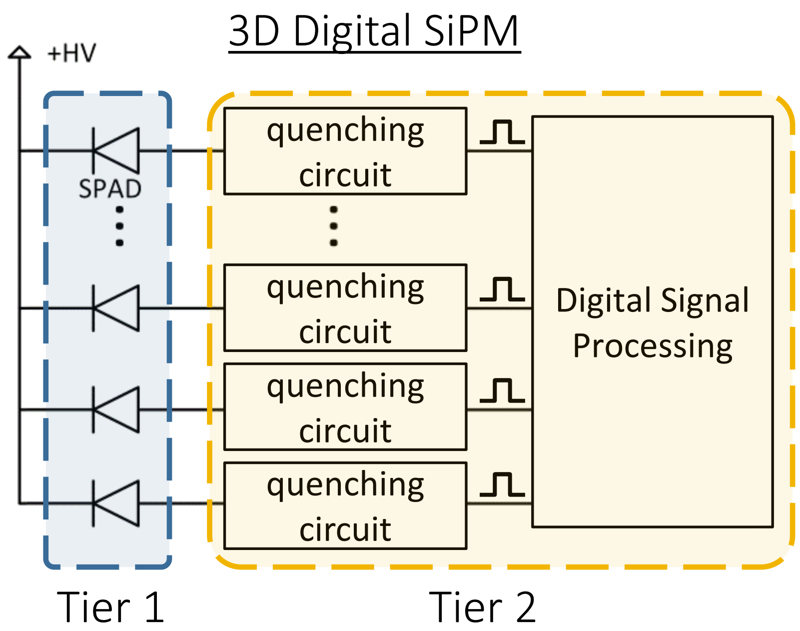
Next step- 3D integrated digital SiPM



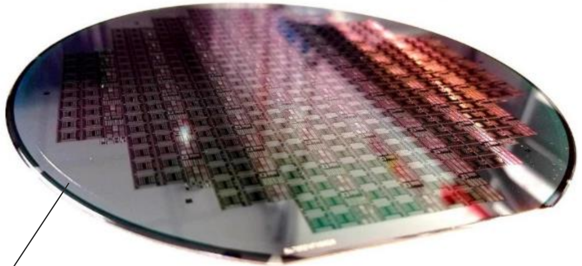


Discovery, accelerated

How to Build a Fully Industrial 3D Digital SiPM ?

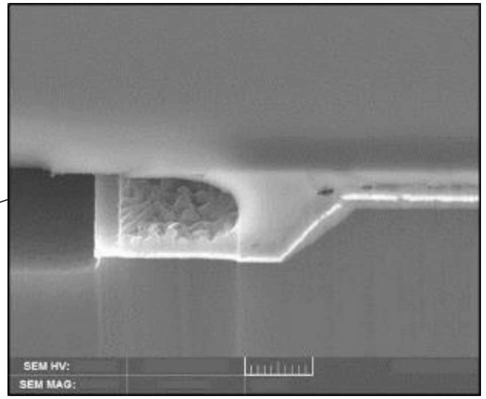
Partnership with Teledyne DALSA Semiconductor Inc.
(Bromont QC, Canada)

TELEDYNE DALSA
Everywhereyoulook™

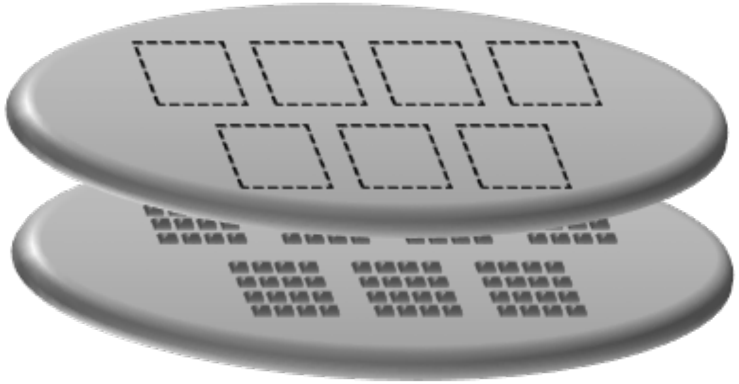


SPAD process

3D process



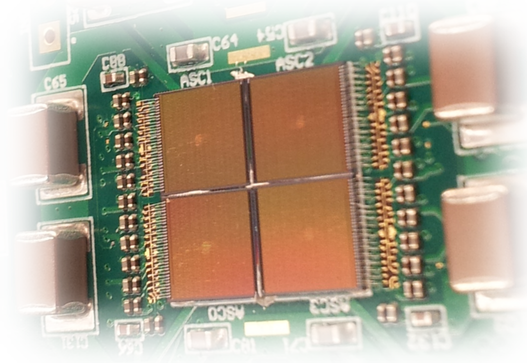
Wafer scale 3D digital SiPM technology



SPAD array layer

Wafer level process

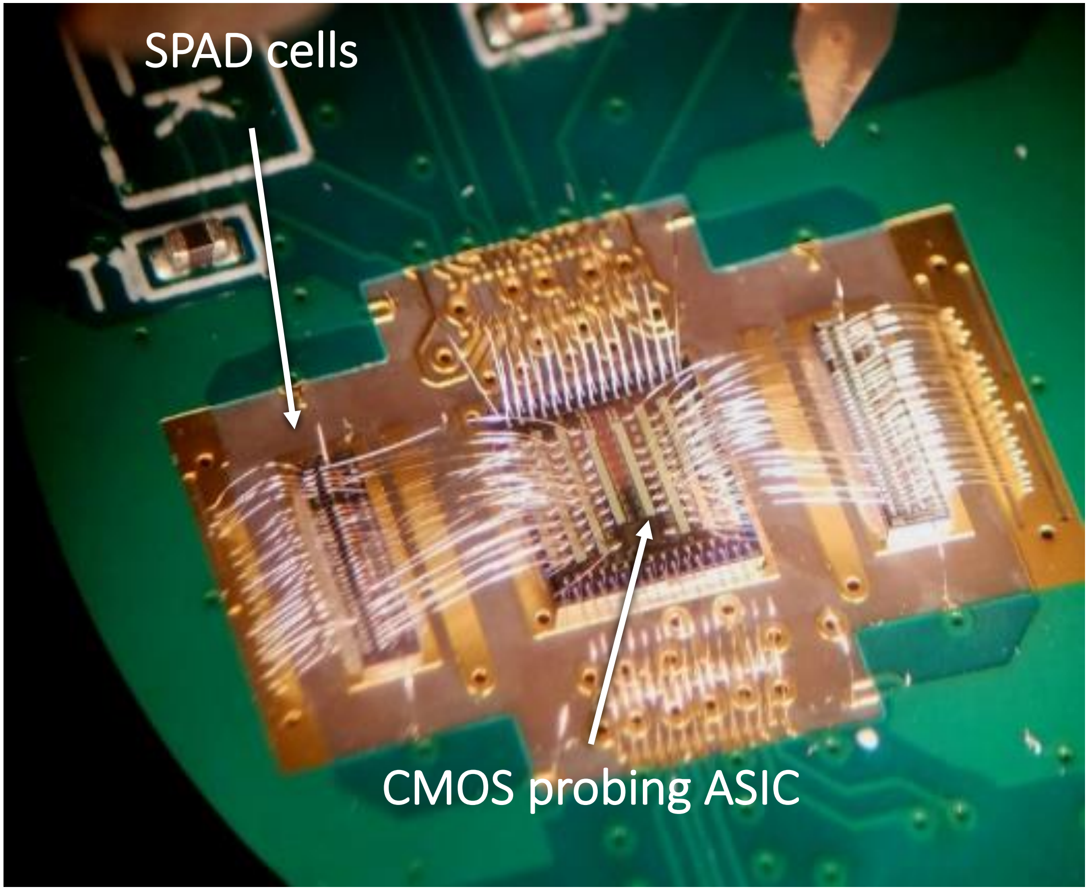
CMOS readout

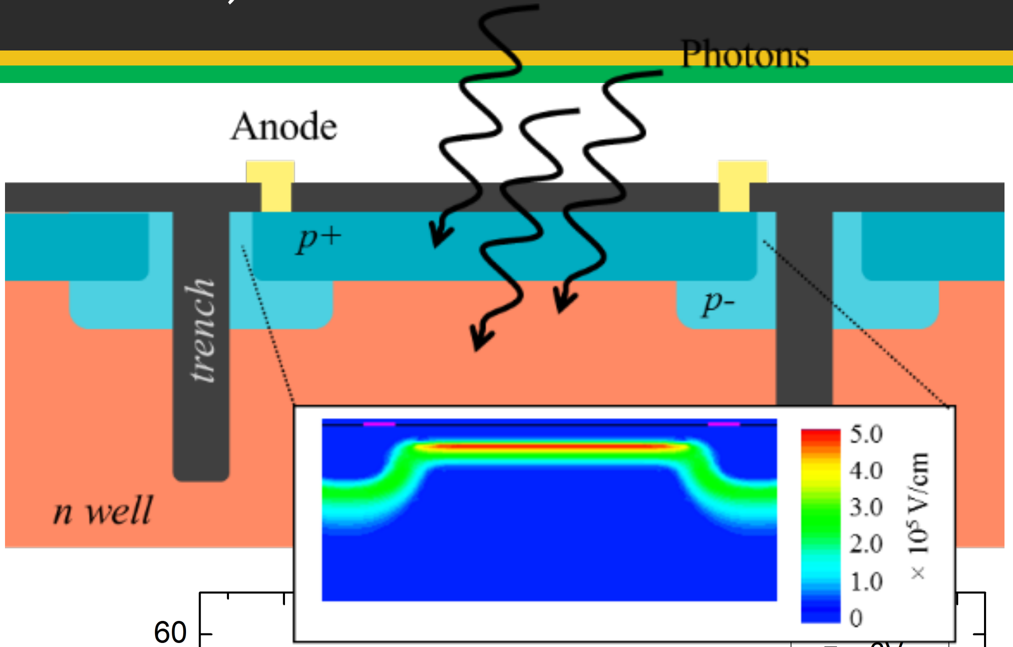


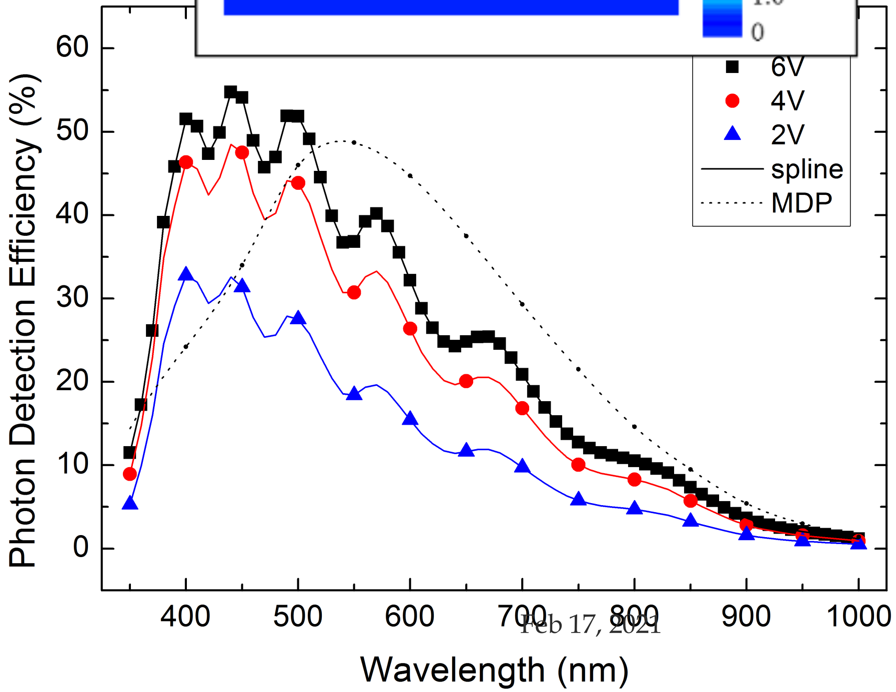
TSMC CMOS readout

2D SPAD made-in Canada (Bromont, QC)

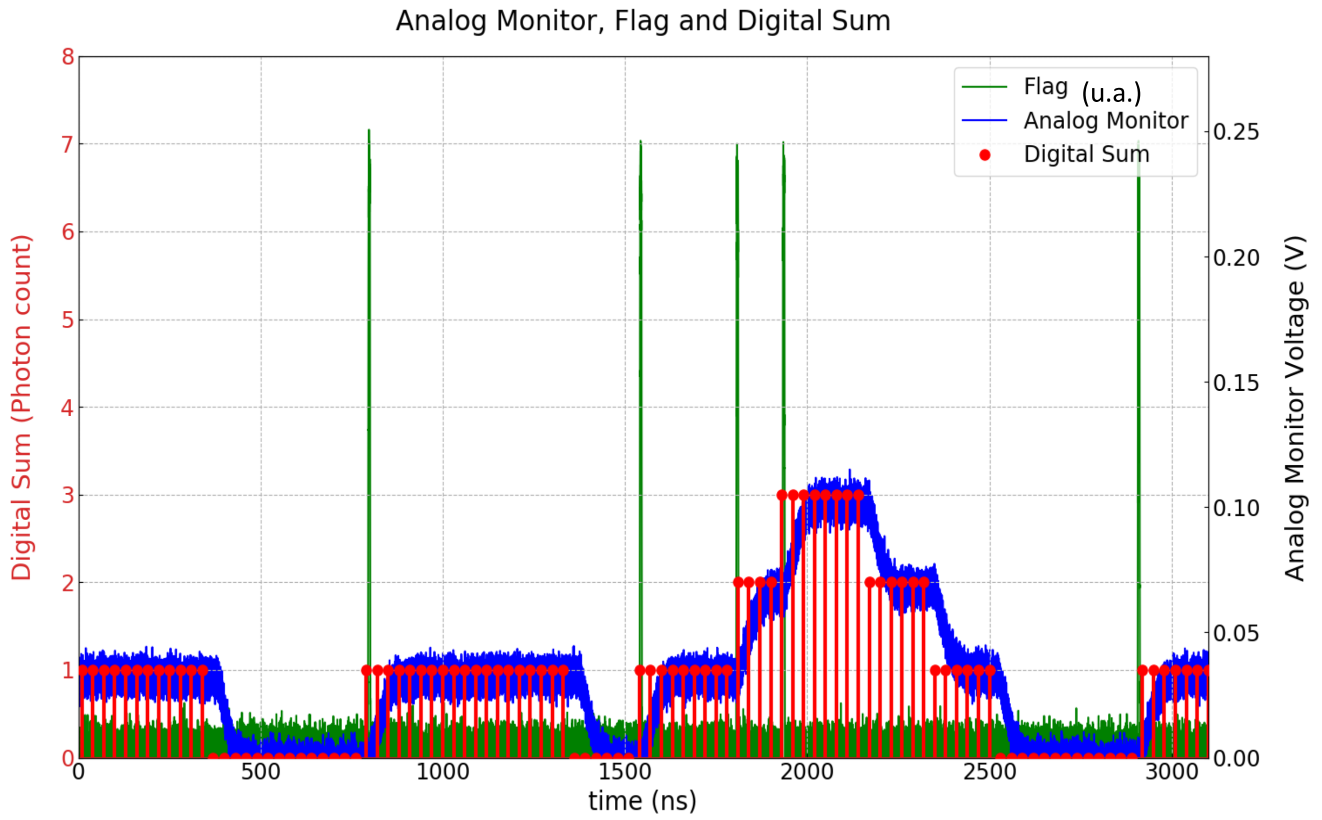
- 150 mm wafer (custom process using DALSA CCD production line)
- 1x1 to 5x5 mm^2 SPAD array



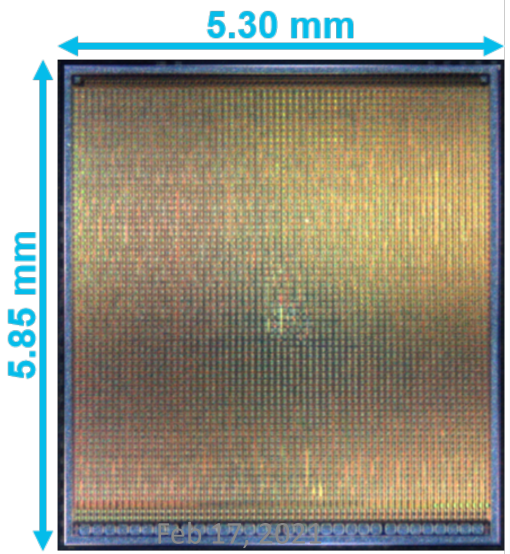




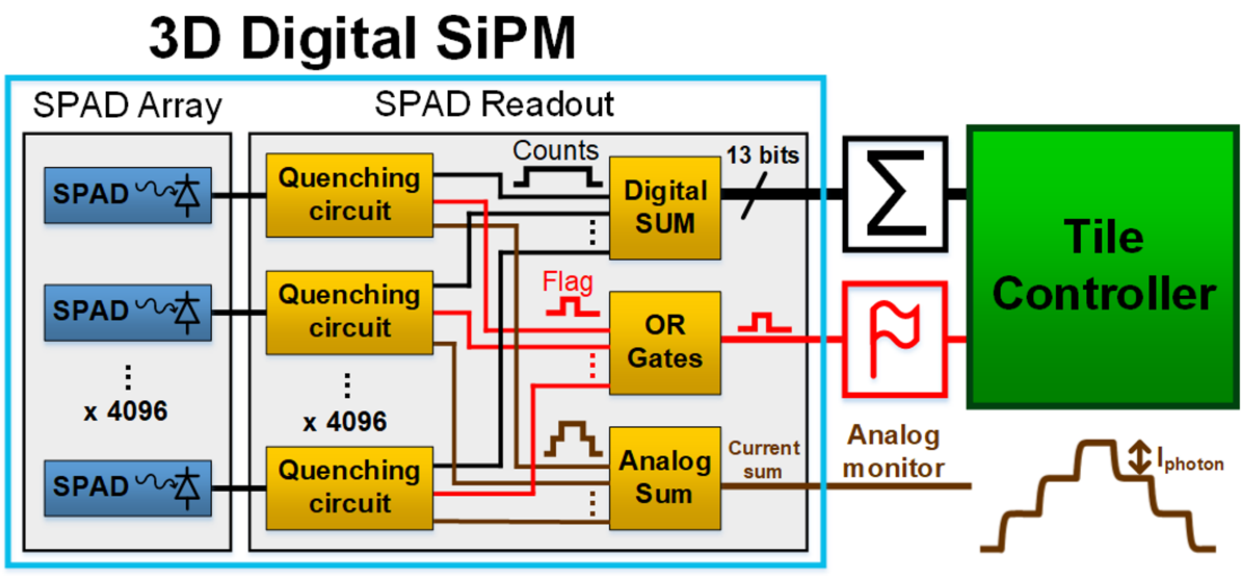
CMOS



Analog Monitor, Flag and Digital Sum
Flag (u.a.)
Analog Monitor
Digital Sum
Digital Sum (Photon count)
Analog Monitor Voltage (V)
time (ns)
0
500
1000
1500
2000
2500
3000
0.00
0.05
0.10
0.15
0.20
0.25



5.30 mm
5.85 mm



3D Digital SiPM
SPAD Array
SPAD Readout
SPAD
x 4096
Quenching circuit
Counts
Digital SUM
13 bits
Flag
OR Gates
Analog Sum
Current sum
Analog monitor
Tile Controller
I_{photon}

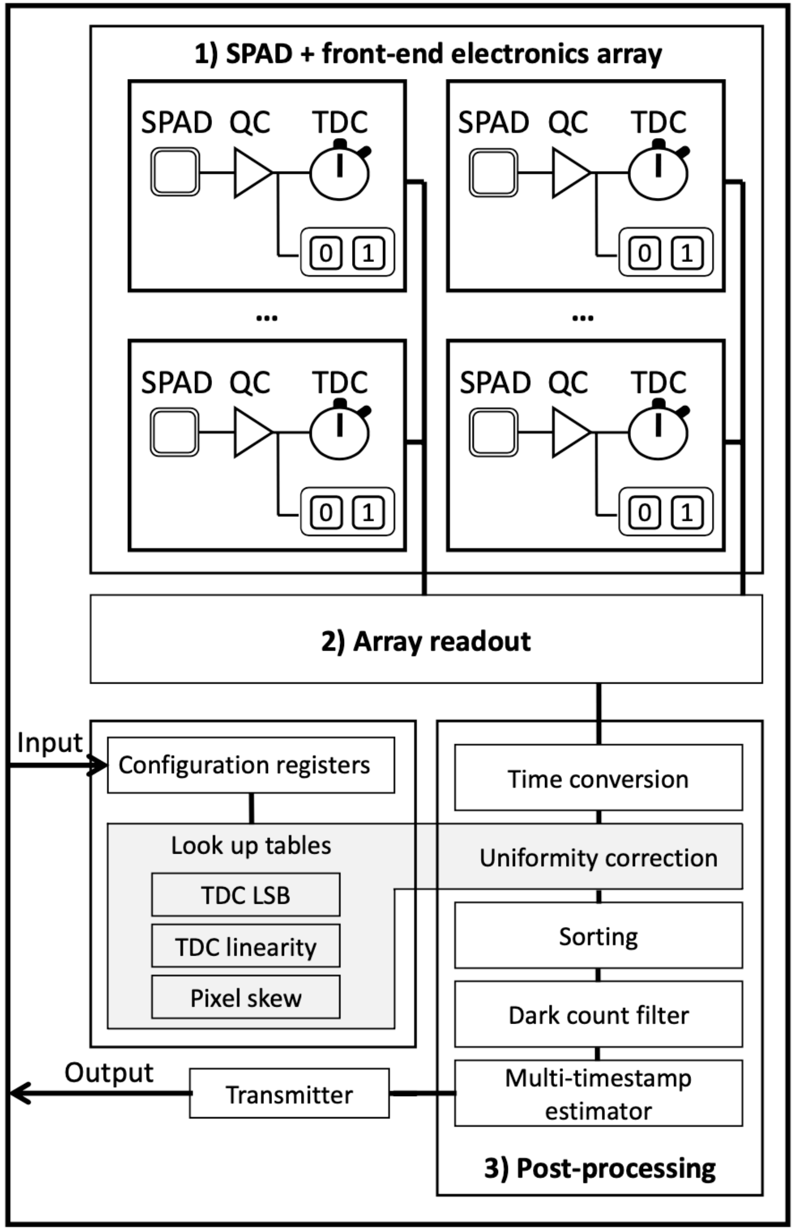
CMOS functionalities

- Timing with minimum position information for SPADs
- Not an intrinsic limitation
- In principle, can be tailored as needed

Review

3D Photon-to-Digital Converter for Radiation Instrumentation: Motivation and Future Works

Jean-François Pratte *, Frédéric Nolet *, Samuel Parent, Frédéric Vachon, Nicolas Roy, Tommy Rossignol, Keven Deslandes, Henri Dautet, Réjean Fontaine and Serge A. Charlebois



Direct Bond interconnect, the enabling technology

- Teledyne DALSA in Quebec expected to provide access to technology

Bloomberg

Business

Invensas Announces Teledyne DALSA Signs DBI Technology Transfer and License Agreement

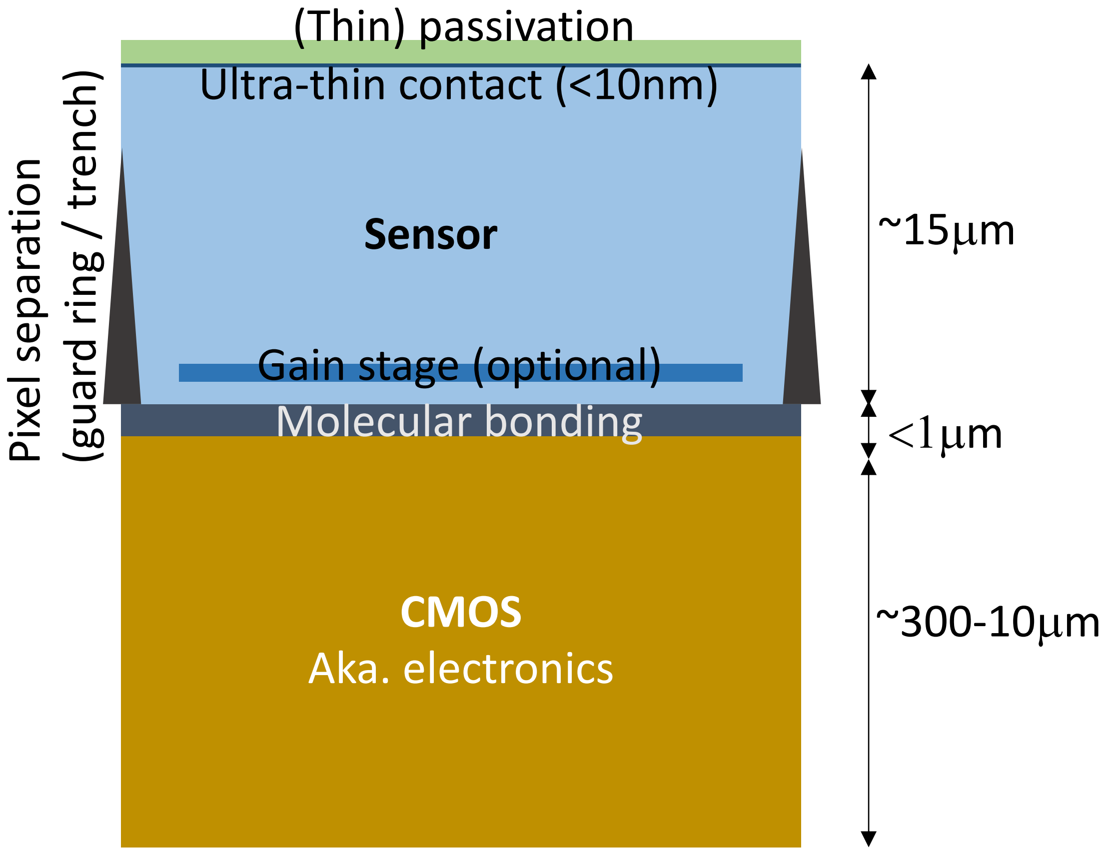
February 16, 2017, 1:05 PM PST

Oxide to oxide initial bond at room temperature

Heating Closes Dishing Gap (Metal CTE > Oxide CTE)

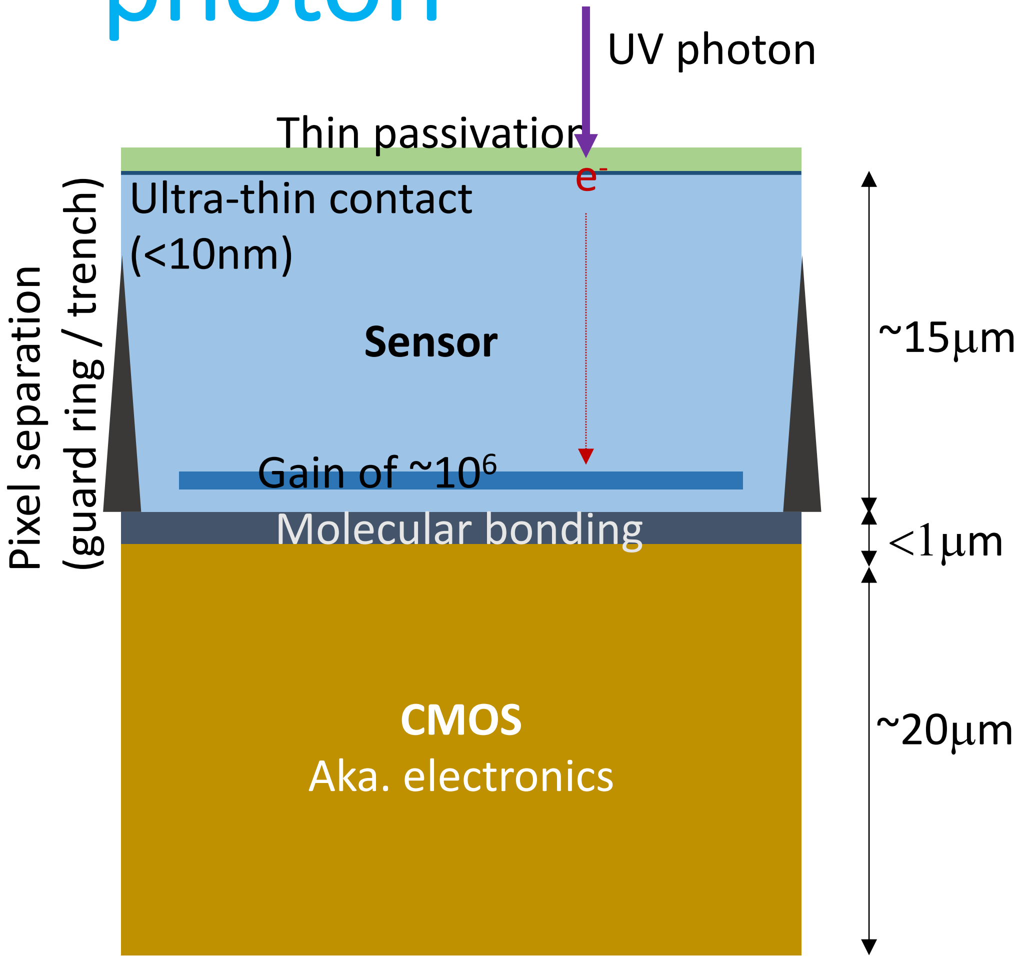
Further Heating Compresses Metal w/out External Pressure

Next step – backside illuminated



- Motivated by VUV photon detection
  - Need ultra-thin top contact (<10nm)
- Enabled by molecular bonding (Direct bond Interconnect)
  - Enable back-side thinning post bonding
  - CMOS chip is handle wafer

Hybrid solution for UV to visible (120-600nm) photon



- Main motivation
  - LXe (175nm) and LAr (128nm) scintillation light
  - $0\nu\beta\beta$ and dark matter search
- Single photon avalanche diode
  - Gain > 10^5
- Advantages
  - Very high efficiency expected (>50%) in UV and visible
  - Single photon timing resolution <50ps

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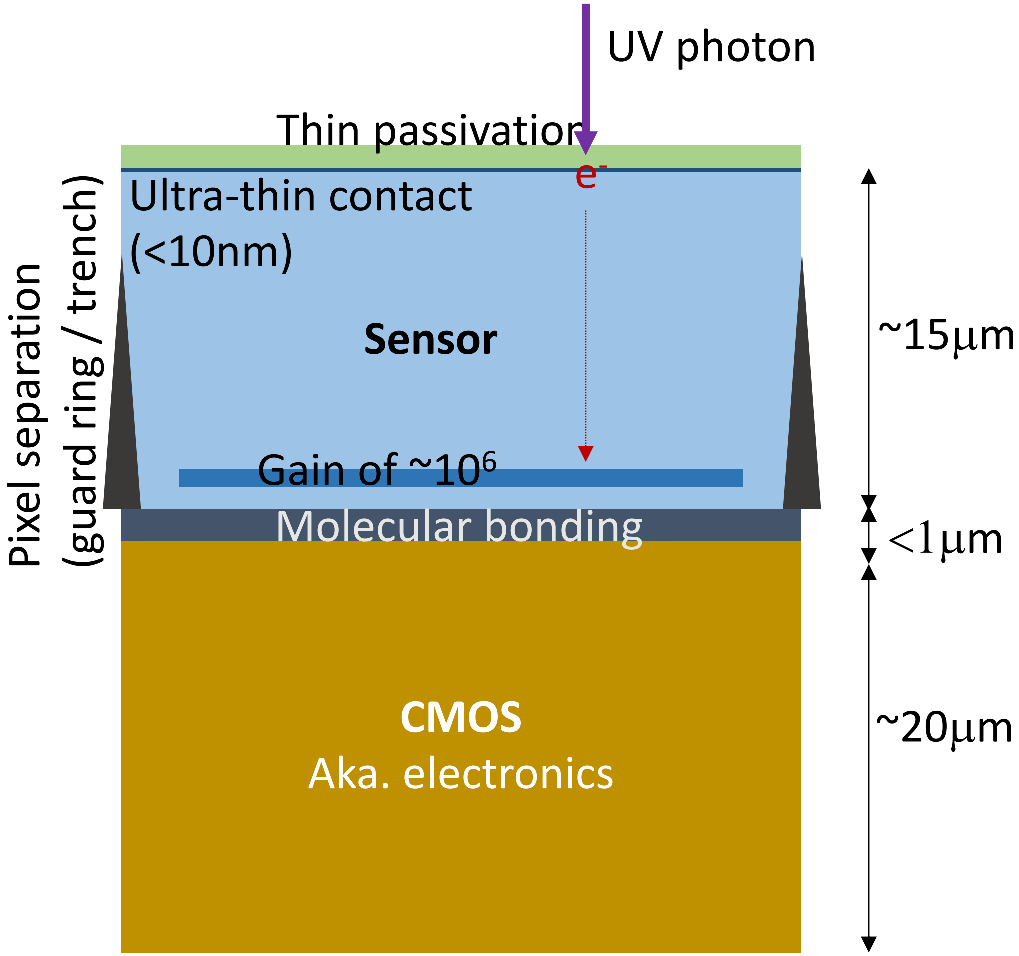
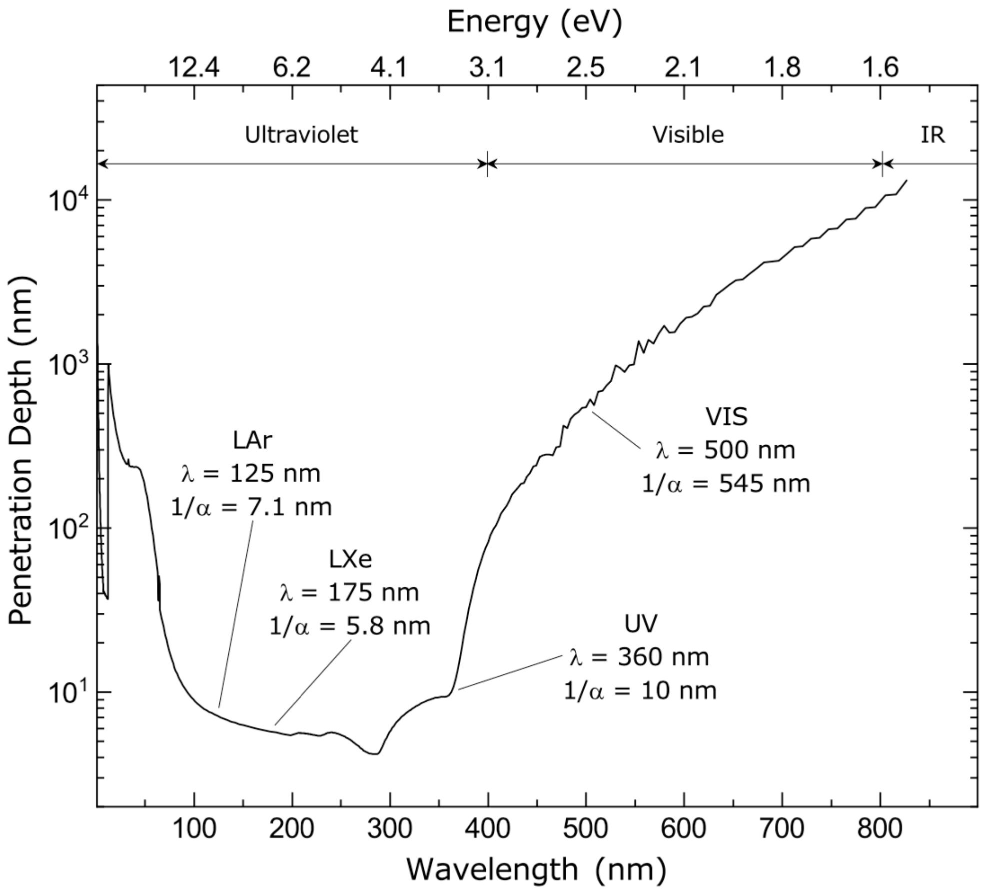
Hybrid solution for red to NIR photons?

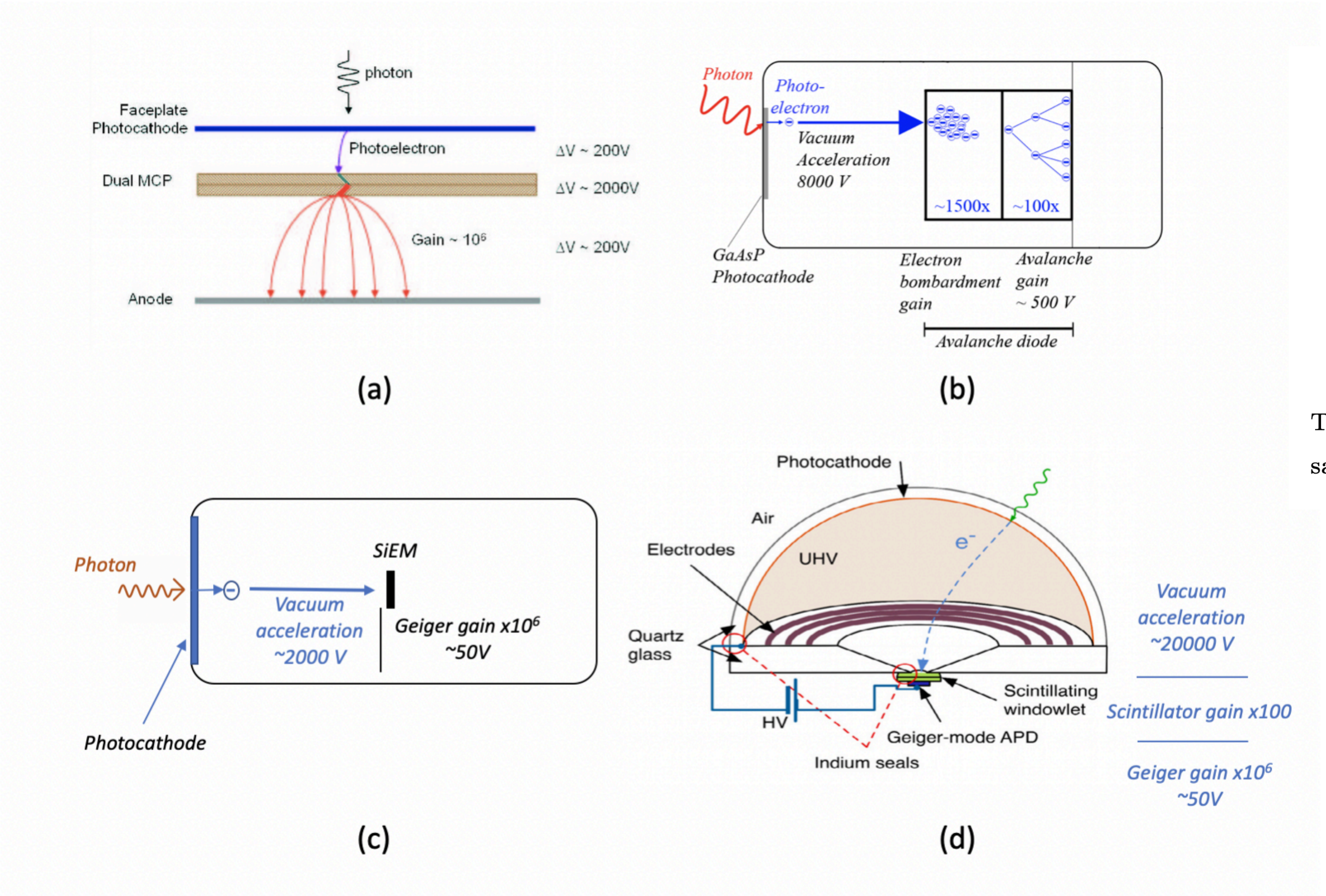


- How far can the sensor be depleted?
- If not depleted – diffusion dominated



Discovery, accelerated

Hybrid photo-detector for lower dark noise



Photodetector	High Gain	Linearity	Photon Counting	Time Response	No Dependance Linearity-Gain	Low Dark Count
PMT	✓	✓	—	✓	—	✓✓
MCP	✓	✓	—	✓✓	—	✓✓
HPD	—	✓✓	✓	✓	✓	≈
VSiPMT	✓	✓✓	✓✓	✓	✓	—
ABALONE	✓✓	≈	≈	✓	✓	✓

Table 1: Resuming table of the outcomes due to physical behaviours. Legend: ✓✓Fully satisfied; ✓Satisfied; ≈ Partially satisfied; — Not satisfied

Understanding VSiPMT: a comparison with other large area hybrid photodetectors

F.C.T. Barbato[a,b,*], G. Barbarino[b]

[a] Department of Physics, University of Naples Federico II
[b] Istituto Nazionale di Fisica Nucleare - Section of Naples

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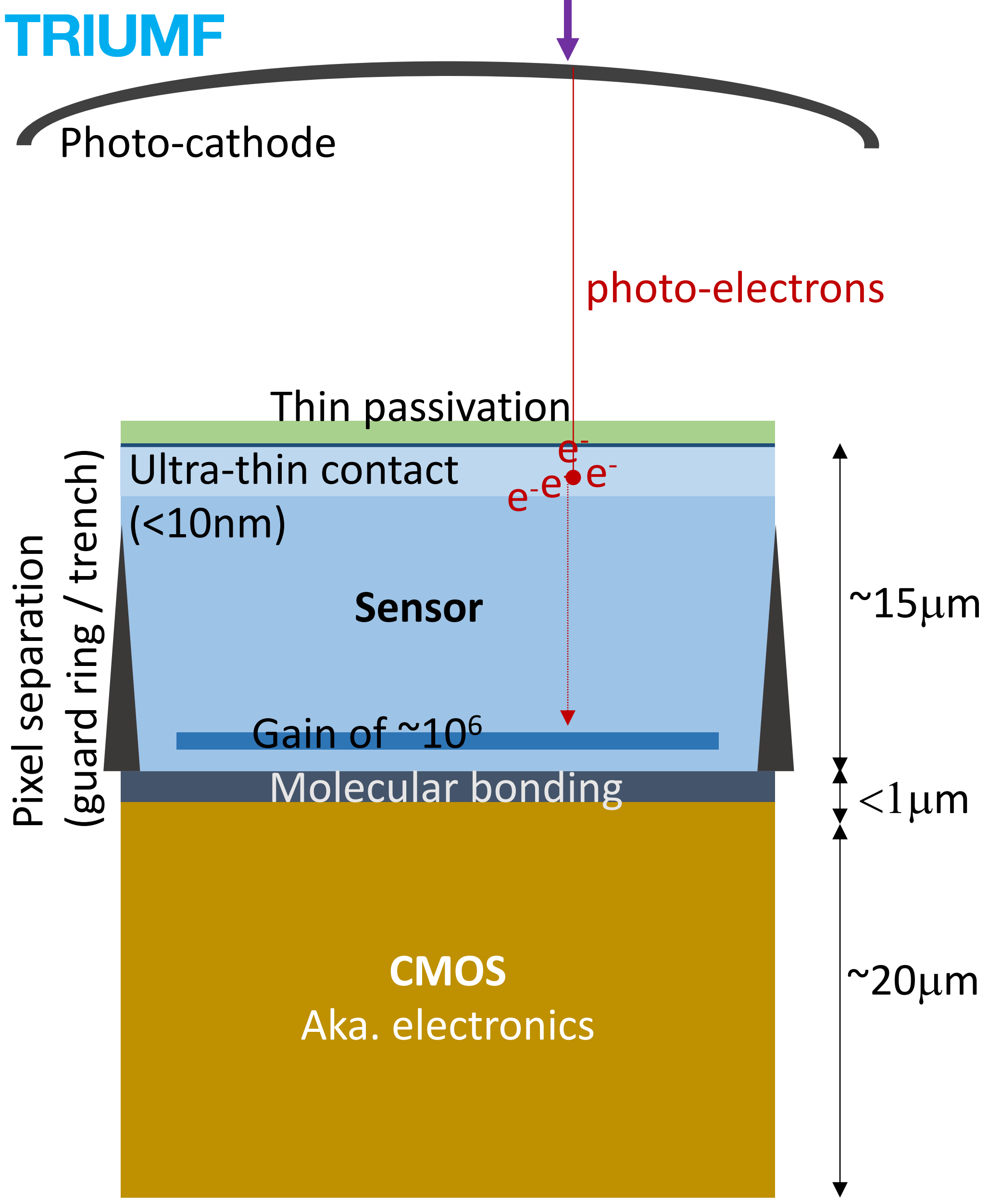
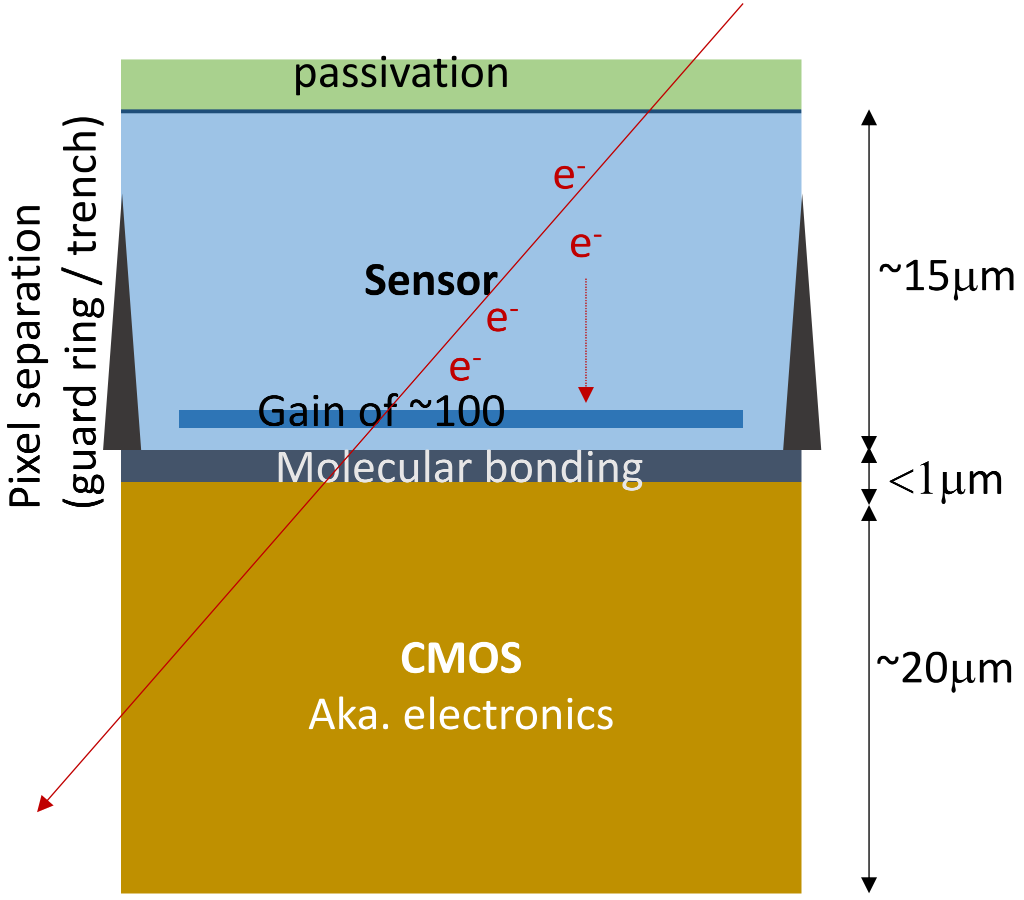


Beating down dark noise using diffusion

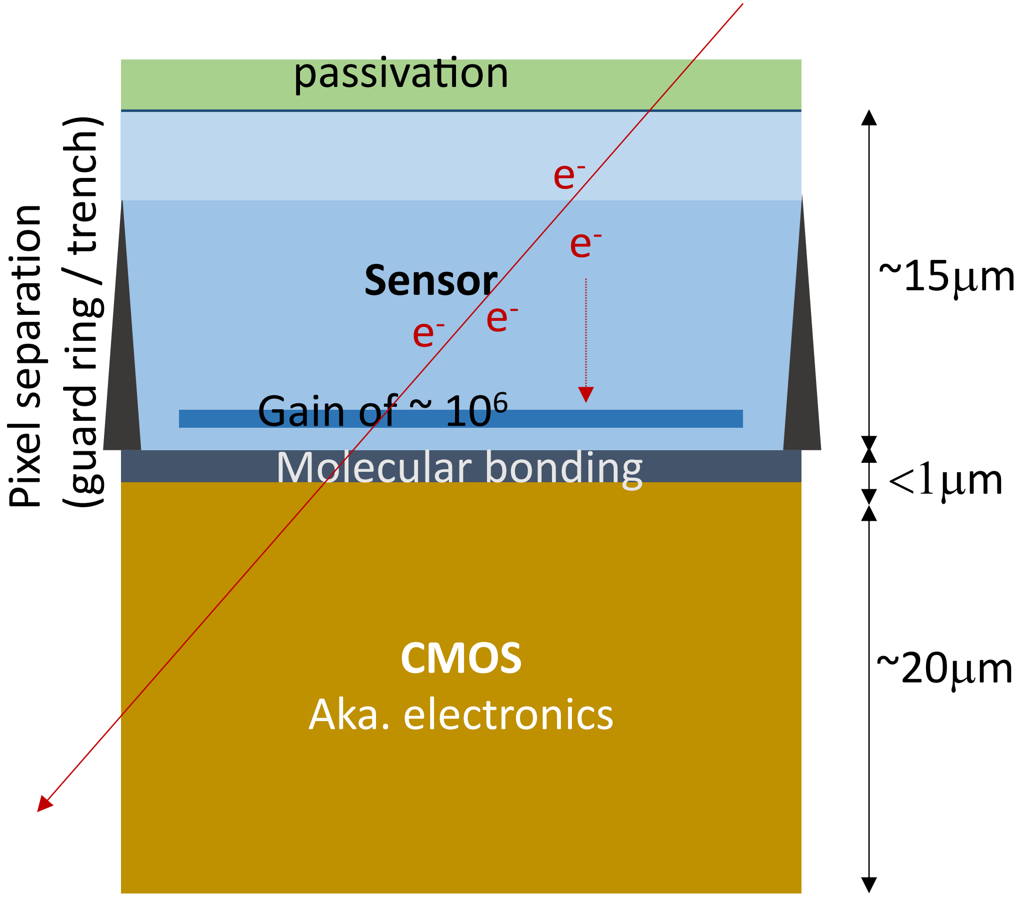
- Essentially identical constraints to VUV photon detections
  - Limit material in path of photo-electron
  - Charge collection very close to surface
- Use diffusion to spread charge on more than one SPAD

Hybrid solution for tracking



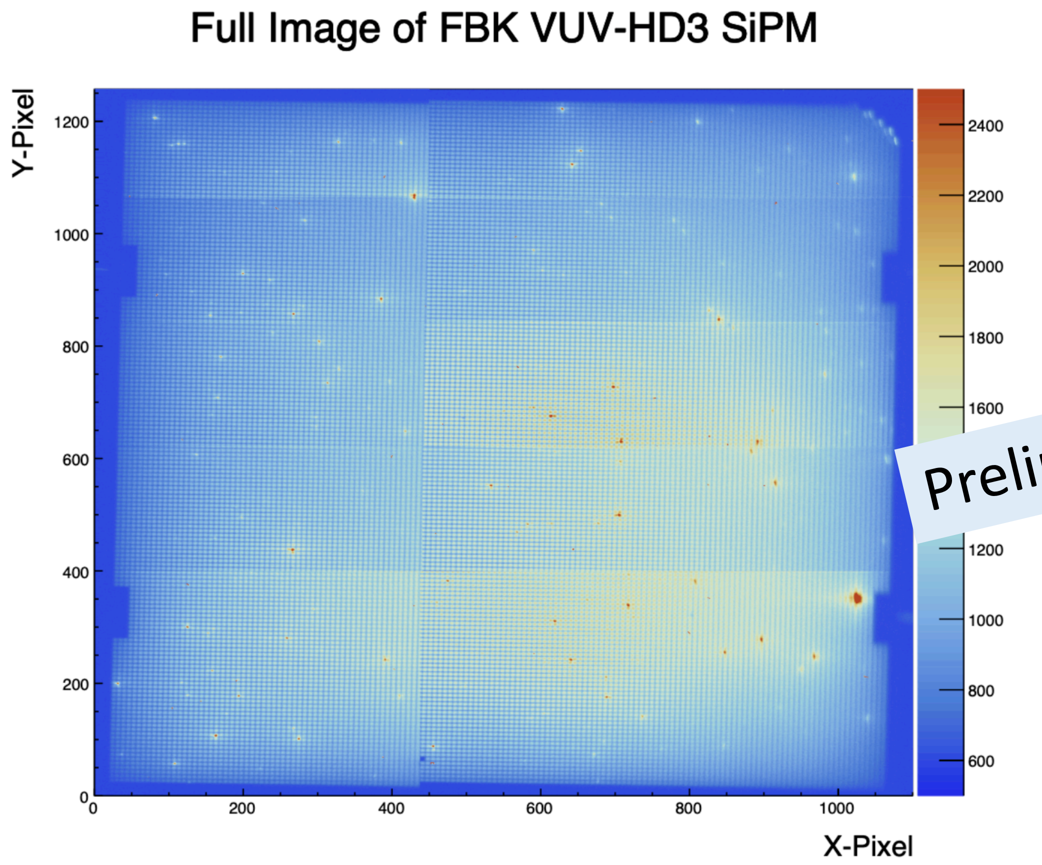
- Low Gain Avalanche diode
  - You are the expert
- Very similar to SPAD though:
  - Proportional gain
    - No light production
  - Does not need trench but may be best for fill factor

SPAD + diffusion for tracking?

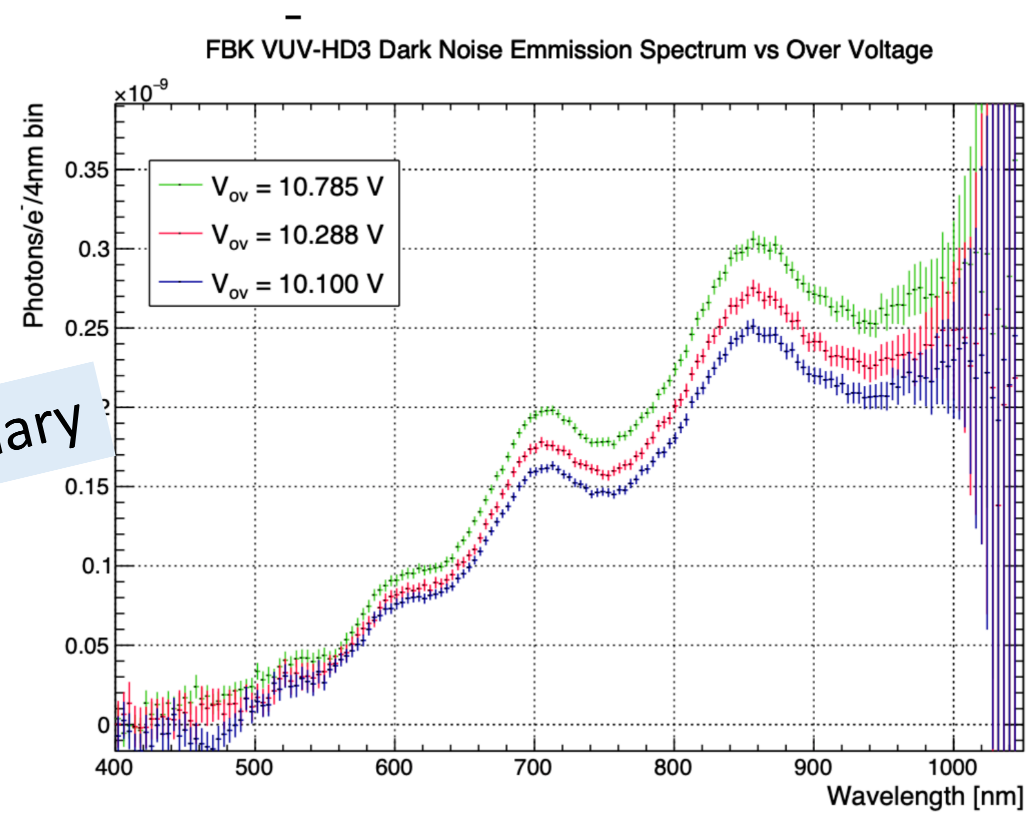


- Pros: timing of SPAD
  - <100ps
- Cons:
  - Need to fire multiple SPADs
    - Diffusion is slow (10-50ns)
  - Radiation hardness of high gain region
  - Photon emission

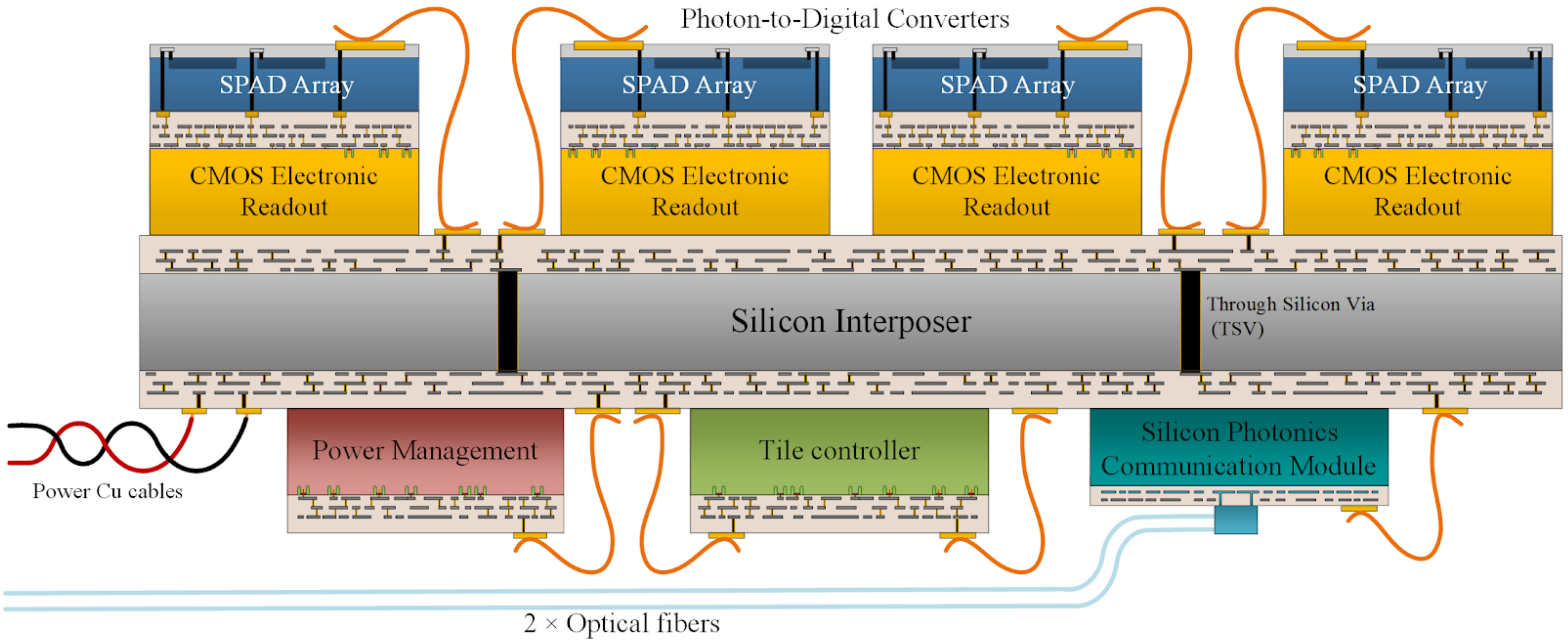
Luminescence, a SPAD problem



Preliminary

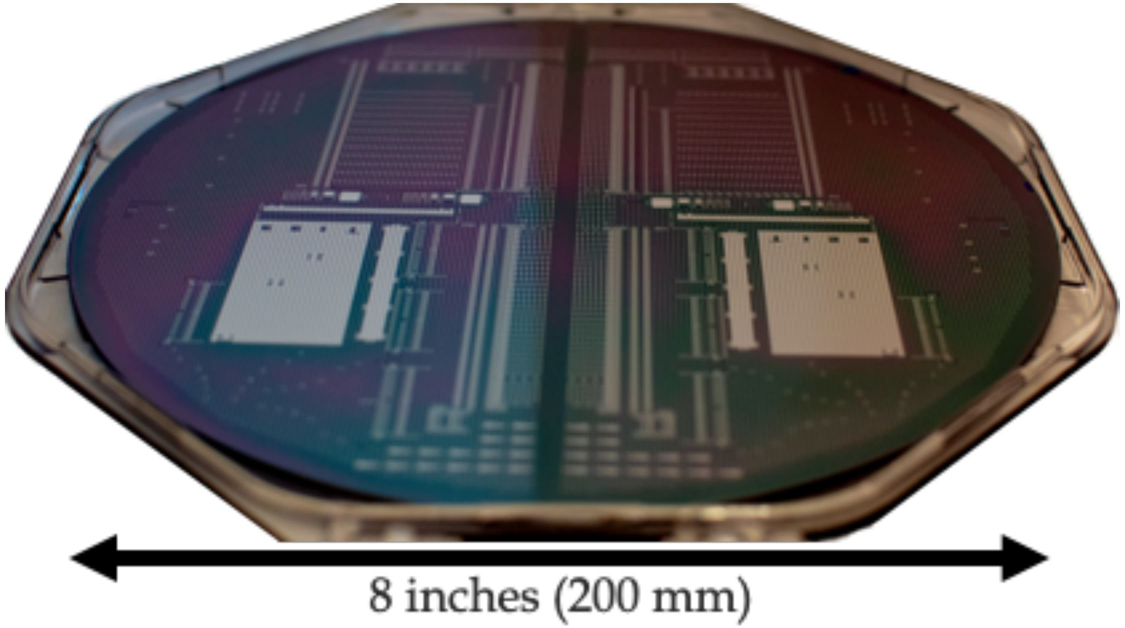


From sensor to module



Silicon interposer

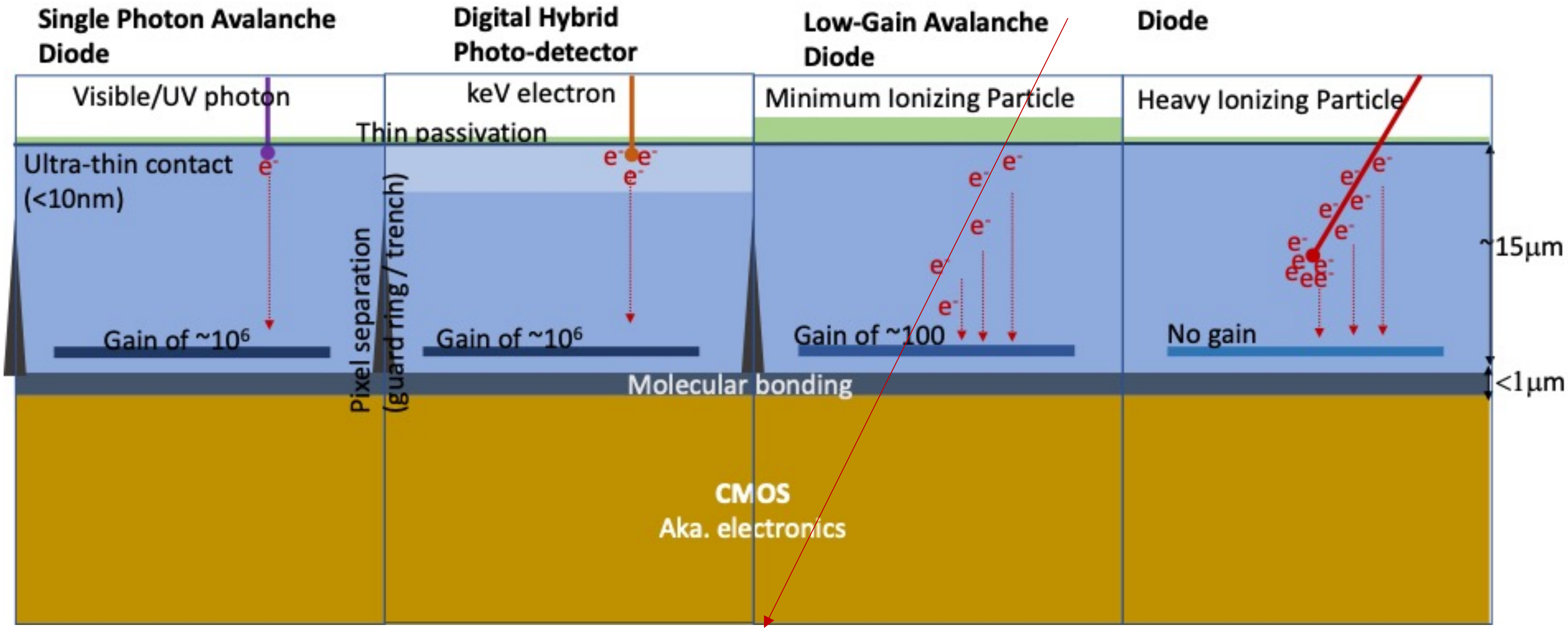
- Motivated by low radioactivity constraint
- Development with Franhoffer IZM



Scaling up to m^2

- Tiling constraints depend on application
  - Silicon interposer compelling for cryogenic, low radioactivity constraint
  - Minimizing radiation length and radiation damage at colliders would probably require a different solution
- Ultra-low power data transfer using photonics is attractive
- Building the capabilities for mass production with industry

Summary


Single Photon Avalanche Diode
Digital Hybrid Photo-detector
Low-Gain Avalanche Diode
Diode
Visible/UV photon
keV electron
Minimum Ionizing Particle
Heavy Ionizing Particle
Thin passivation
Ultra-thin contact (<10nm)
Pixel separation (guard ring / trench)
Gain of ~10⁶
Gain of ~10⁶
Gain of ~100
No gain
~15μm
<1μm
Molecular bonding
CMOS
Aka. electronics

Many technology transfer opportunities

- Time of Flight Positron Emission Tomography Single Photon Air Analyser (led by TRIUMF)
  - Used for smoke (even early forest fire detection) and pollution detection
- Quantum communication and computing
  - Very promising with compelling physics experiment “spin-off”
- 3D imaging coupled to pulse light source
  - LiDAR – major market but probably too big to chew