NIR-sensitive single-photon devices (SiPM and SPADs in custom technologies), for industrial and automotive LIDAR applications

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Outline

- Introduction on FBK research topics
- Single photon avalanche diodes (SPADs) and Silicon photomultipliers (SiPMs)
  - SiPM characteristics and typical applications
  - FBK SiPM technologies roadmap: “High-density” and “ultra high density” tech.
- Emerging applications for SiPMs
  - NIR spectroscopy and diffuse optics
  - LiDAR (automotive and industrial): requirements, working principle
- NIR-sensitivie SiPM technology optimization
  - Issues and requirements
  - Current development and performance
- IPCEI at FBK: roadmap and plans for future NIR tech. with 3D integration
  - TSVs on front-illuminated 3D integrated structures
  - Back side illuminated, with charge-drift engineered future NIR SiPM for LiDAR

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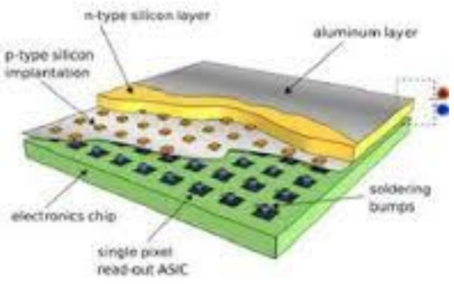
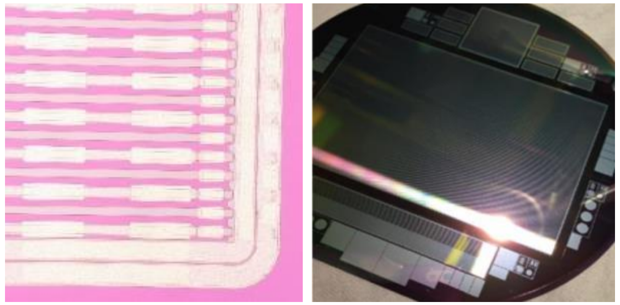
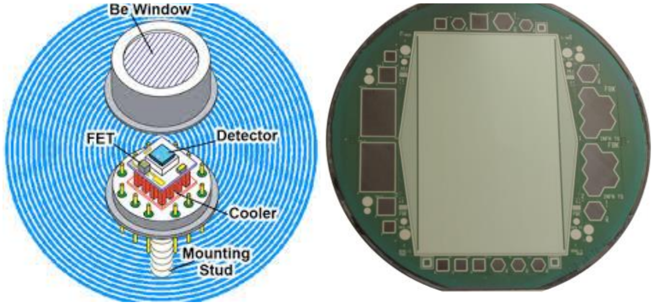
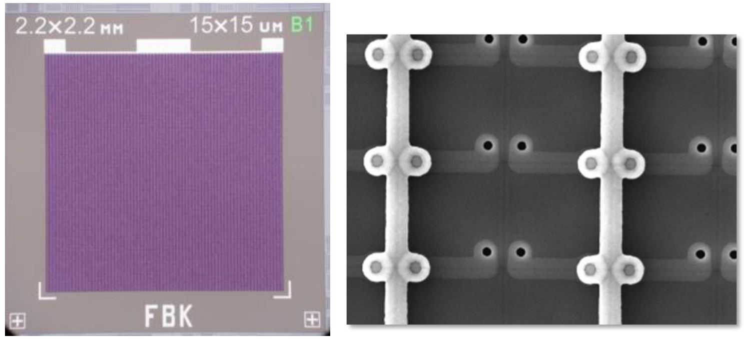
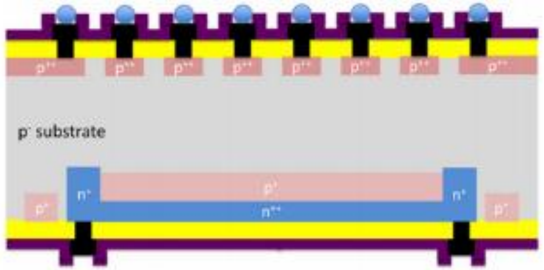
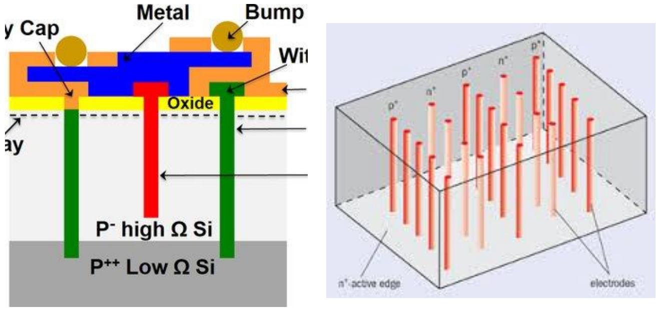
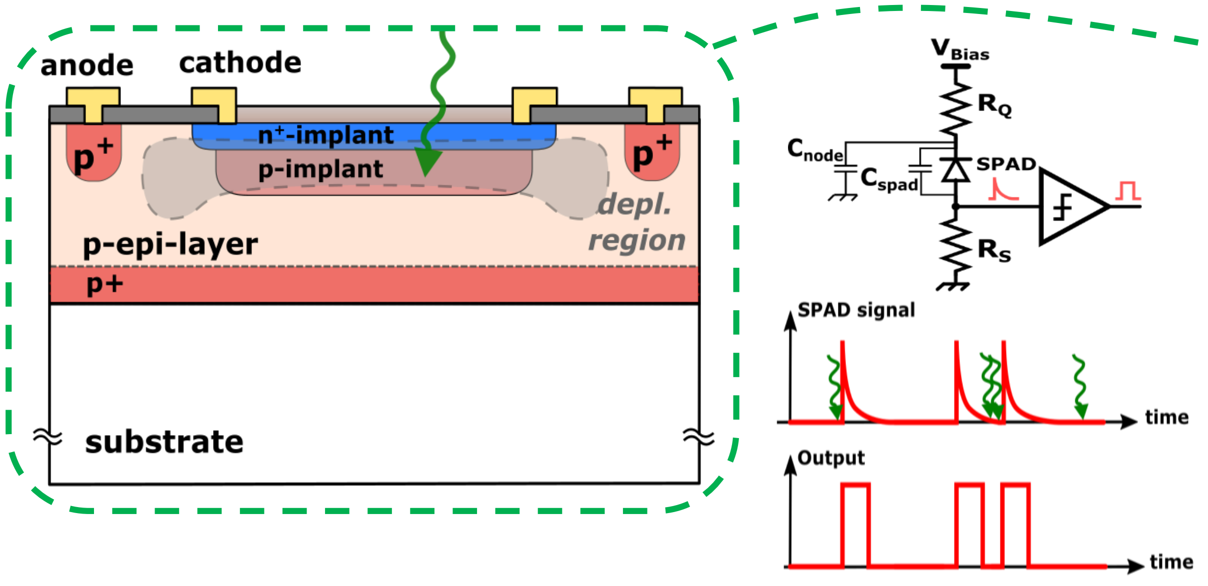
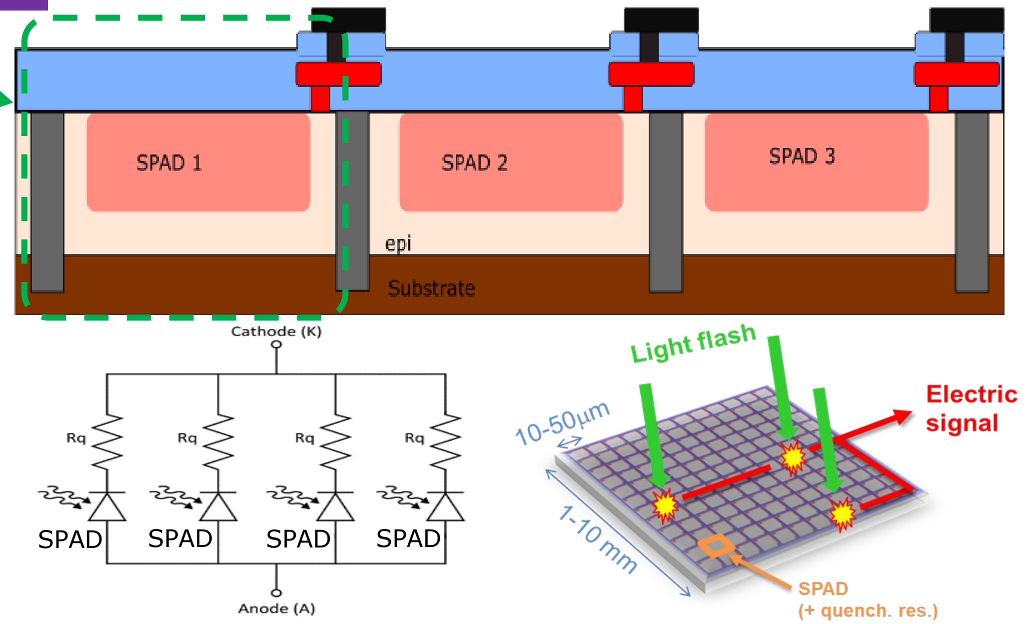
Silicon-based detector in full-custom technologies:

SPD silicon pixel detectors	SSD silicon strip detectors	SDD silicon drift detectors
		

SPADs & SiPM	Low Gain Avalanche Detectors	3D detectors
		

SPADs and SiPMs

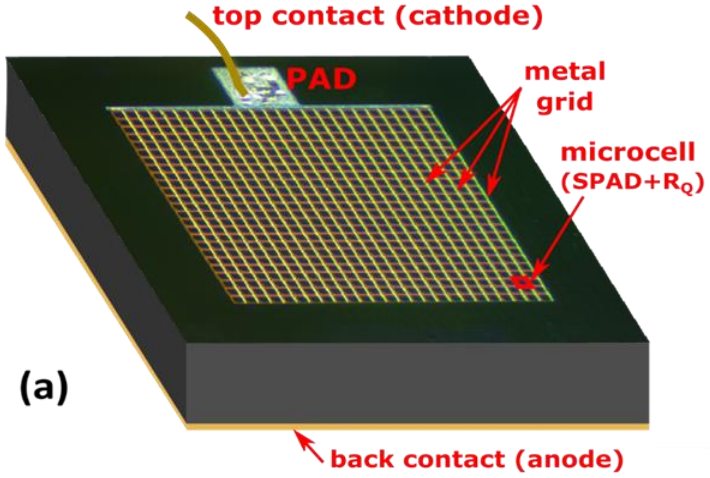


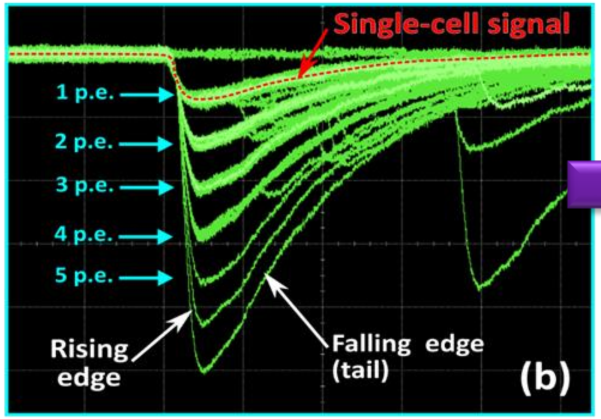


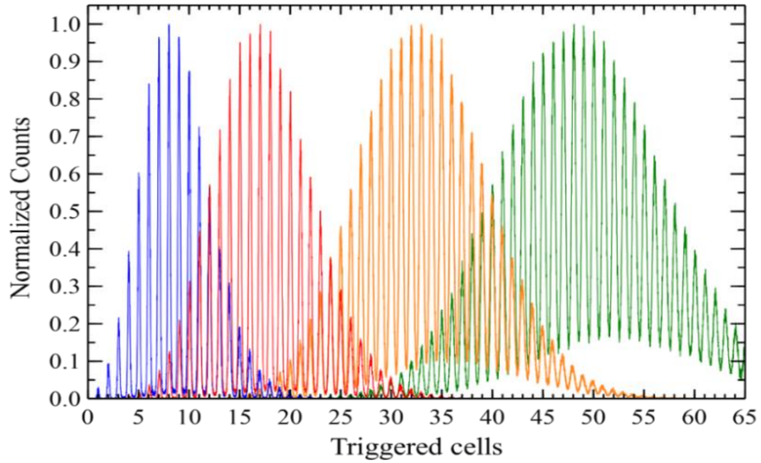
- **SPAD: Single-Photon Avalanche Diode**
  (Geiger-mode, single photon counting capabilities).
  Available in:
  - Full-Custom Technology
  - CMOS Technology

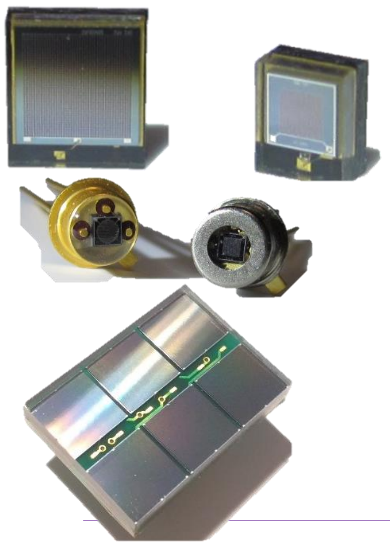
- **SiPM: Silicon photomultiplier**
  → thousands of SPADs in parallel
  (single detector, single-photon sensitive, but with photon counting capability) Available in:
  - Full-Custom Technology
  - Digital SiPM d-SiPM (CMOS)

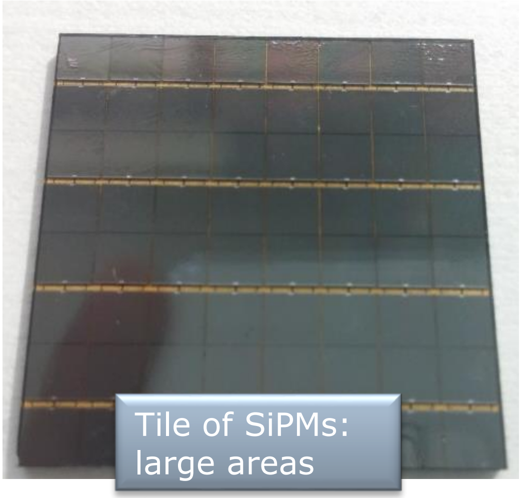
Silicon Photomultipliers (1)

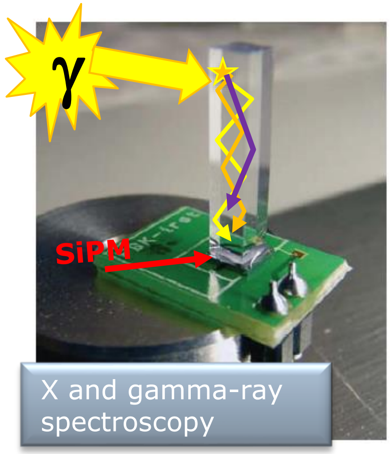








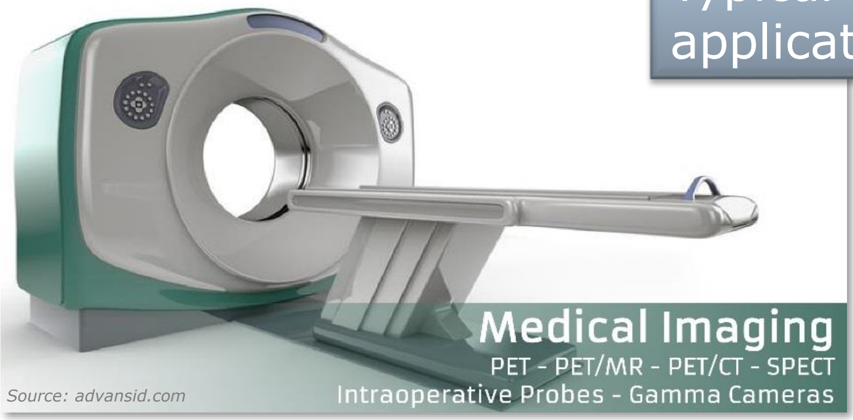




- Silicon photomultipliers: Thousands of cells in parallel
- But still single-photon sensitive
- High detection efficiency (PDE), up to 50-60%
- Very good time resolution (better than 100ps)
- High linearity and photon-number resolution

Silicon Photomultipliers (2)

Typical SiPMs applications:



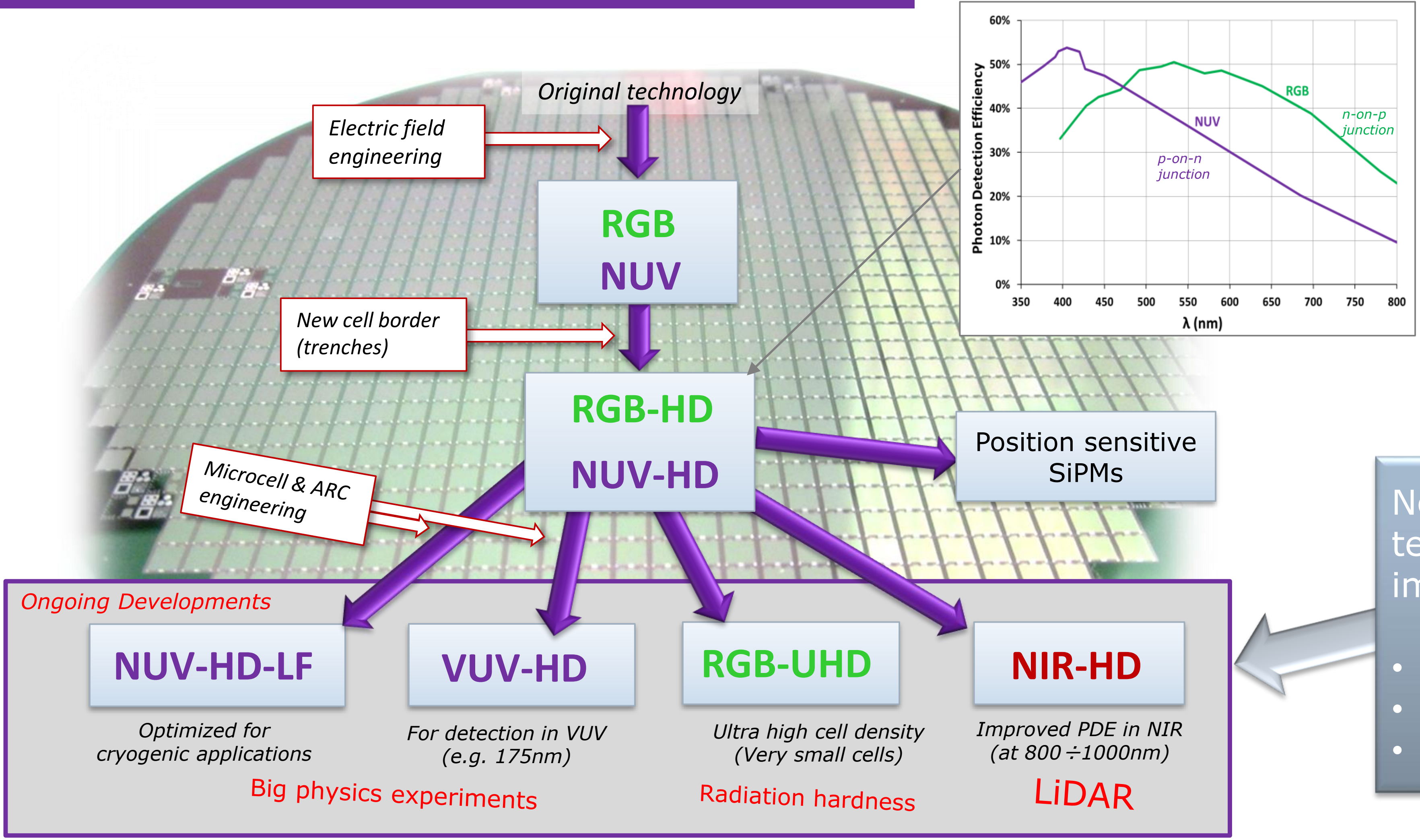
a SiPM is:

Radiation detector (with scintillator)
- Medical imaging
- High-energy physics

Substitute of PMT (photomultiplier tube)
- Spectroscopy
- Calorimetry

Single-photon detector (with photon number resolution)
- Single-photon spectroscopy
- LiDAR

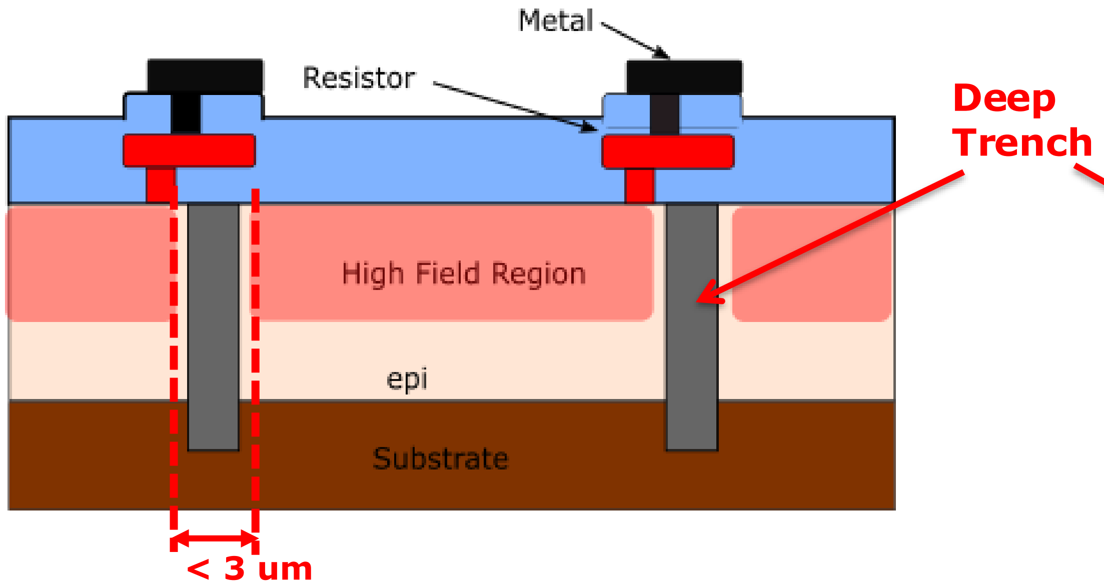
FBK: SiPM tech. roadmap

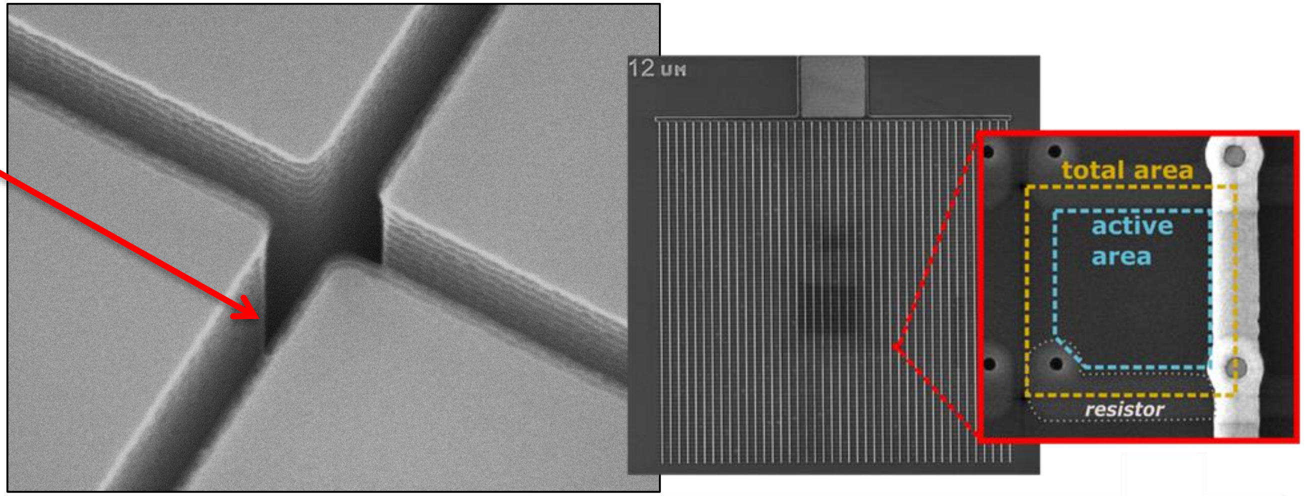


New enabling technological improvements:

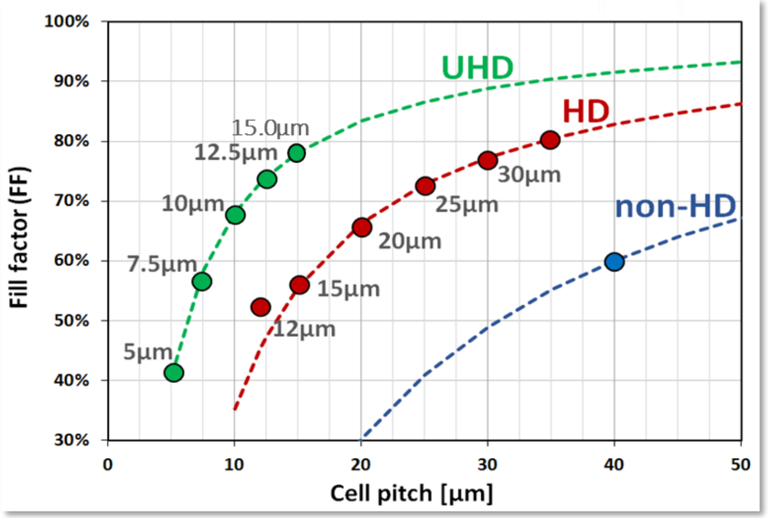
- 3D integration
- TSVs
- BSI

“High-density” technology

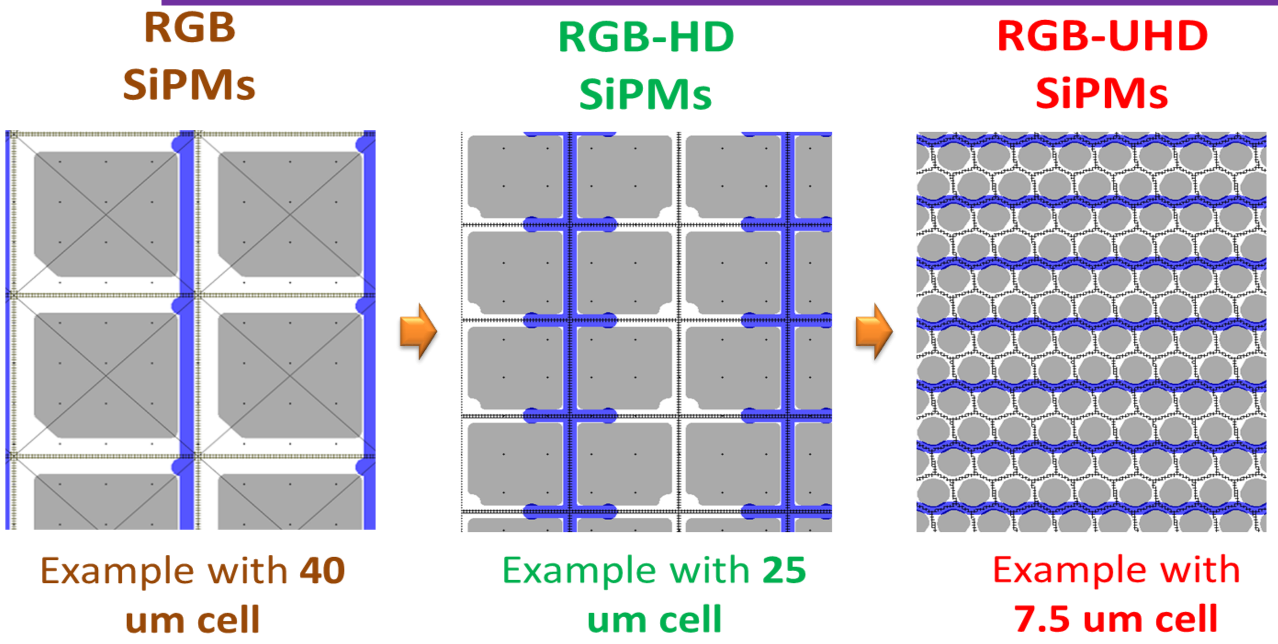


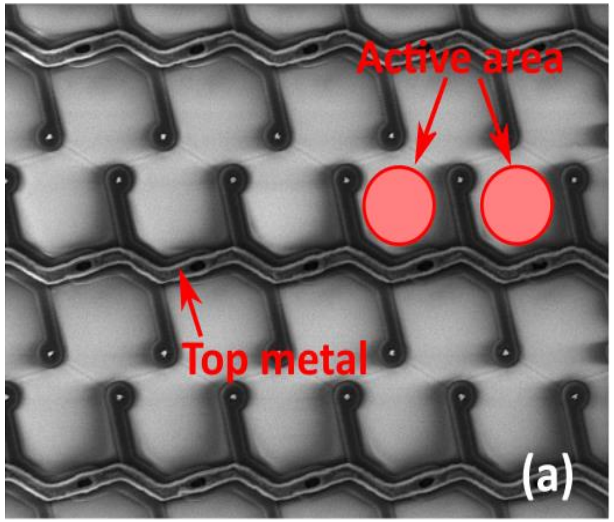


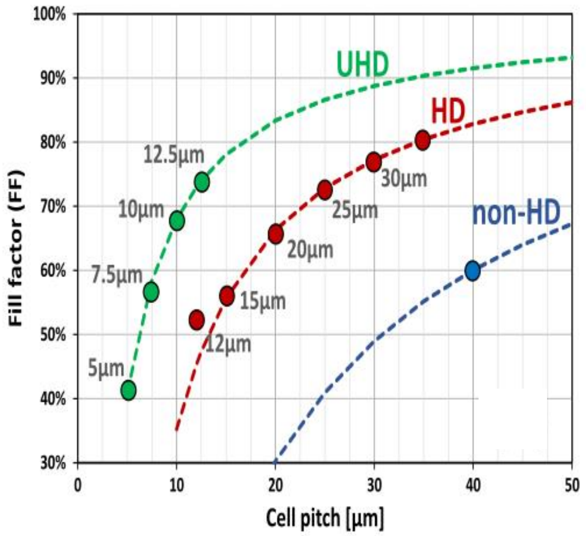
- Trenches between cells → Lower Cross-Talk
- Cell pitch: 15 – 50 um
- Narrow dead border region → High Fill Factor (>80%)
- “simple” fabrication process: 9 lithographic steps



"Ultra-high-density"

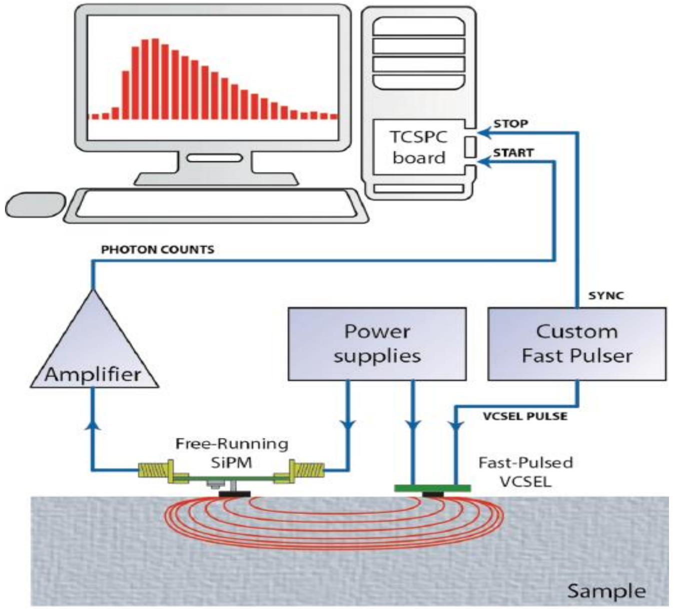




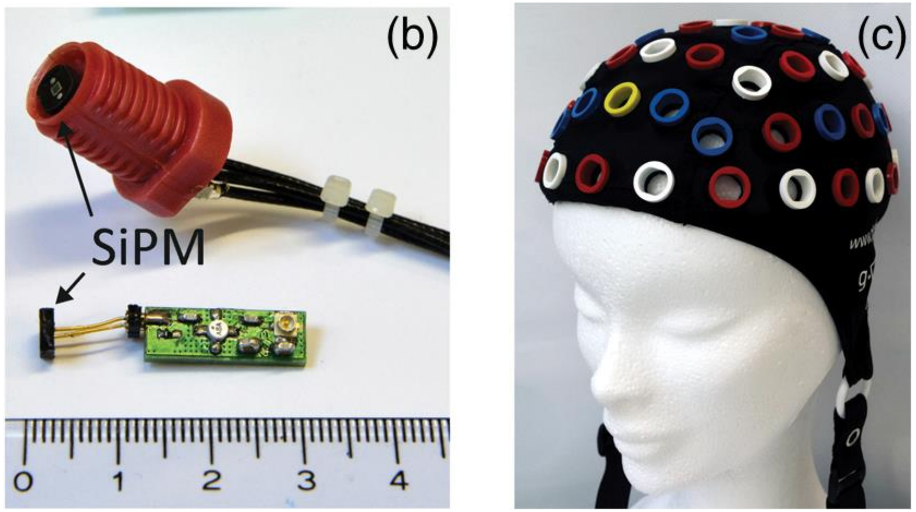


- Reduction of all technological features, including trenches width and contacts.
- Circular active area in honeycomb SPAD configuration.
- High fill-factor despite the small pitch
  - (down to 5µm, with 40% nominal FF !)

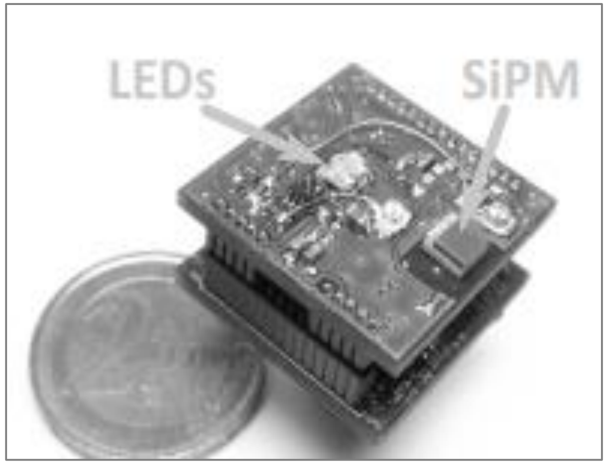
SiPM new application: diffuse optical spectroscopy



Source: Dalla Mora et. al. "Fast silicon photomultiplier improves signal harvesting and reduces complexity .. "



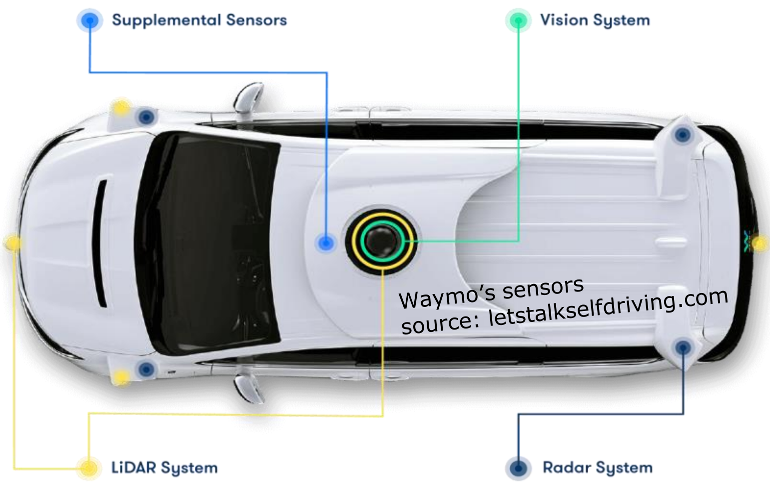
Source: Re et. al. "Probe-hosted silicon photomultipliers for time-domain functional near-infrared spectroscopy …"



Source: R. Zimmermann, et. Al. "Silicon photomultipliers for improved detection of low light levels in miniature near-infrared spectroscopy instruments …"

- Applications: near-infrared spectroscopy / time-domain diffuse optics
- SiPMs have been a "revolution" thanks to their
  - Large active area, (large numerical aperture in light collection)
  - But still with single-photon sensitivity, high detection efficiency and good time resolution.

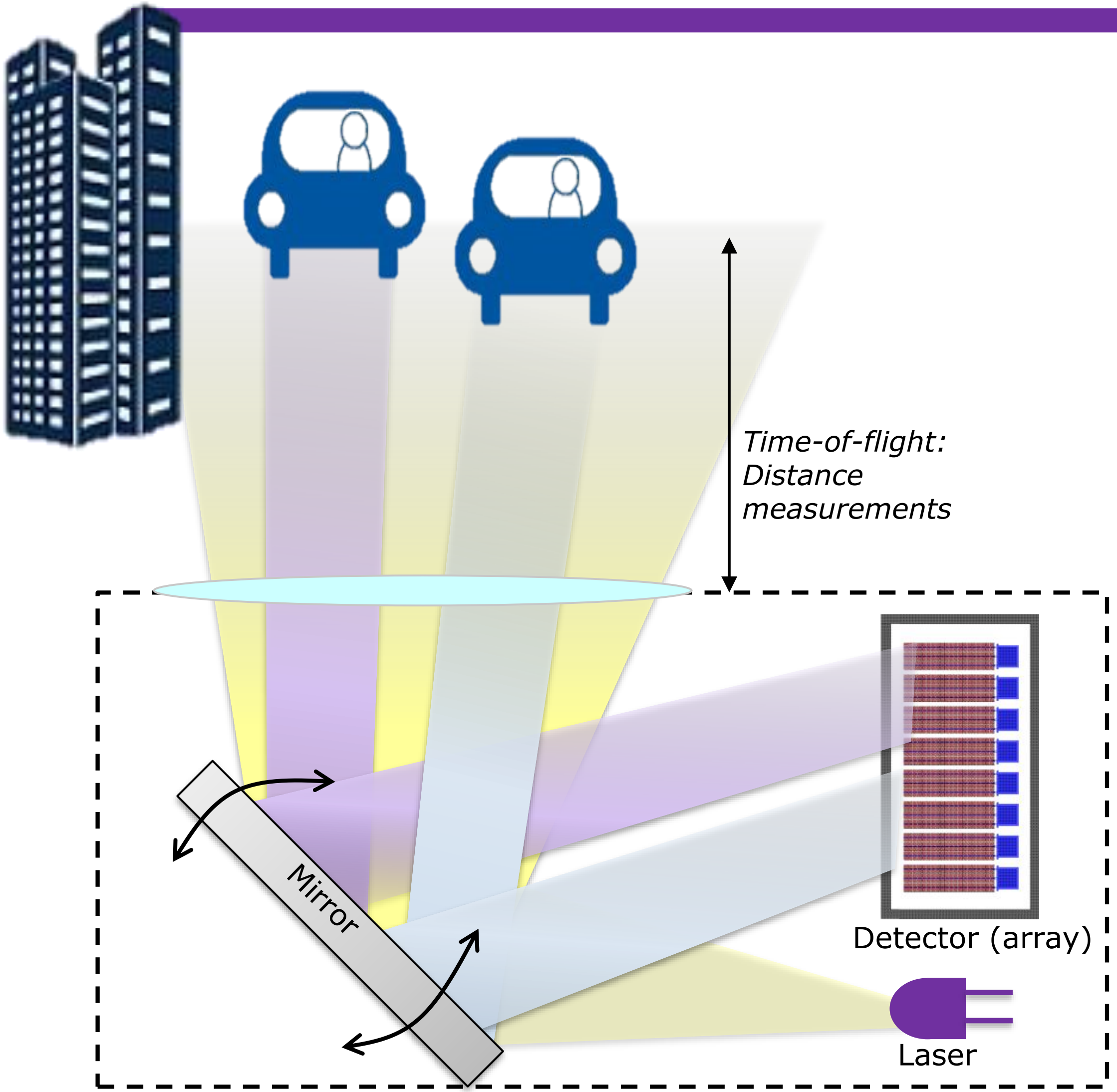
SiPM new application: LiDAR

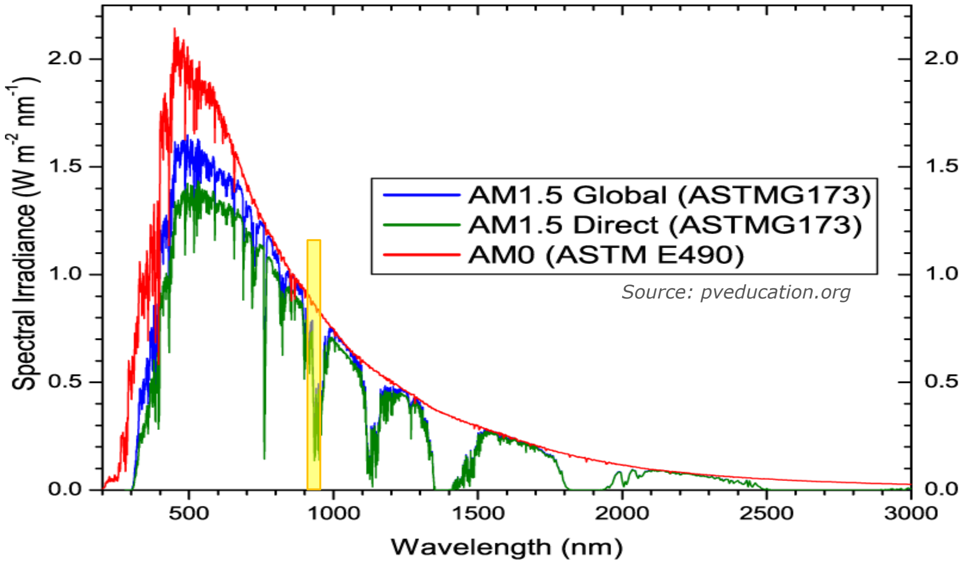


- Requirements: detect up to 200m.
- Detectors requirements:
  - High-sensitivity
  - Good time resolution
  - High dynamic range
  - Small dead-time
- SiPMs are a promising choice
- 905÷950 laser → need optimized SiPM technology

- Example: collision protec. on automated vehicles
- Requirements:
  - Smaller range
  - But high precision
  - Large field of view
- Reliable and compact system
- SiPMs, APDs, … are promising choices

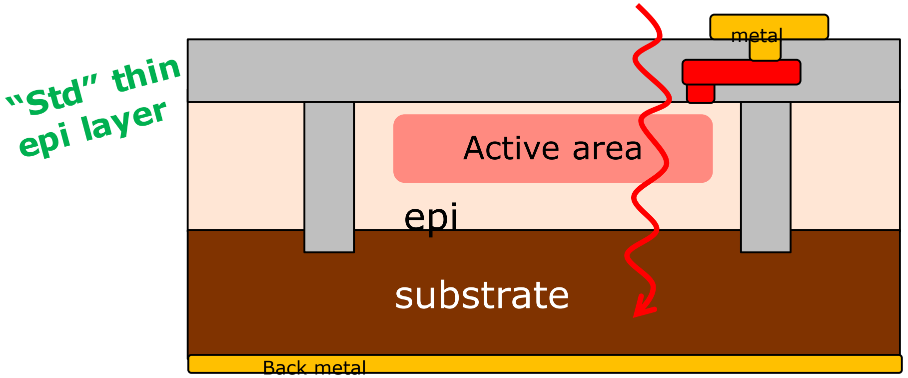
Automotive LiDAR

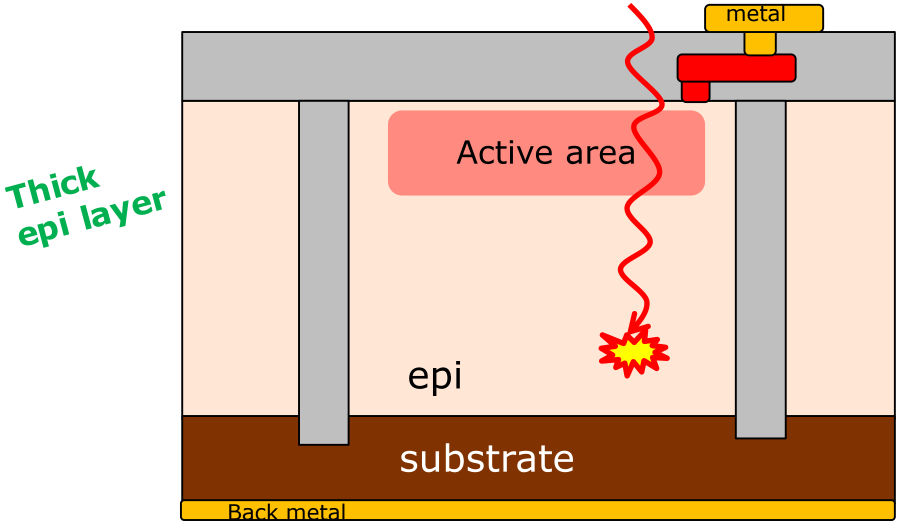




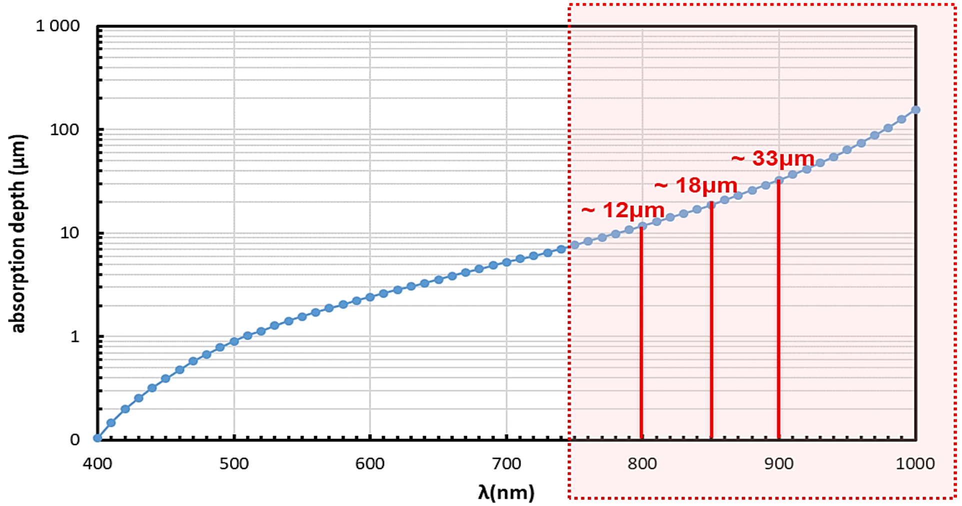
- Flash-LiDAR, or scanning LiDAR (with mirrors, metamaterials, ...)
- Scanning LiDAR: 1D detector-array
  - to reduce scanning time.
- Typical VCSEL at 905nm or 940nm (eye safer but still silicon sensitive)

SiPM for Near Infrared (1)

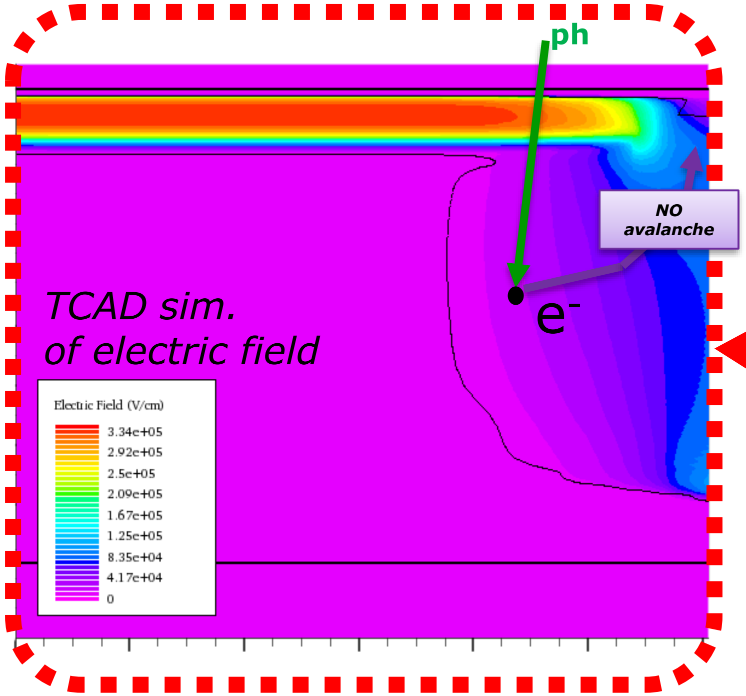


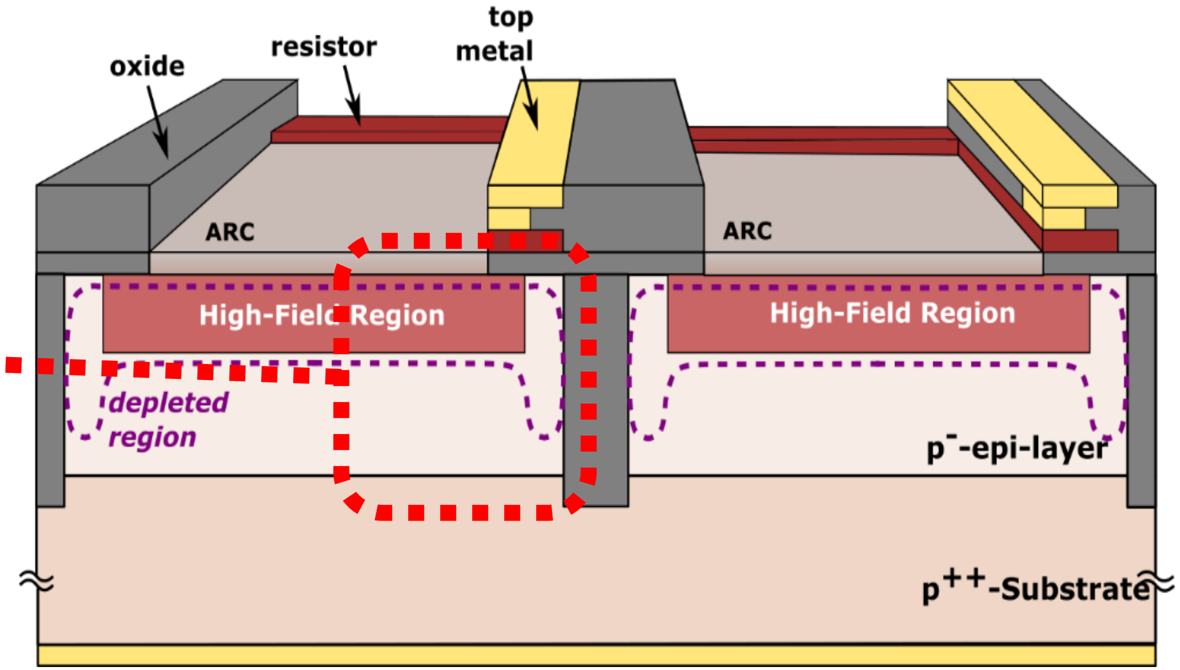


- Red and NIR photons
  → longer absorption depth in silicon (tens of micrometers)
- Thicker epi-Silicon must be used to increase absorption
- Technology adjustment:
  - thicker trenches (high aspect ratio)
  - Electric field modification to collect deeper in epi-layer



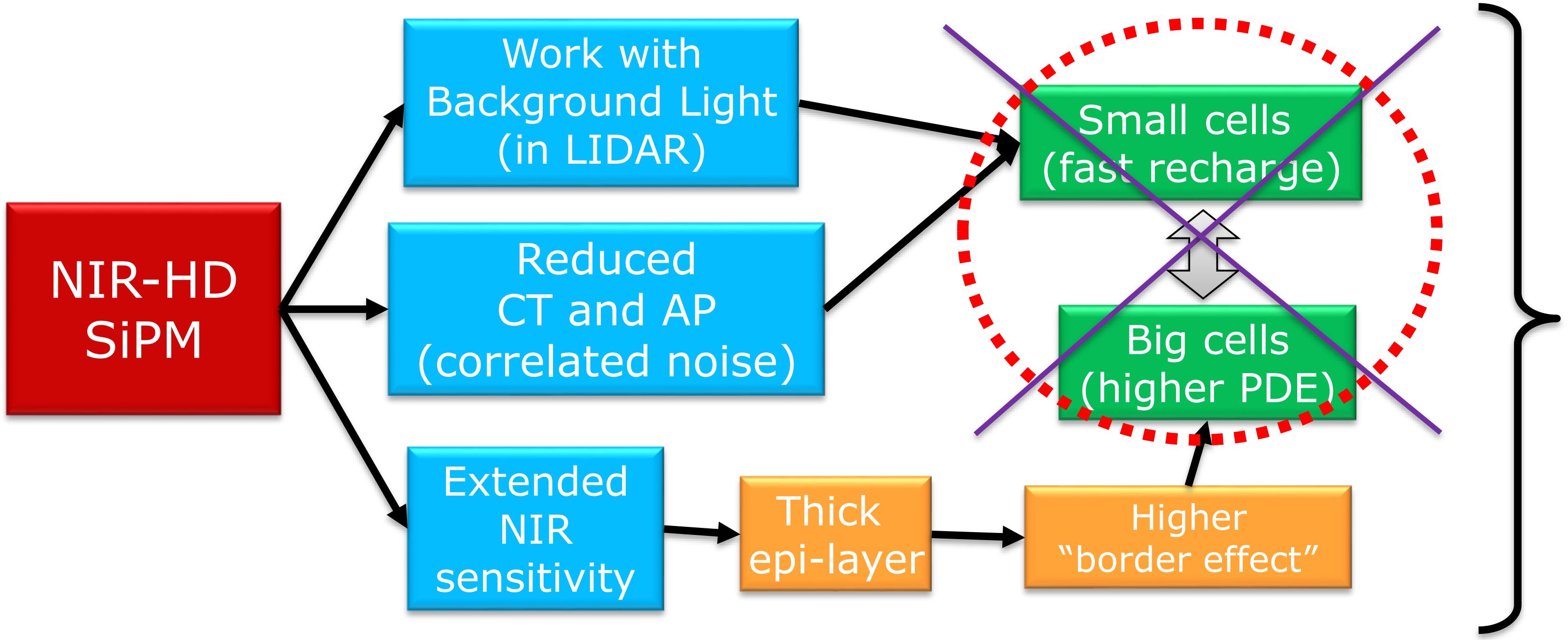
SiPM for Near Infrared (2)





- Issue: the “border effect”
- When increasing epi-layer thickness → more important border effect
- Important reduction of effective active area (with respect to nominal AA)
  - It needs a modification of the internal SPAD structure to get high detection efficiency

SiPM for Near Infrared (3)



Strategies:

Small cells but with improved sensitivity

Big cells but with reduced CT

Medium cells / small AA
- with back reflector
- with *micro-lens*
(improved sensitivity)

Back-side illuminated cells with *charge-drift engineering* (improved sensitivity)

- Applications like LIDAR need:
  - Small cells → fast recharge, to cope with background light
  - but with high PDE
  - Not possible, because of border effect
- New strategies and technological improvements are needed

IPCEI on Microelectronics

SiPM for Near Infrared (4)

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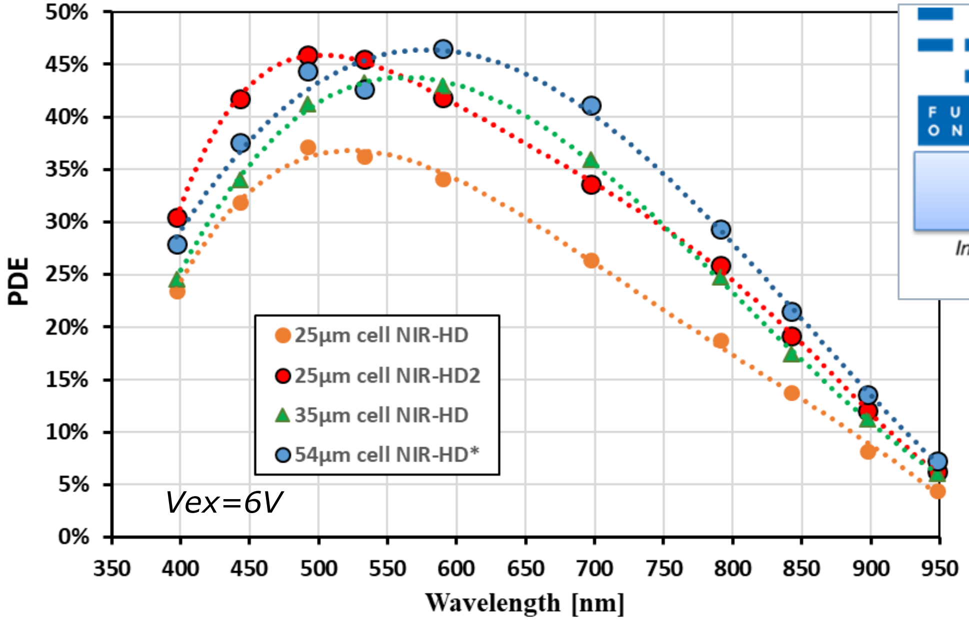
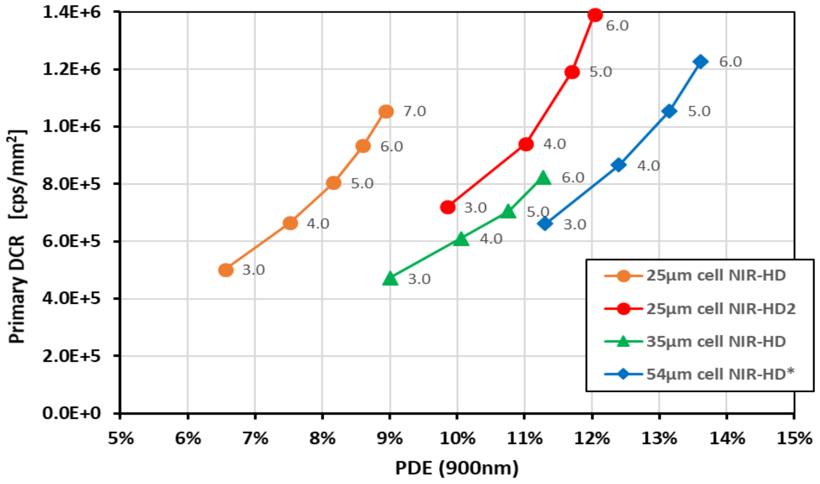
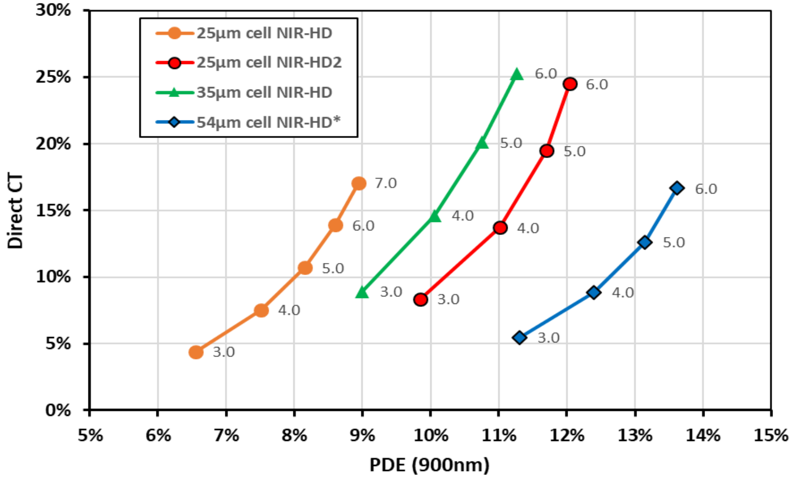


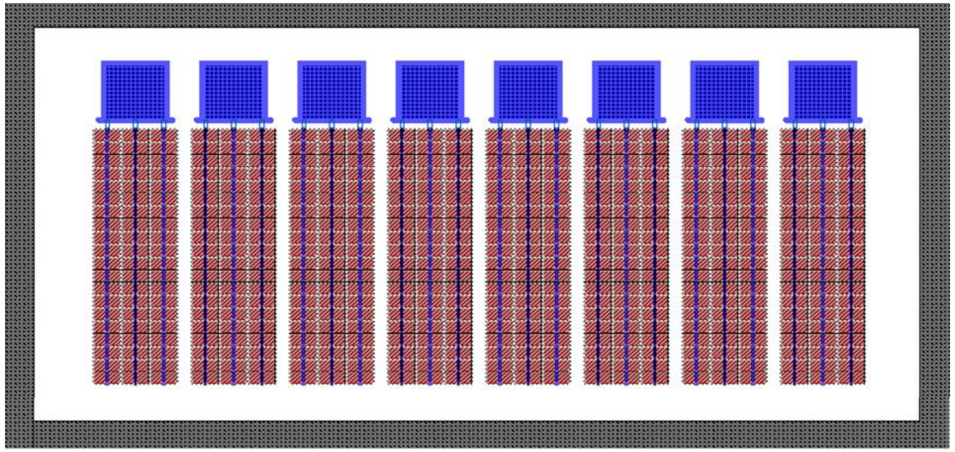
FONDAZIONE BRUNO KESSLER
FUTURE BUILT ON KNOWLEDGE
NIR-HD
Improved PDE in NIR (at 800÷1000nm)

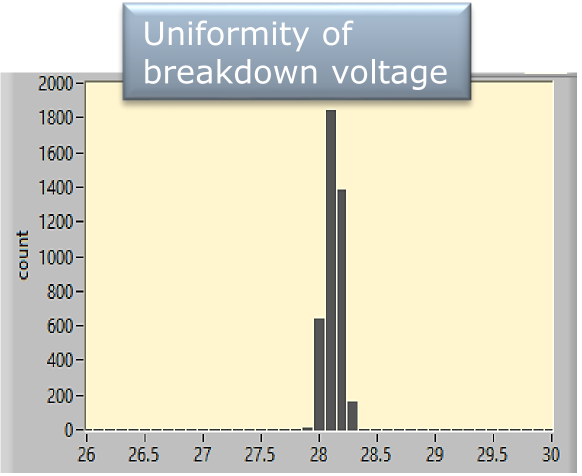


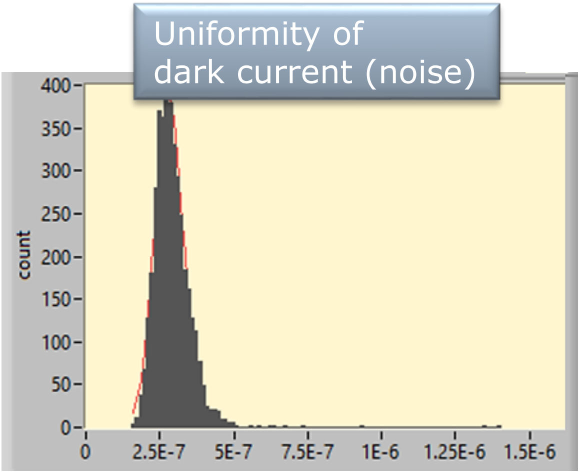


- NIR-HD tech: current developments status
  - Detection efficiency: ~12% (25µm SPAD pitch), ~14% (54µm* SPAD pitch)
  - Dark count rate (DCR): ~800kcps/mm^2 →500cps per SPAD
  - Crosstalk: ~10% *(for both 25µm and 54µm pitch)*

NIR SiPM array





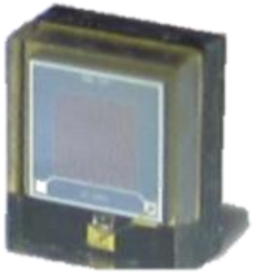


Over 4000 device tested over the wafer

- For LiDAR: array of miniSiPMs
  - 8÷16 elements.
  - Small cell pitch (25µm) for reducing saturation issues.
  - Fast single-SPAD recharge time.
- Good uniformity in performance is needed (e.g. noise and efficiency)
  - Breakdown voltage: typ. ±0.15

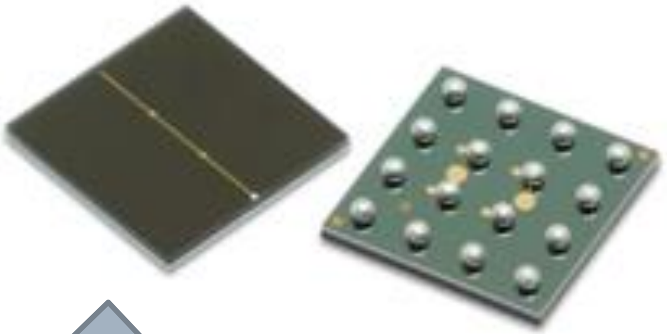
FBK IPCEI Roadmap for 3D-integrated SPADs & SiPMs

- Standard SiPM



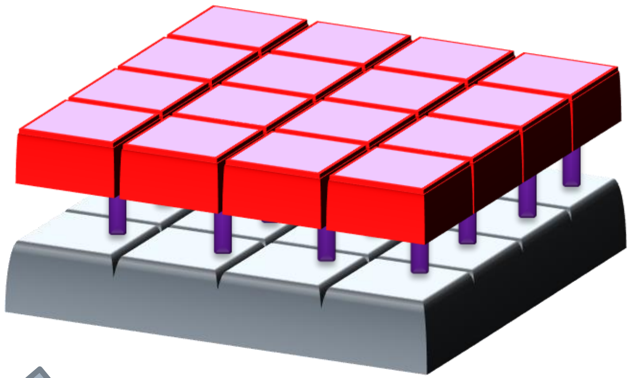
1 channel

- TSV SiPM



1 channel

- Full-3D-integrated

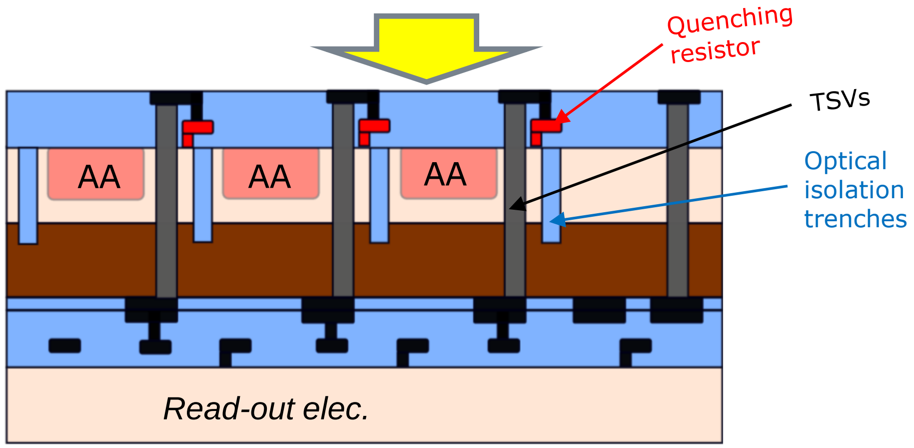


SPAD array
or array of mini-SiPMs
(Thousands of channels)

- 3D integrated SPADs and SiPMs:
  - better sensitivity
  - more functionality per pixel
  - each tier can be independently optimized using dedicated processes

3D Integration at FBK

- Front Side Illumination with TSVs: for NUV/VUV-sensitive detector



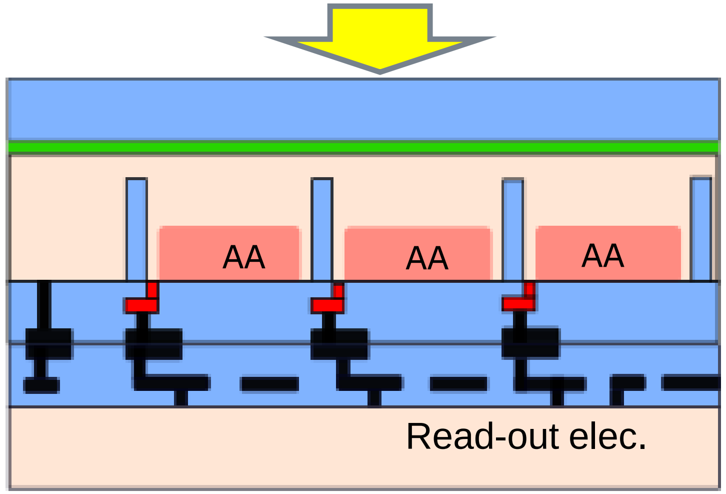
Pro:

- shallow junction → UV sensitive
- Same device performance (as today tech.)

Cons:

- FF losses due to TSV and BEOL

- Back Side Illumination: for NIR-sensitive detector



Pro:

- ~ 100% FF
- Higher detection efficiency
- TSV-free

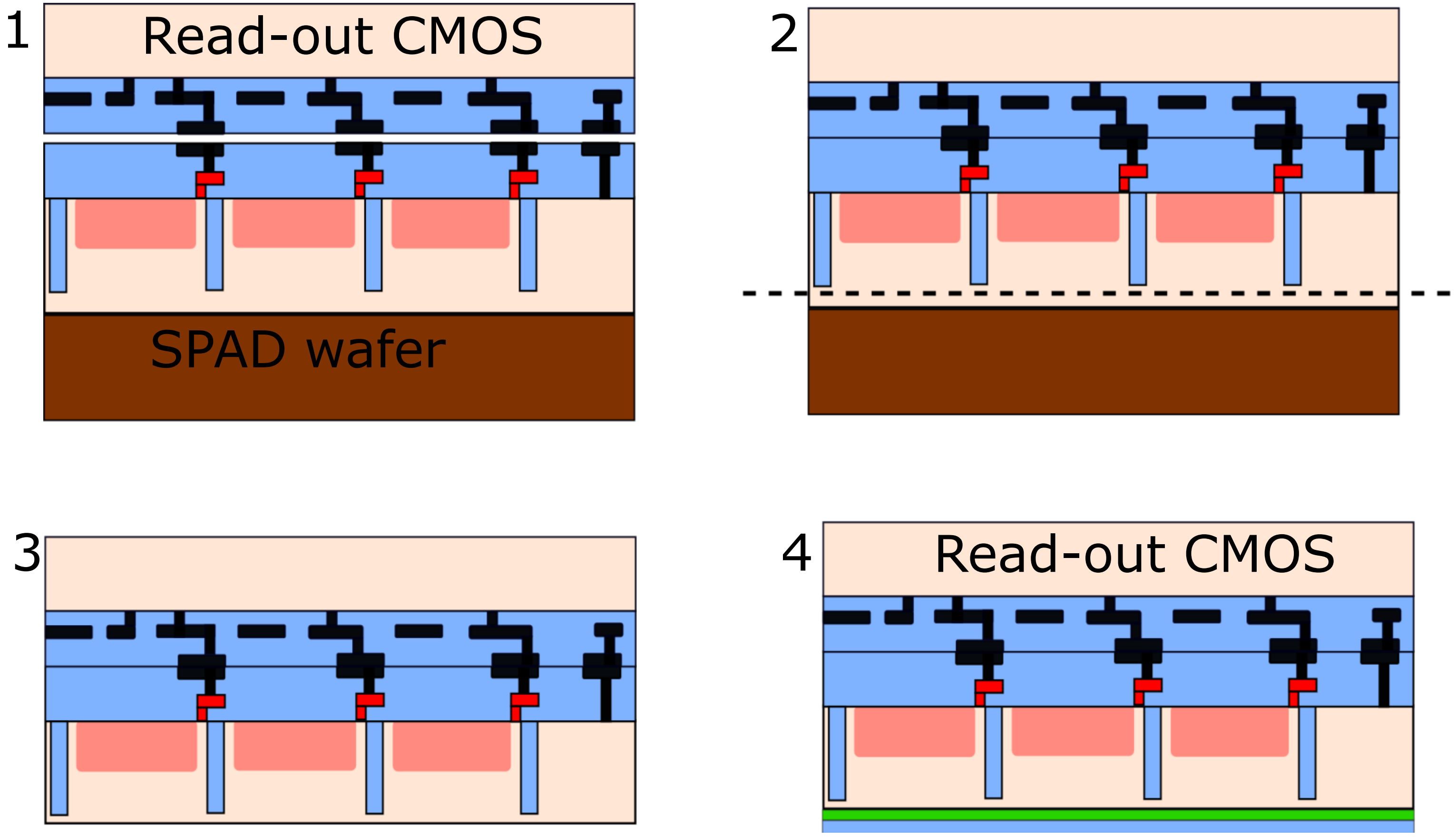
Cons:

- Deeper junction (not suited for UV)
- Need full depletion

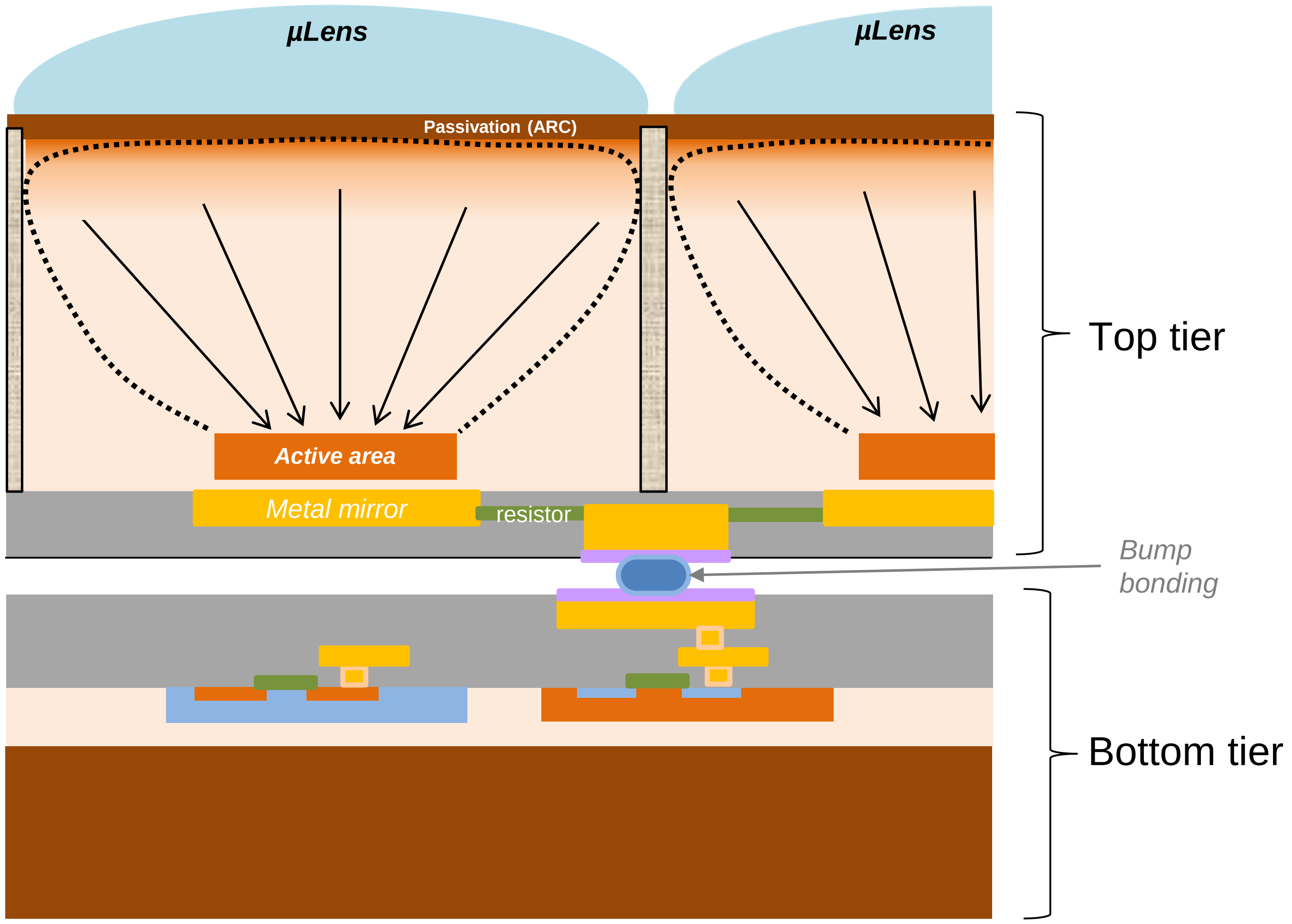
3D Integration at FBK

- Example of Back Side illumination for Visible/NIR SiPMs
  - Wafer bonding
  - Wafer thinning (down to epi layer)
  - Surface passivation (new ARC)

- Metal reflector can be used → increasing the effective absorption length of NIR photons.



Future NIR-HD tech. developments: charge-drift engineered SPADs



- Back side illuminated
  - With metal mirror → double effective absorption length.
- With microlens
  - Shaping light spot inside active volume
- Charge-drift paths engineering
  - Small active area, but with big collection volume!
- Bump bonding to read-out chip or discrete electronics

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Thank you