5th International Workshop on New Photon-Detectors
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Development of High-density NIR-sensitive Silicon photomultipliers at FBK

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https://iris.fbk.eu/
silicon-photomultipliers

Outline

- **FBK silicon photomultipliers (SiPM) technology**
  - Roadmap & new development ongoing
- **NIR detection with SiPMs**
  - Applications
  - Technological challenges and design requirements
- **NIR technology at FBK**
  - TCAD simulations:
    - Thin vs. thick epi-layer
    - The border effect
  - Design strategies → produced SiPMs 2nd batch
    - Small cells: PDE improvement
    - Large cells: CT reduction
- **Conclusion & future developments**

FBK SiPM technology roadmap

Original technology

Electric field engineering

RGB 2010

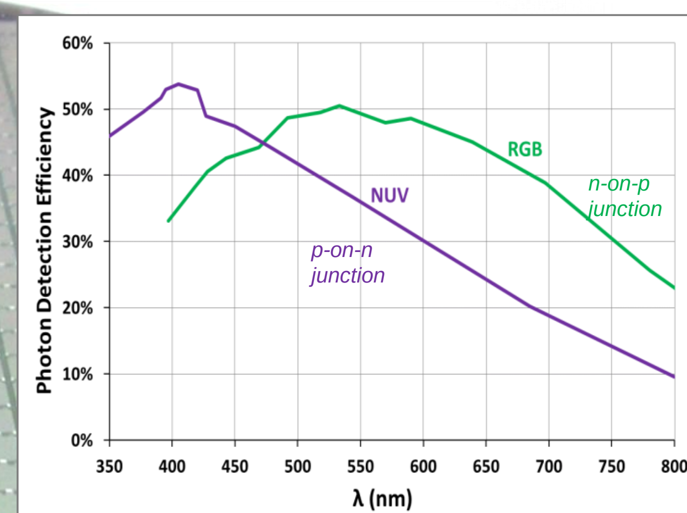
NUV 2012

New cell border (trenches)

RGB-HD 2012

NUV-HD 2015

Position sensitive SiPMs

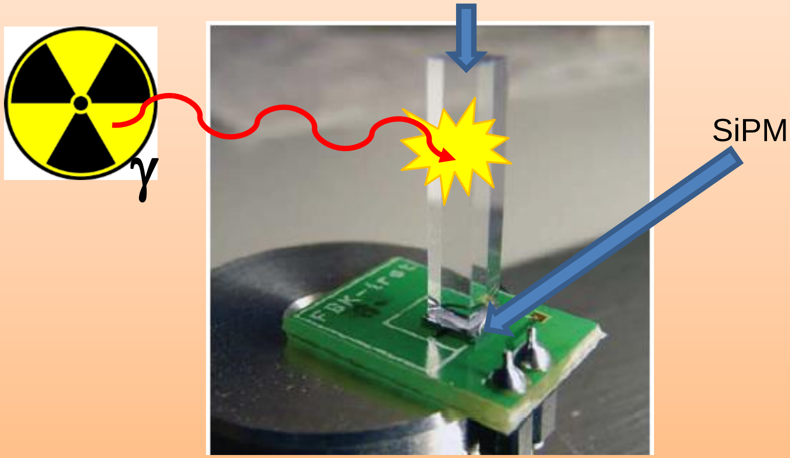


Ongoing Developments

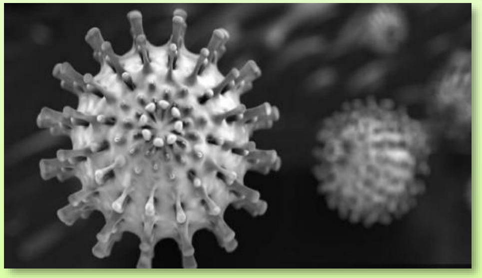
NUV-HD-LF	VUV-HD	RGB-UHD	NIR-HD
Optimized for cryogenic applications	*For detection in VUV (e.g. 175nm)*	*Ultra high cell density (Very small cells)*	*Improved PDE in NIR (at 800÷1000nm)*

Typical SiPM applications

Scintillation detectors: crystals emit light signals interacting with X/γ rays

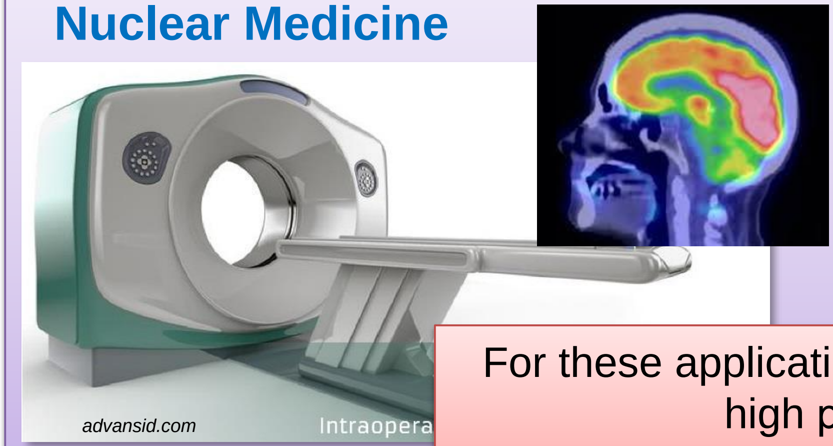


Biology applications
e.g. spectroscopy



Analytical instrumentation
e.g. SEM, microscopy

Nuclear Medicine



High energy physics

(low noise, dynamic range, radiation hard)

For these applications NUV-HD provides very high performance…
PDE is very high: easily >55%

NIR: new applications

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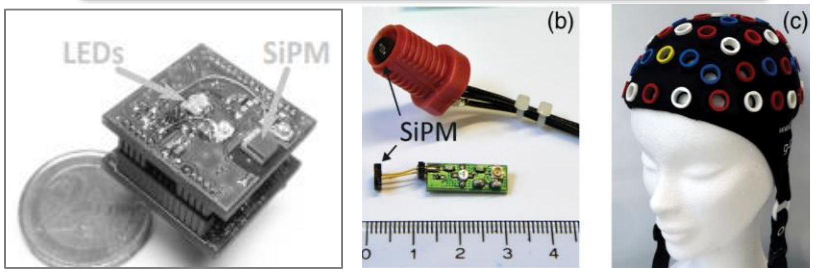
fNIRS (functional NIR Spectroscopy)



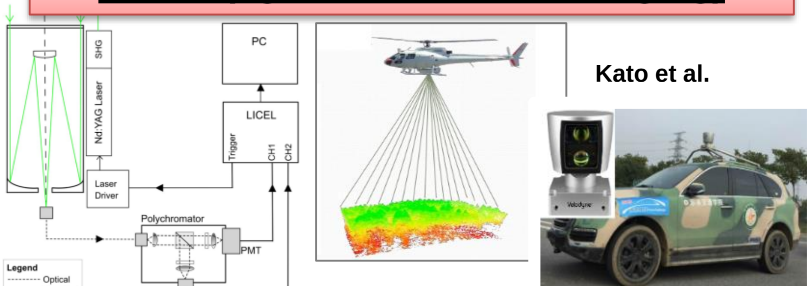
R. Zimmermann, et. Al. "Silicon photomultipliers for improved …"

Re et al. *Neurophoton.* 3(4), 045004 (2016)

fNIRS: non-invasive investigation of brain activation, chest, tissue composition, etc.

- SiPMs are emerging over other detectors
- Direct contact with skin → enhanced light harvesting
- **Large active area (3x3 mm² or more) with good PDE and timing**
- Enhanced NIR sensitivity → reduced laser power

LIDAR (light detection and ranging)



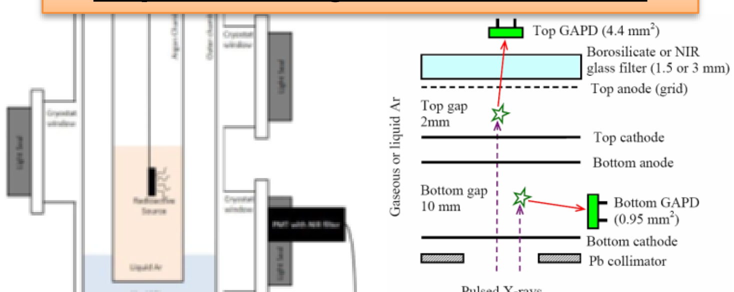
Kato et al.

Riu et al. DOI: 10.1364/OL.37.001229

LIDAR in industrial and automotive application

- SiPMs are emerging over other detectors
- Need very **high sensitivity** → good time-of-flight res.
- **High dynamic range + fast recharge** → small cell pitches + high efficiency

Liquid noble gases scintillation



C. O. Escobar, JINST 13, C03031, 2018

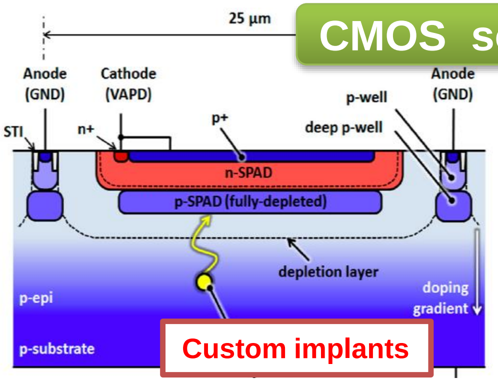
Bondar et. al JINST 7 (2012) P06015

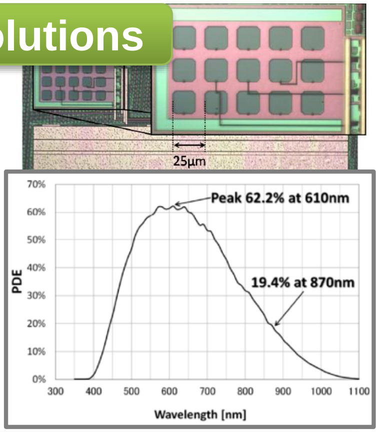
Readout of NIR scintillation from liquid noble gases

- SiPMs are good candidate
- Good light yield in the NIR
- no Rayleigh scattering and absorption on metallic surfaces (as for VUV)

NIR-sensitive SPADs

CMOS solutions

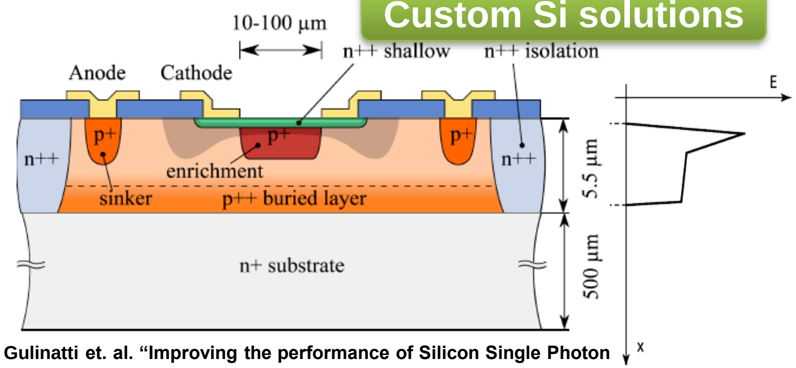




Niclass et. Al. "A NIR-Sensitivity-Enhanced Single-Photon Avalanche Diode in 0.18µm CMOS"

CMOS SPAD array: deep junction
- nwell/p-epi or CUSTOM implants
- PDP=19.4% @ 870nm (not including FF)
- **FF relatively small: ~30%**

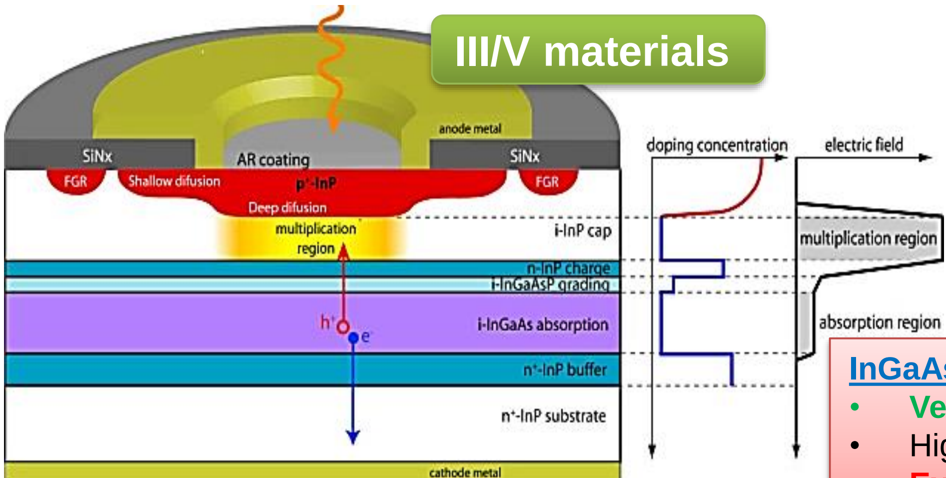
Custom Si solutions



Gulinatti et. al. "Improving the performance of Silicon Single Photon Avalanche Diodes"

"Red-enhanced SPAD" : thicker epi-layer
- **40% @ 800nm, 30% @ 850nm**
- Breakdown voltage: ~60V
- Just single SPAD, relative small active area

III/V materials



F. Acerbi et. al. ,"Design Criteria for InGaAs/InP Single-Photon Avalanche Diode"

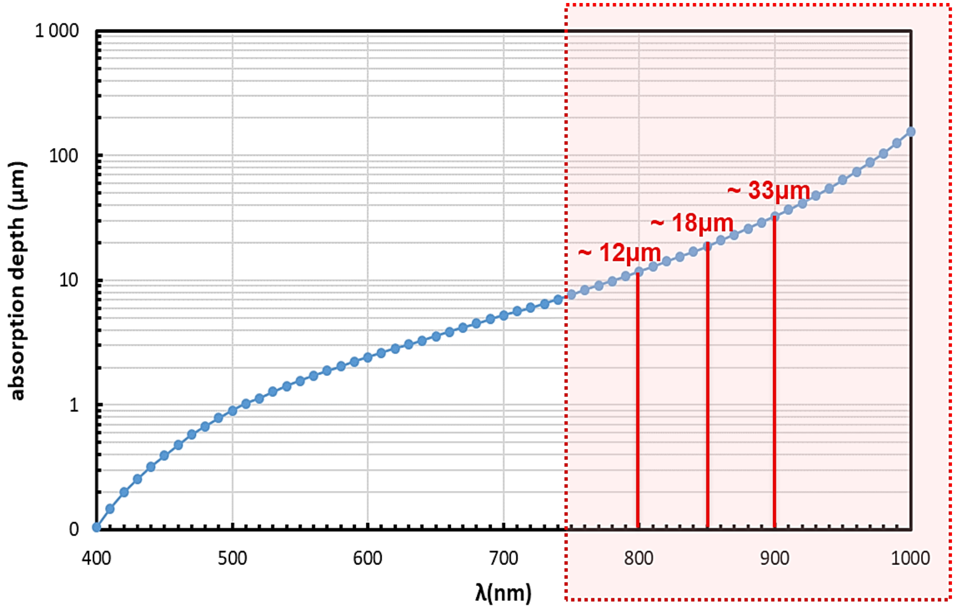
McCarthy et. al. , "**Kilometer-range depth imaging at 1550 nm** wavelength using an InGaAs/InP single-photon avalanche diode detector"

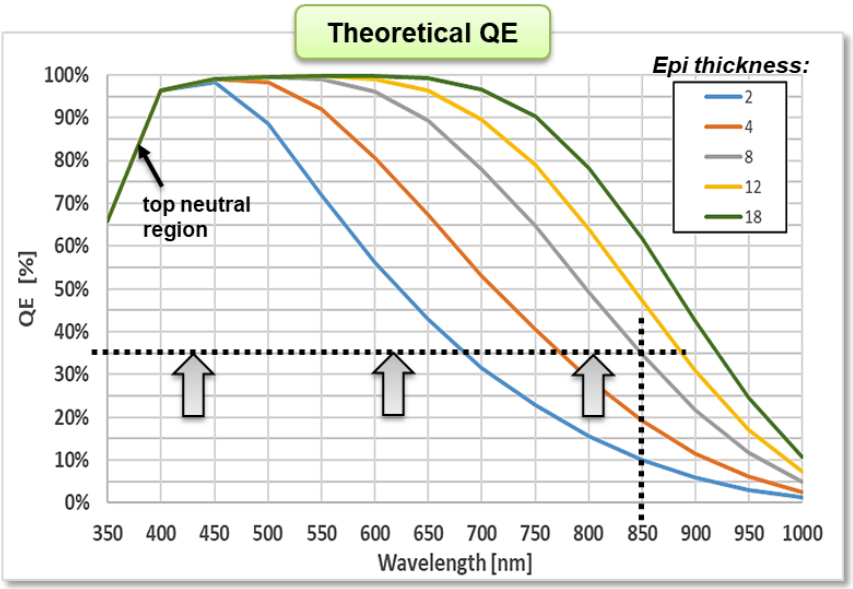
InGaAs(P)/InP SPAD
- **Very good PDE up to 1550nm detection: intrins. eye-safe**
- High DCR and afterpulsing, need Peltier cooling
- **Expensive technology** (especially for arrays)

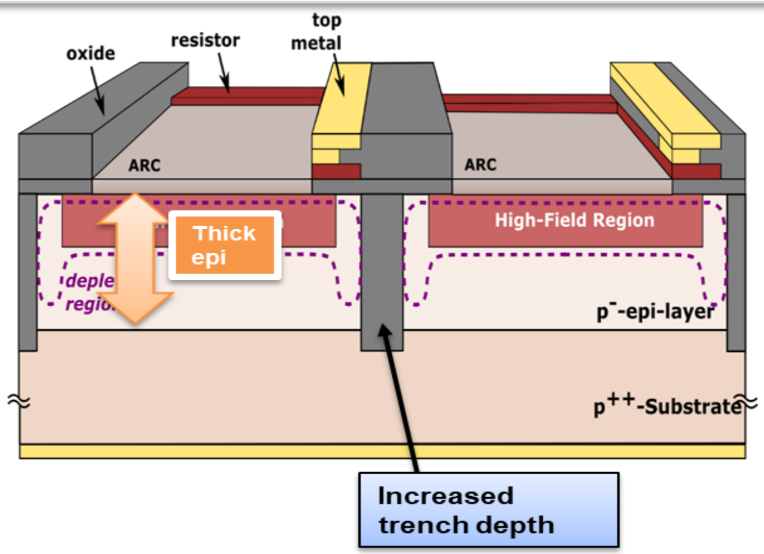
NIR SiPM: design considerations

- **New FBK custom technology: based on RGB-HD**
  - n-on-p junction type
- **Increase PDE at long wavelength**
  - **Thicker epitaxial layer**
  - Deeper trenches for cell electrical isolation
- **In SiPM → High FF has to be preserved (also at high depth)**
  - **This is not a SPAD → *NIR sensitive SiPM is more challenging***
  - The inactive border of the cell can be very important → to be reduced
- **Breakdown voltage should stay low**
  - Keeping the low temperature dependence
    (important in industrial and automotive app.)

Design: thick epitaxial layer



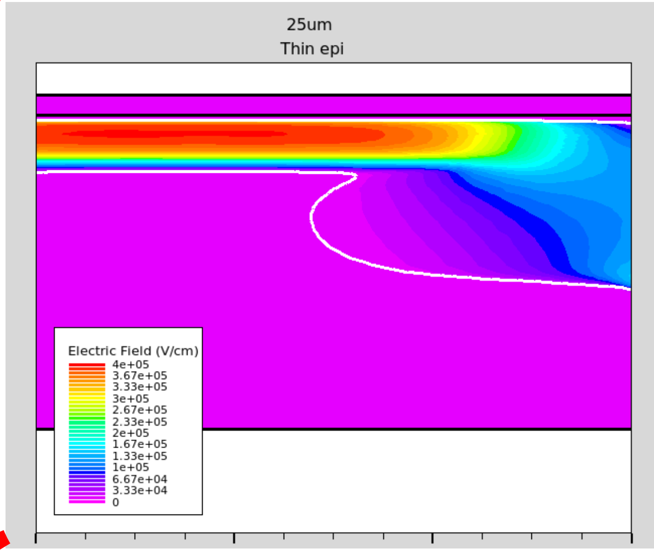


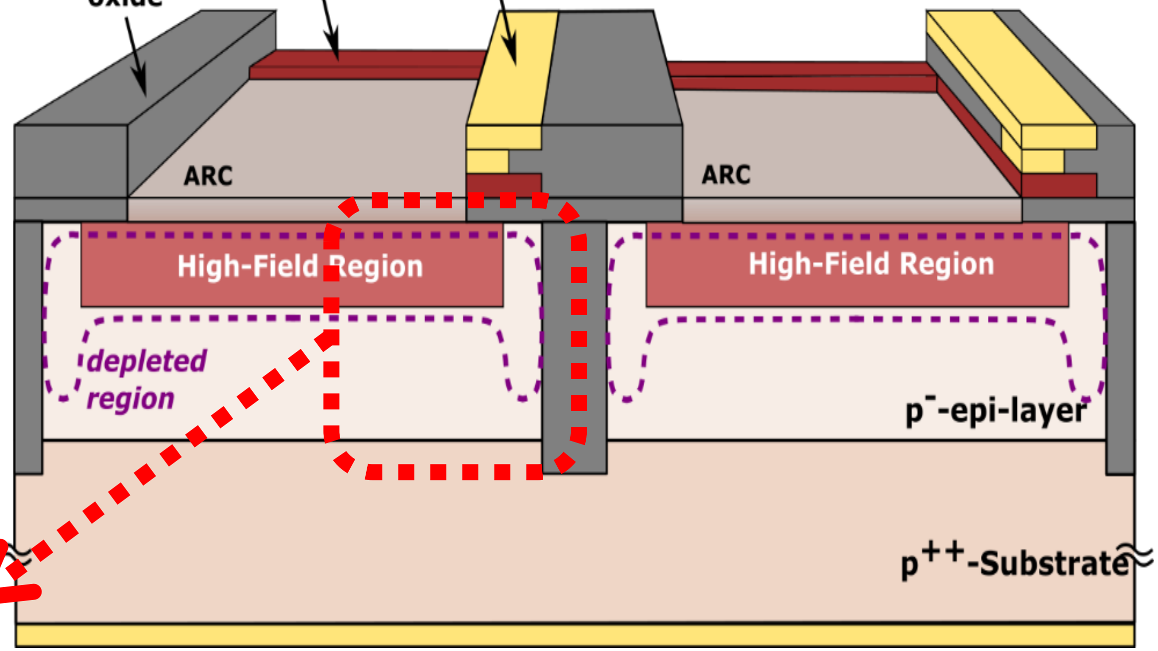


- **At 850nm → silicon absorption depth is 18µm**
  → we used a <u>thicker epitaxial layer: 8µm</u>
  - theoretical **QE at 850 nm: about 35%**
  - Trench depth increased: > 8µm
- **But, other quantities in PDE calculation:**
  - **Triggering probability (Pt)**
  - **Effective geometrical fill-factor (FF)**

Design through TCAD simulations

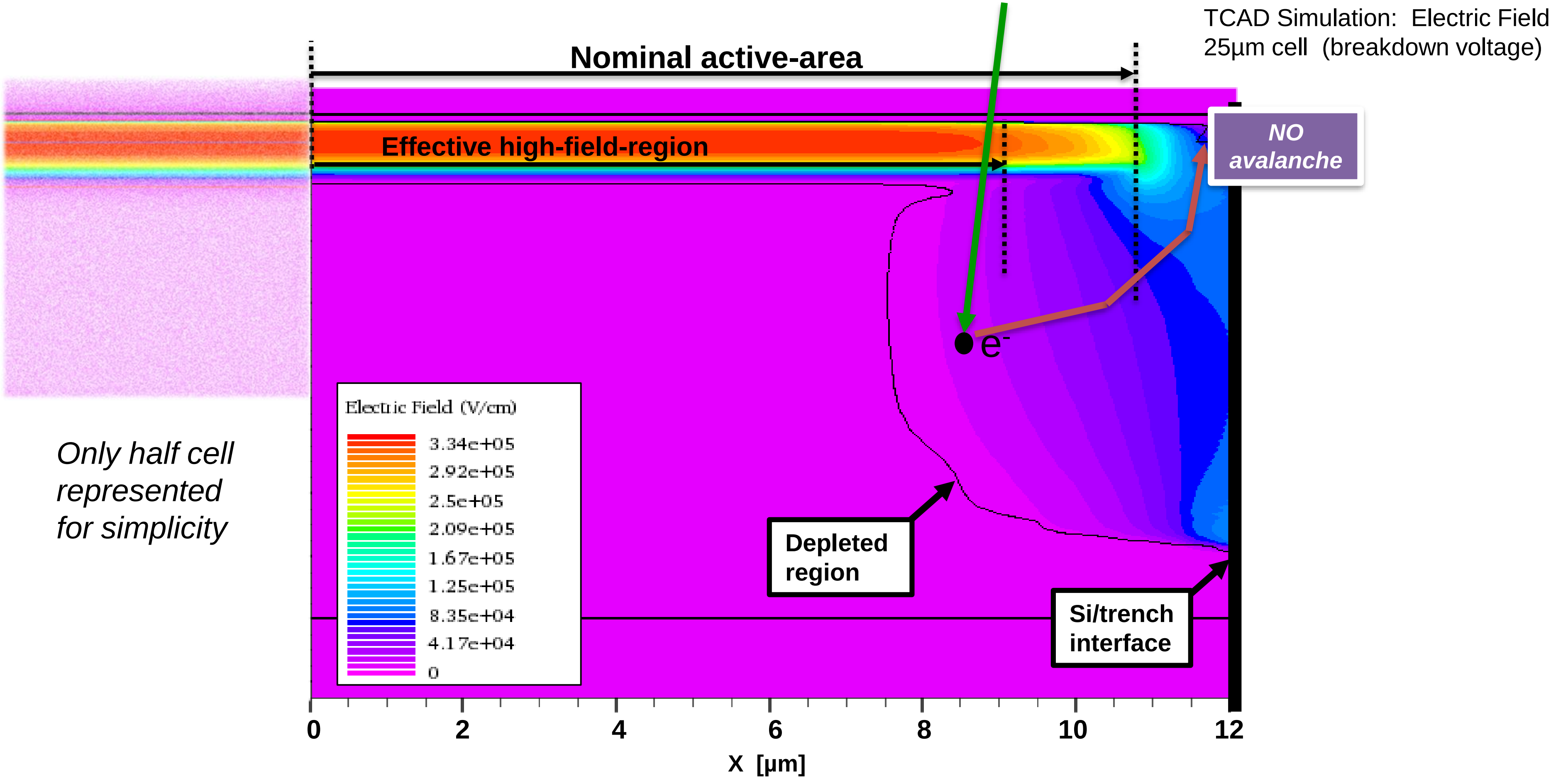
TCAD simulation domain:





Acerbi et al, 2018 10.1109/JQE.2018.2802542

25µm cell: the “Border effect”



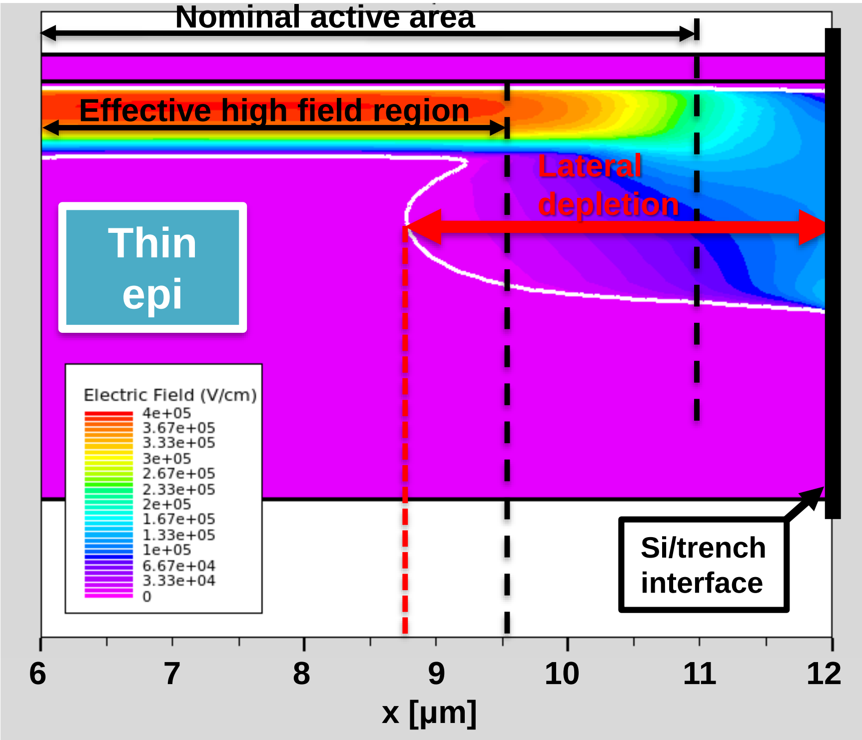
Only half cell represented for simplicity

1. **Effective high-field region is <u>smaller than the nominal one</u>**
2. **Lateral depletion below the high field region → <u>lateral drift</u>**
   – Both these effect → “<u>border effect</u>” → reduction of effective FF

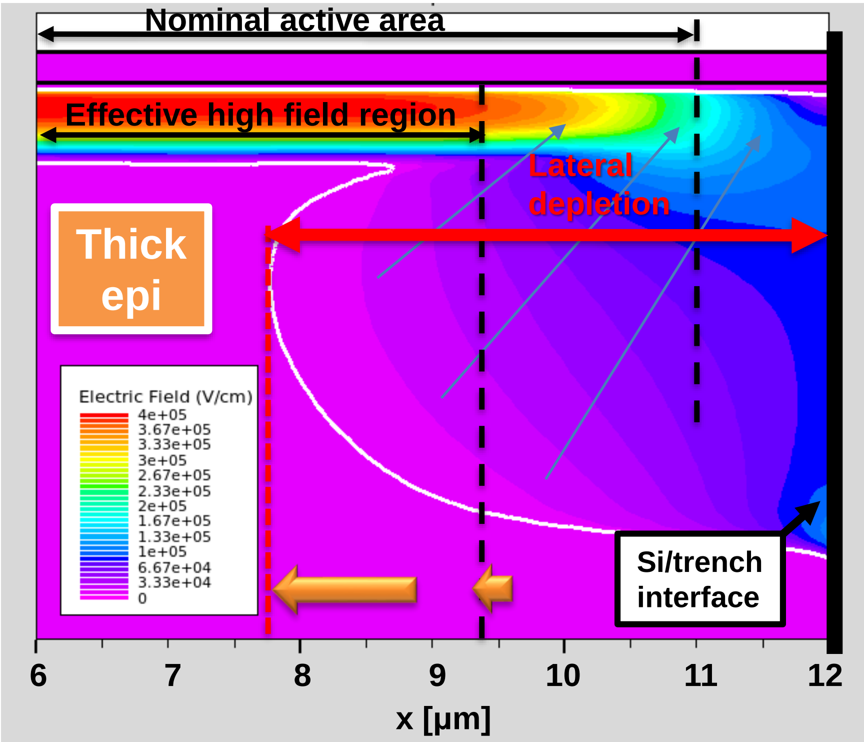
Thin vs. thick epi

TCAD simulation of 25µm cell at breakdown voltage

Thin epi → RGB-HD



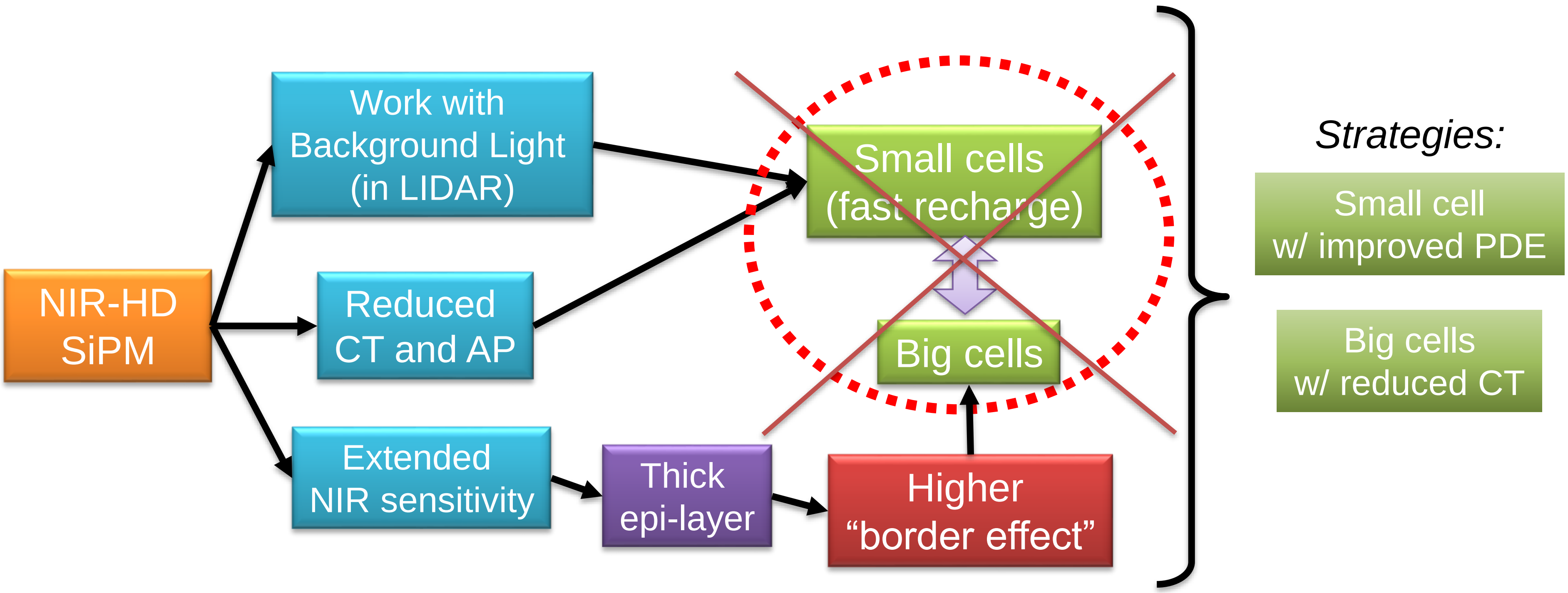
Thick epi → NIR-HD



Thicker epitaxial layer → Higher "BORDER EFFECT"

- *Border effect may compensate the PDE increment due to thicker epi-layer !*

NIR SiPM improvements strategies



- **Applications like LIDAR → need small cells but with high PDE**
  → border effect & small cells not possible

- **2 strategies:**
  – Small cells with improved internal structure
  – Big cells with reduced correlated noise

NIR-HD productions

2017 NIR-HD FBK production

- **First promising results**
  (see presentation F. Acerbi at NDIP 2017)
- PDE limited by high border effect
- New TCAD simulation to reduce border effect
- New ideas on cell design

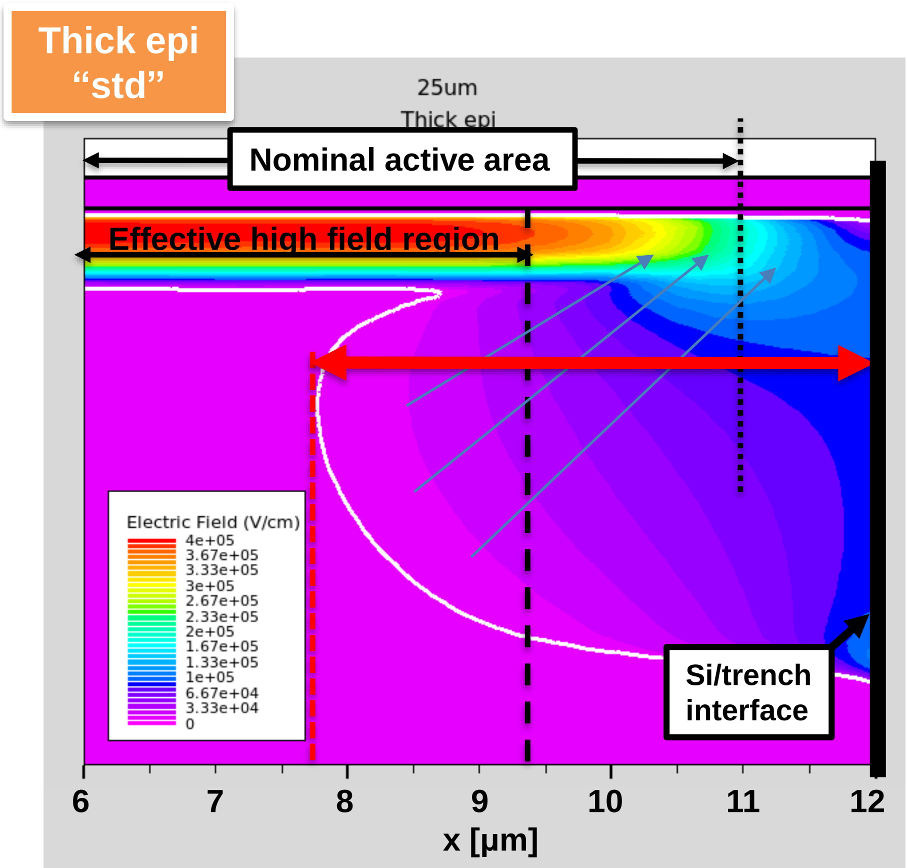
2018 NIR-HD FBK production

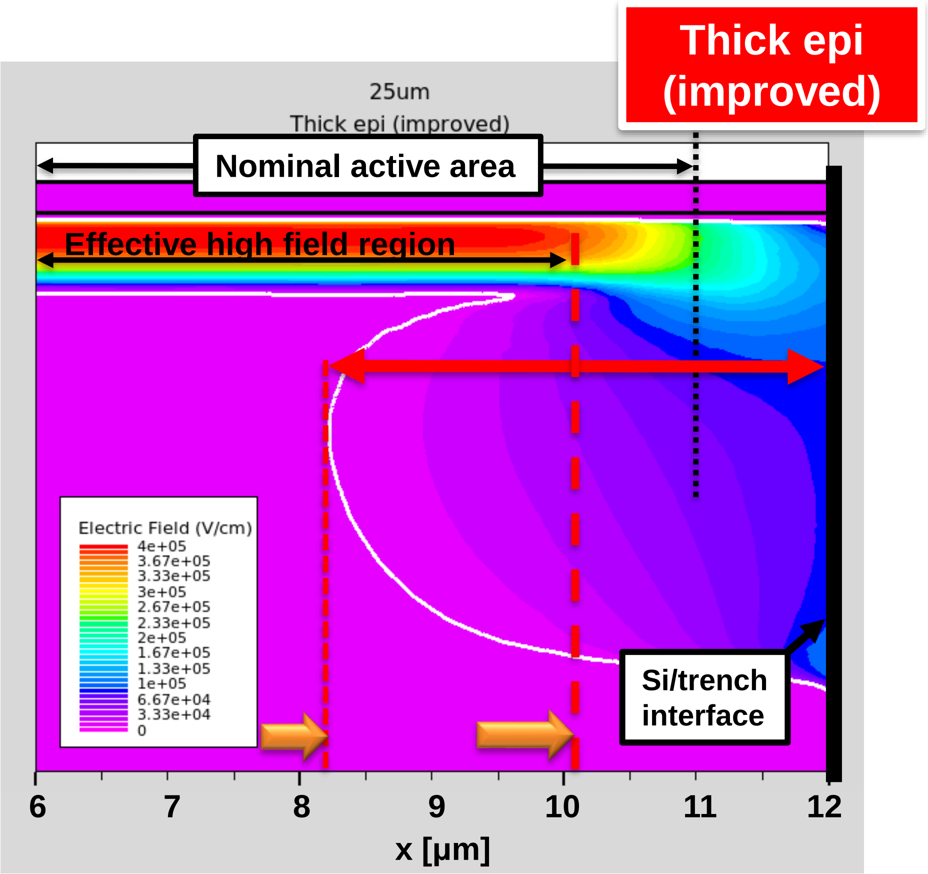
Several layout and variants have been produced and tested.
Here we report a comparison between the following promising ones:

1x1 mm^2 (small pitch)		1x1 mm^2 (large pitch)	
25µm (thick epi)	25µm (thick epi - improved)	50µm (thick epi)	54µm (multiple trenches)
Faster recharge, lower CN influence		Slower recharge, higher efficiency	

Figure of merit:
PDE vs. Correlated Noise
→ to be improved

25µm cell with improved cell structure



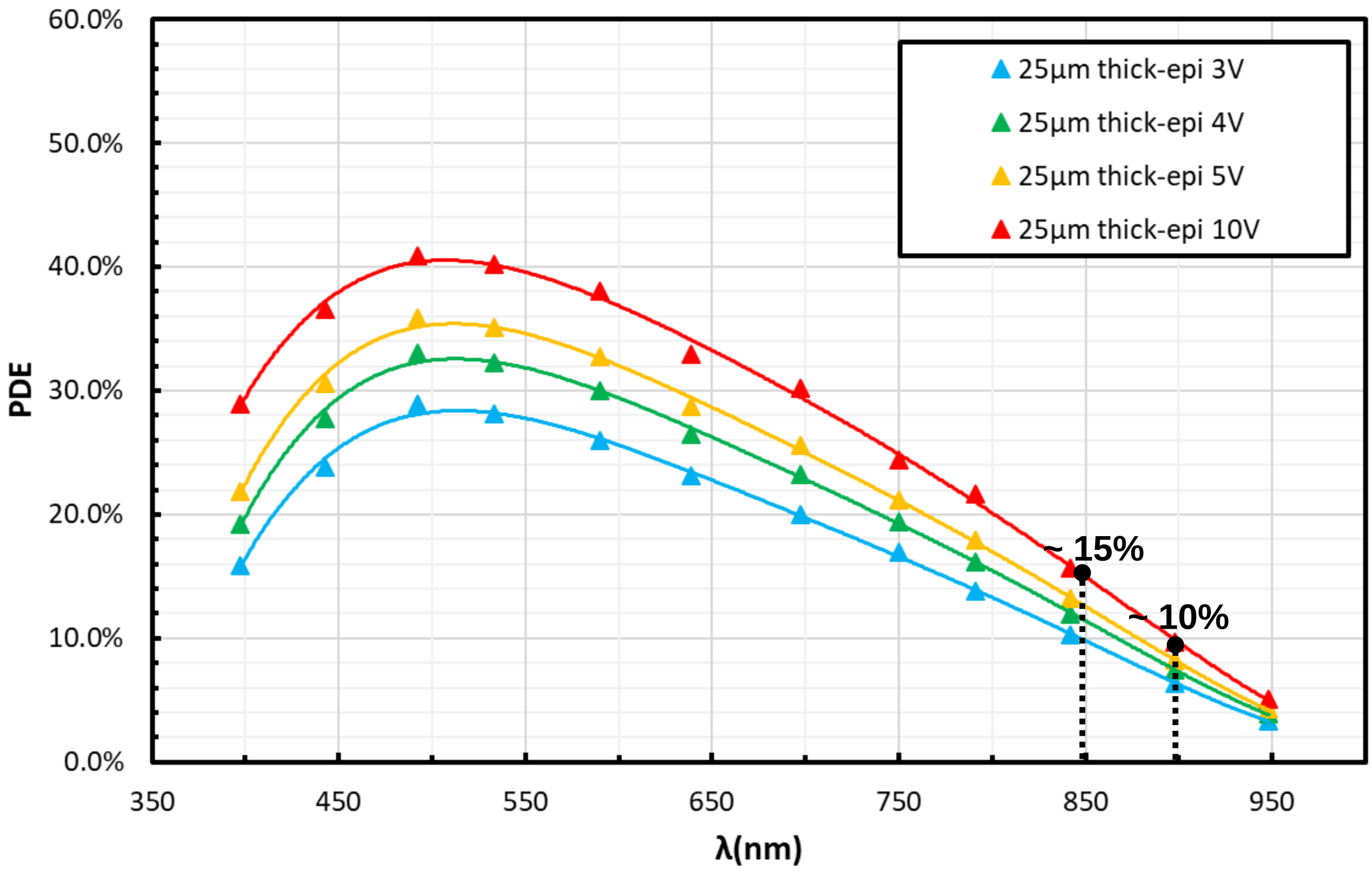


- **Modified doping profile → improved thick epi structure:**
  - Enhancement of the effective high field region (but not close to trench, to avoid higher noise !)
  - Reduction of the lateral depletion

Measurement results:

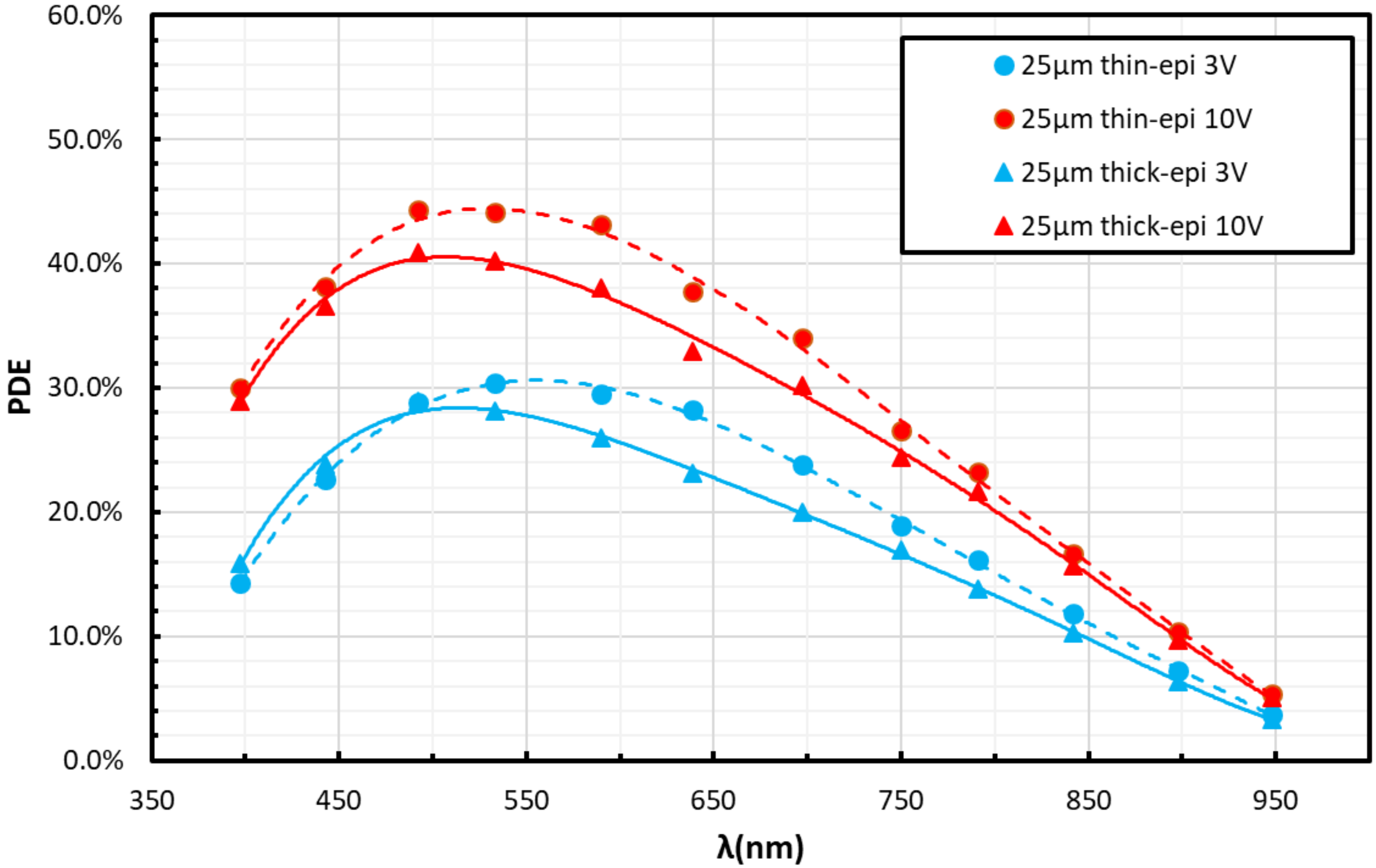
SiPMs with 25µm cell pitch

SiPM 25µm pitch, thick-epi ("std")



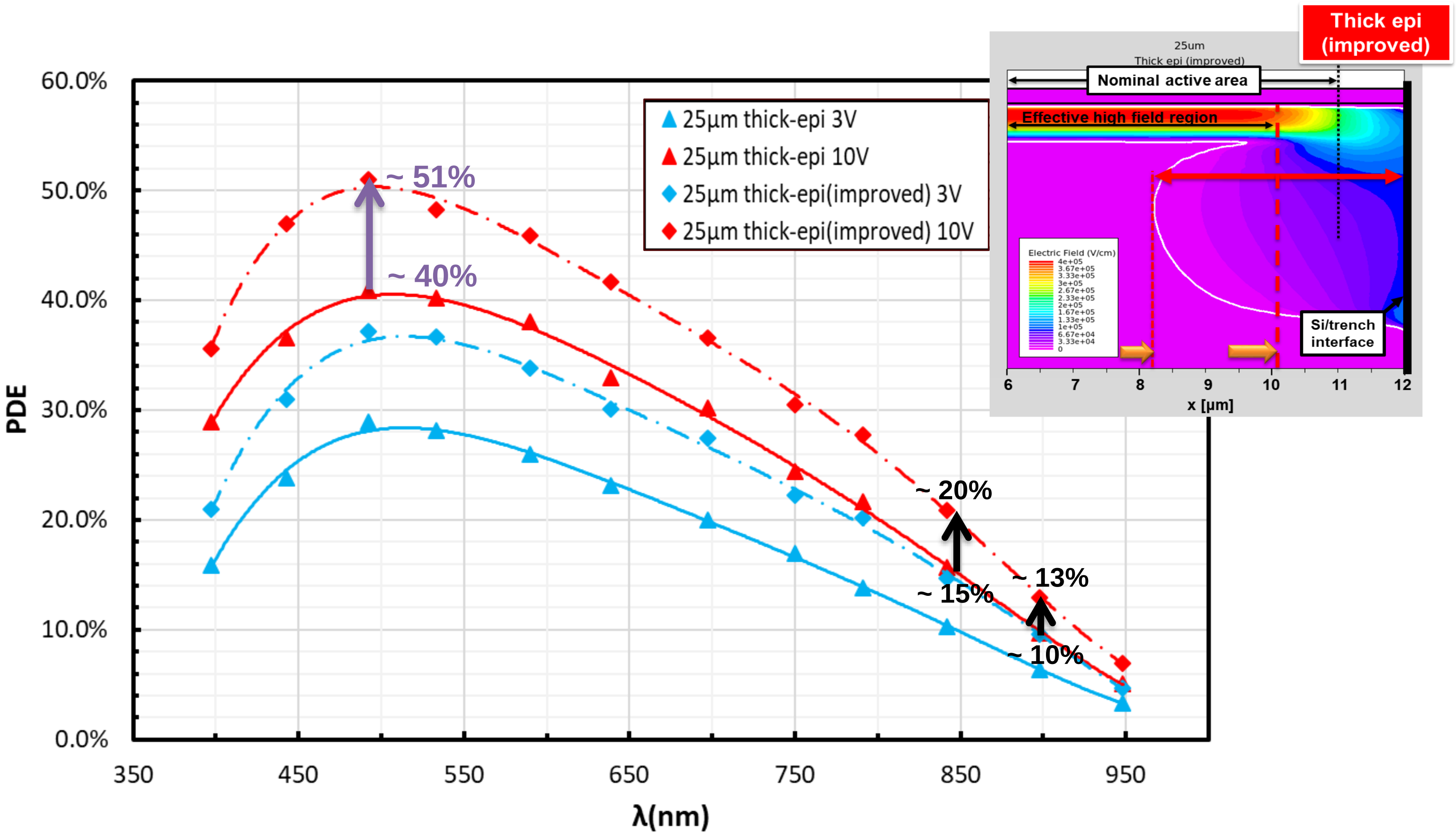
- **Good results with relatively small cell:**
  - ~15% @ 850nm, ~10% @ 900nm
  - But limited by border effect

SiPM 25µm pitch, thick-epi vs thin-epi



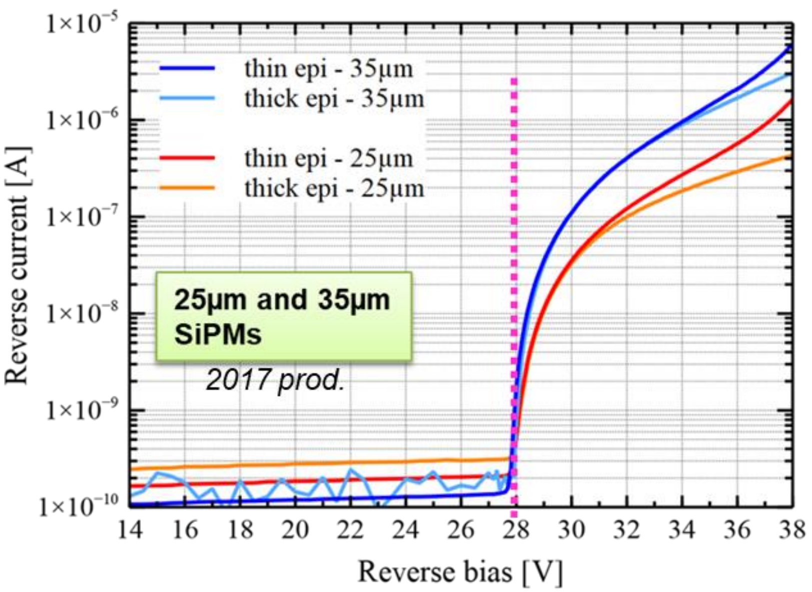
- **For 25µm cell → thick-epi and thin-epi have the same PDE in the NIR !**
  - Advantage of thicker epi balanced by higher border effect.
  - Need structure improvement !

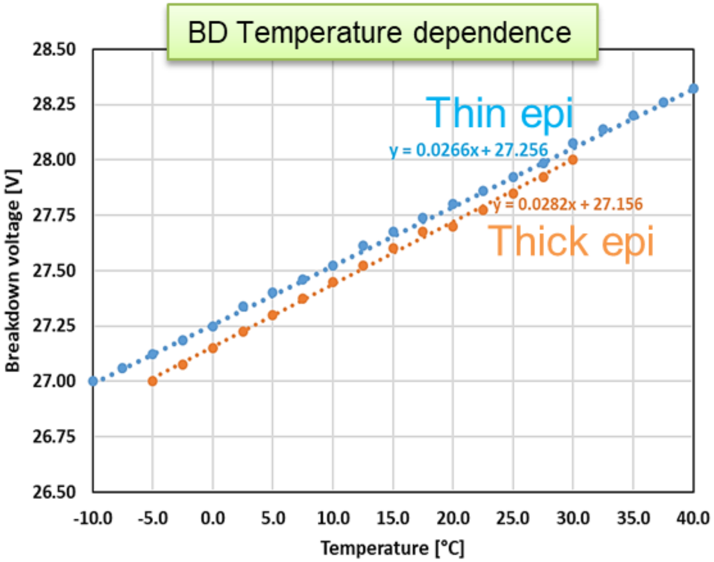
SiPM 25μm pitch, thick-epi, improved



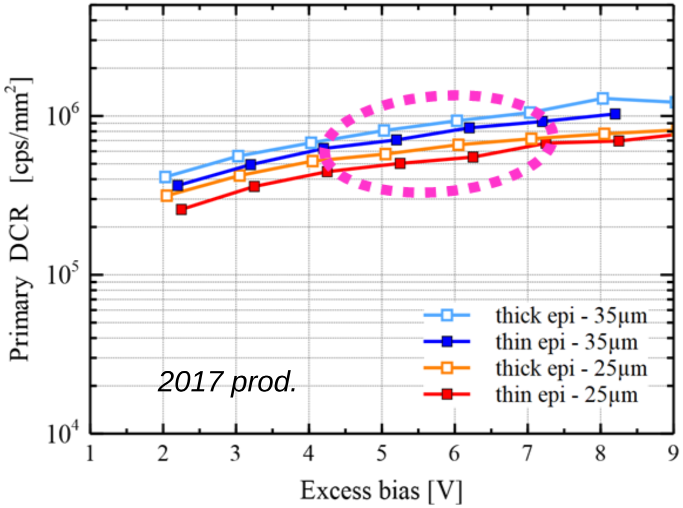
- **Improved PDE both in the peak and in the NIR:**
  - PDE: ~20% @850nm, ~13% @ 900nm
  - with 25μm cell pitch at 10V excess bias

NIR-SiPMs – first results

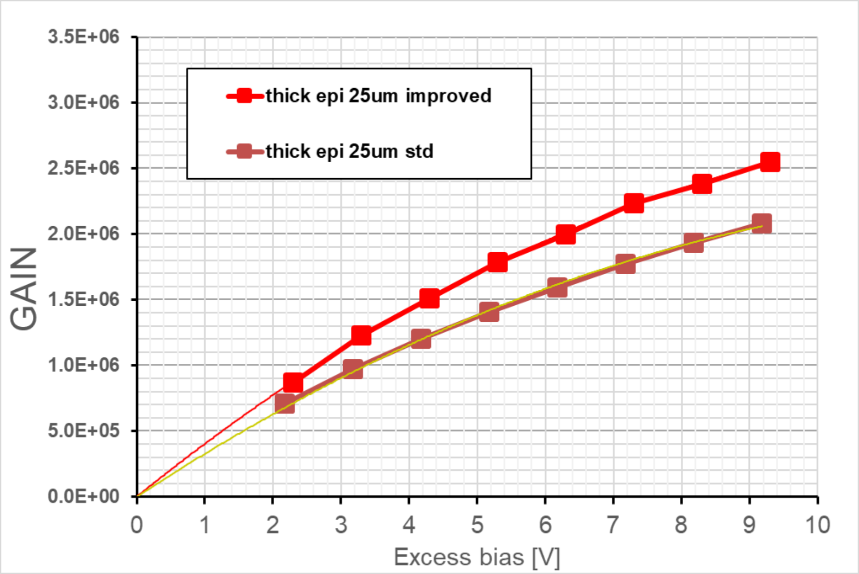


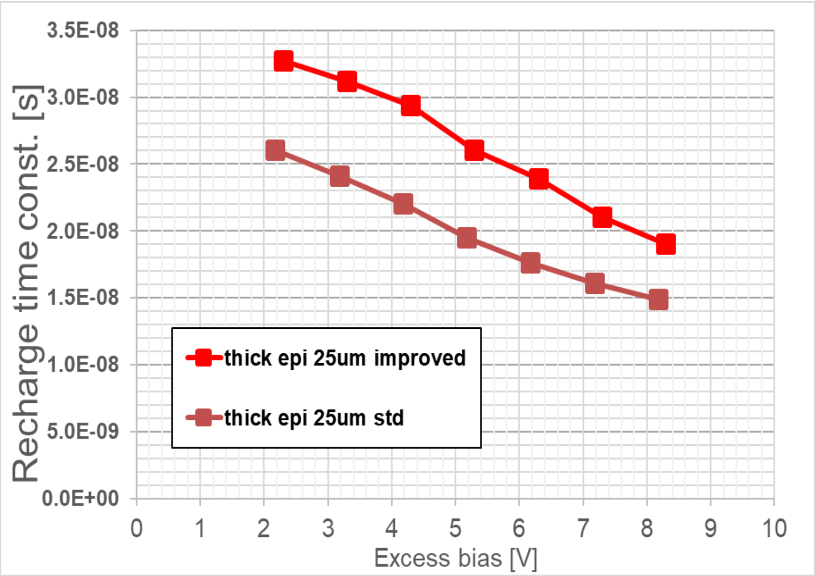


- <u>Breakdown voltage:</u> same of thin-epi (28V 20°C)
- Small breakdown temp. dependence
- Primary DCR slightly higher than thin epi (expected due to thicker depleted region)

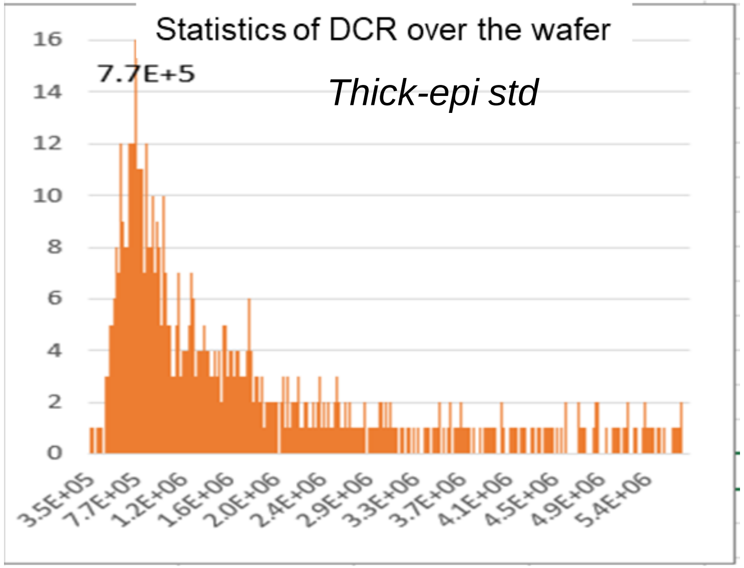


Performance of 25µm std and improved





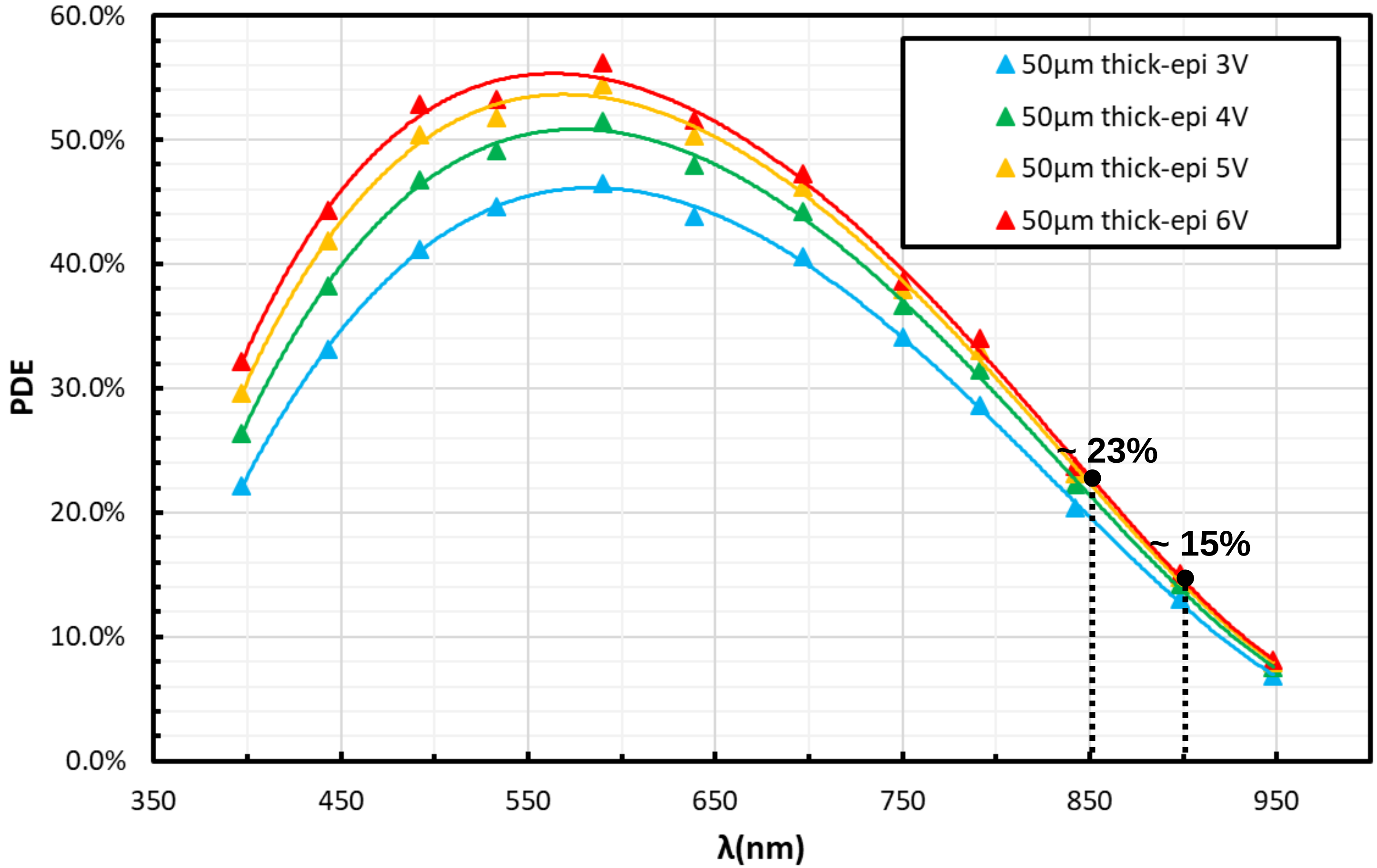
- **Effect of the improved structure is visible also in the GAIN**
  - Higher GAIN and CT for the improved structure.
  - DCR ~800kcps/mm^2 for std. ver.
    DCR ~1Mcps/mm^2 for improved ver.
  - BUT overall better PDE-vs.-noise.
    (see next slides)



Measurement results:

SiPMs with 50µm cell

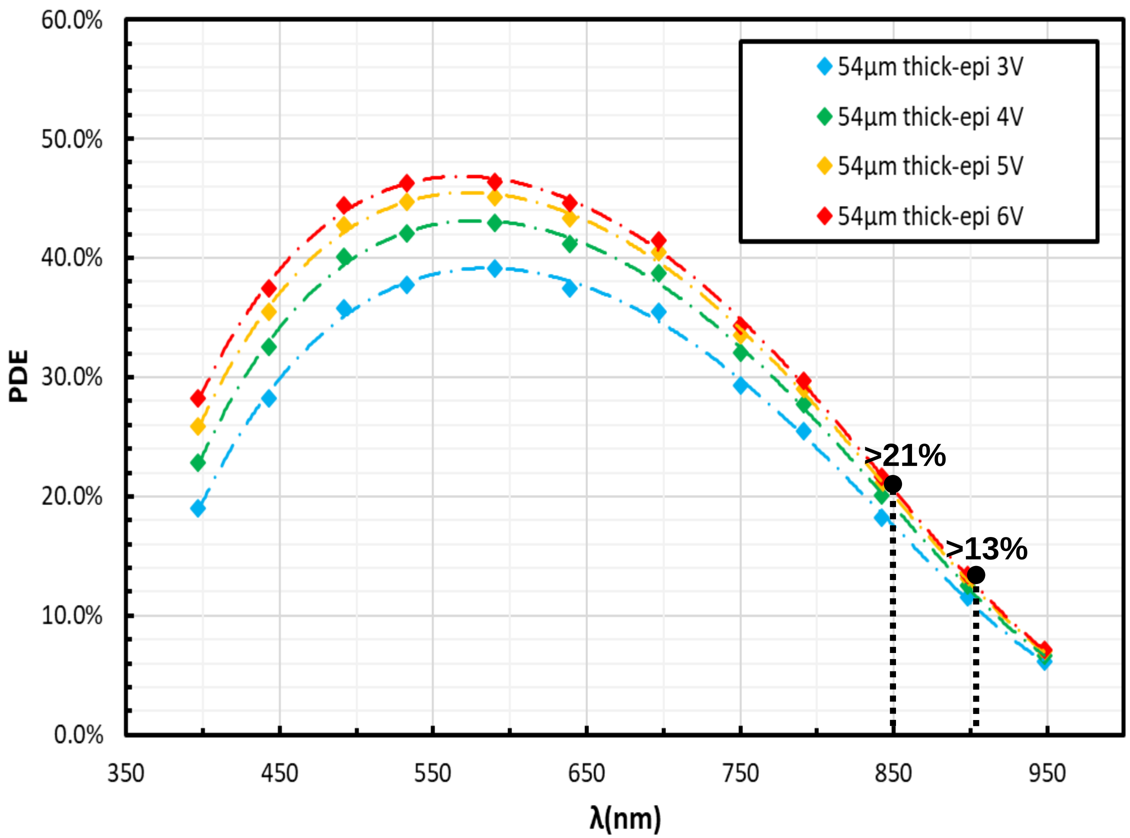
SiPM 50µm pitch, thick-epi (“std”)

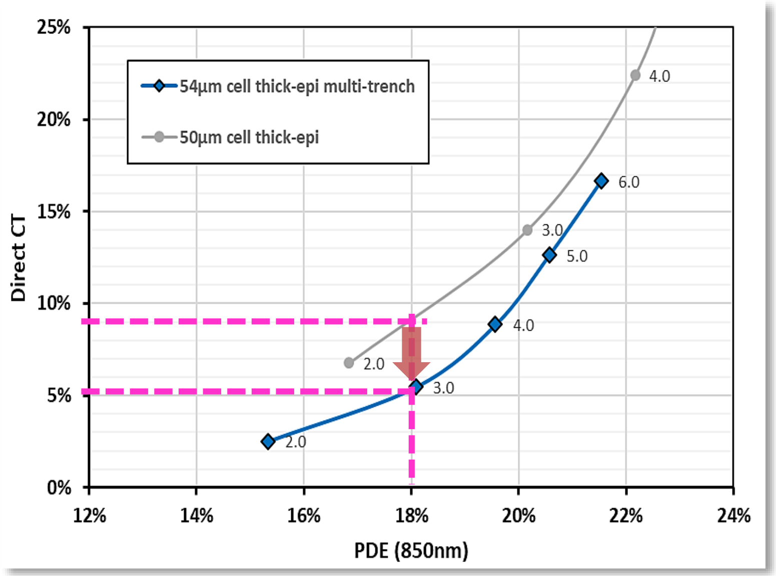


- **Bigger cell → much smaller border effect**
  - PDE: ~22% at 850nm, ~15% at 900nm

Very good PDE, but big area give higher correlated noise!

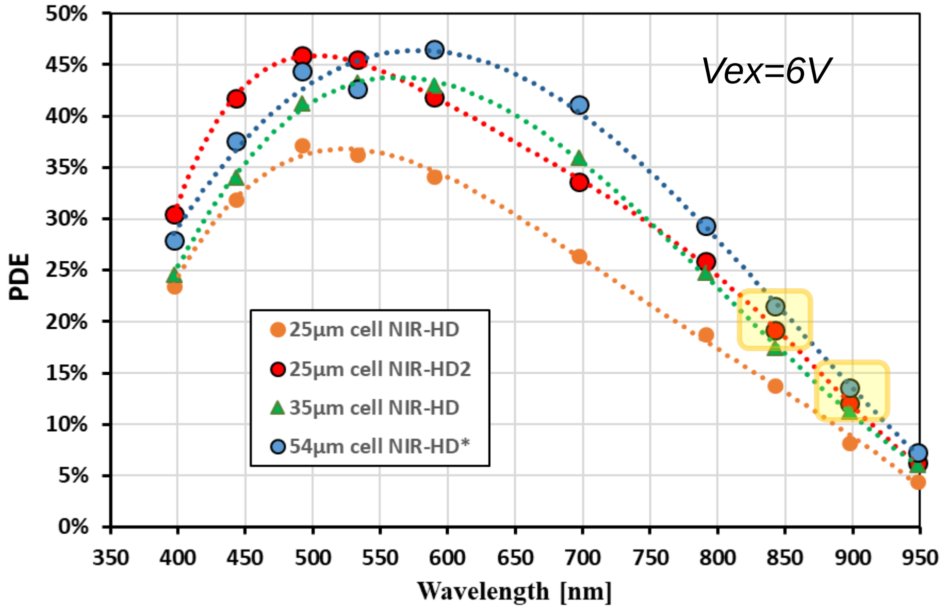
SiPM (54)µm pitch, thick-epi, multi-trench



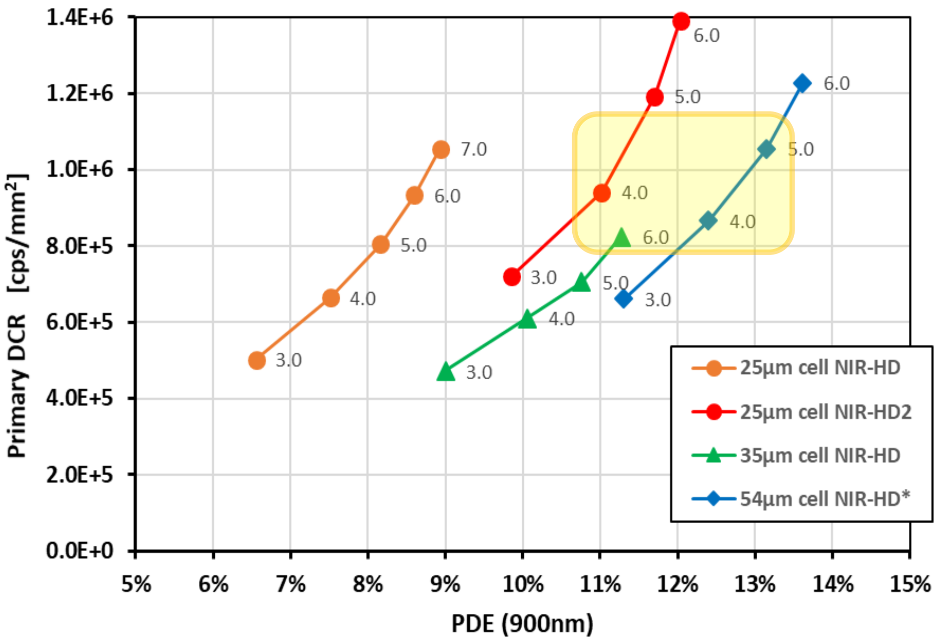


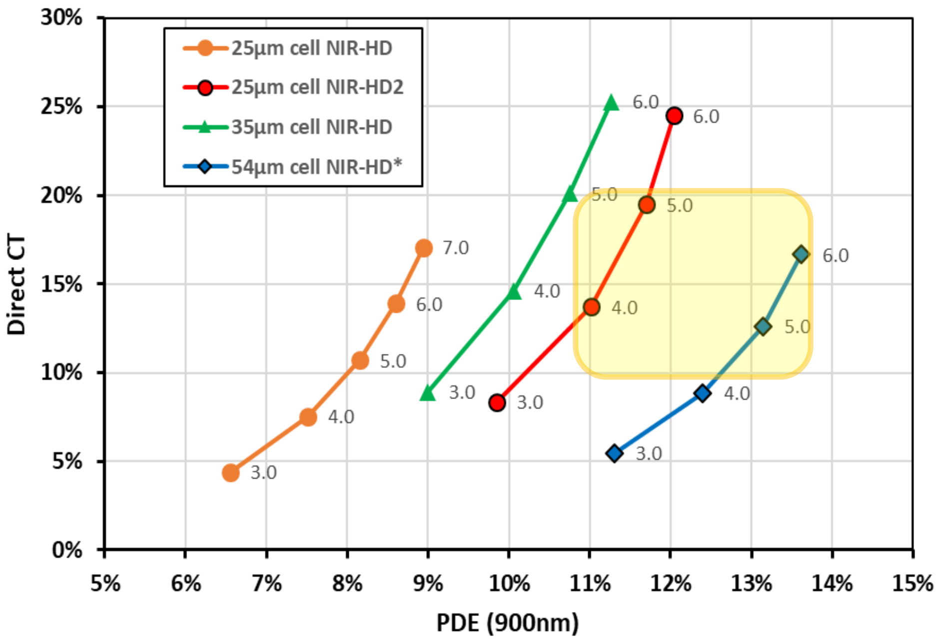
- PDE reduced due to lower FF… but also CT is reduced.
- Correct comparison → figure of merit: PDE-vs.-CT → Enhanced !

Summary: new FBK NIR-HD summary



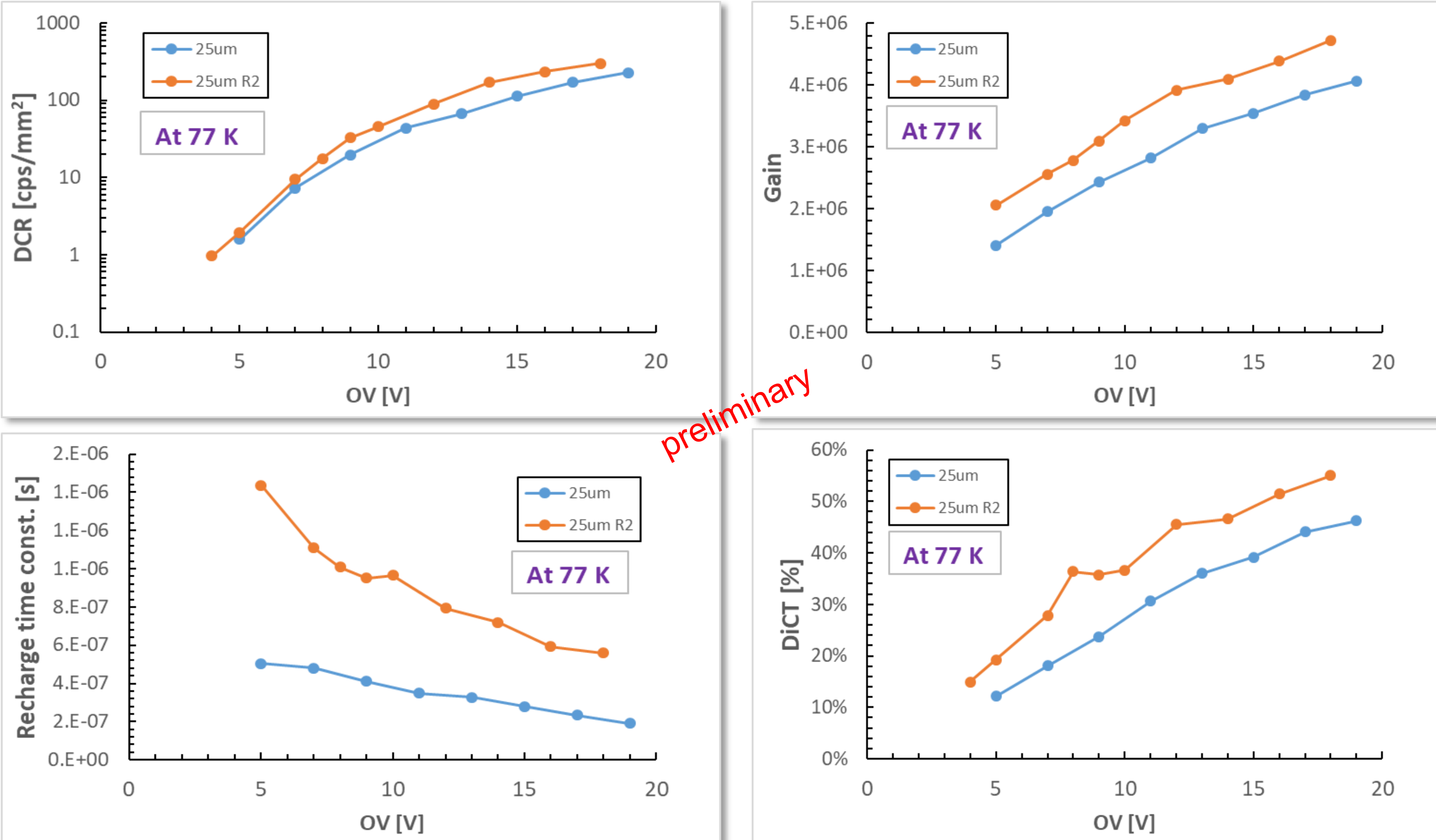
- **New NIR-HD technology:**
  - Primary DCR in the order of ~1Mcps/mm^2
  - Direct CT: ~10÷20%
  - With a PDE:
    17% ÷ 20% @850nm
    11% ÷ 13% @900nm





Measurements at cryogenic temperature

NIR-HD 25µm cell → Measurements in liquid nitrogen @77 K



Conclusions

- NIR range appealing for several applications
  - SiPM design is challenging (especially for small cells) → border effect !
- First production in 2017
  - Thicker epi structure with “standard” cell structure → promising results
- Second production in 2018
  - Improved performances through
    - Modified doping profiles **25µm cell**: at 10% DiCT **>10% PDE at 900nm**
    - Multiple trenches **54 µm cell**: at 10% DiCT **~12.5% PDE at 900nm**

Next steps

- Further tests at cryogenic temperatures
- Further SiPM improvements for better PDE

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FUTURE BUILT ON KNOWLEDGE

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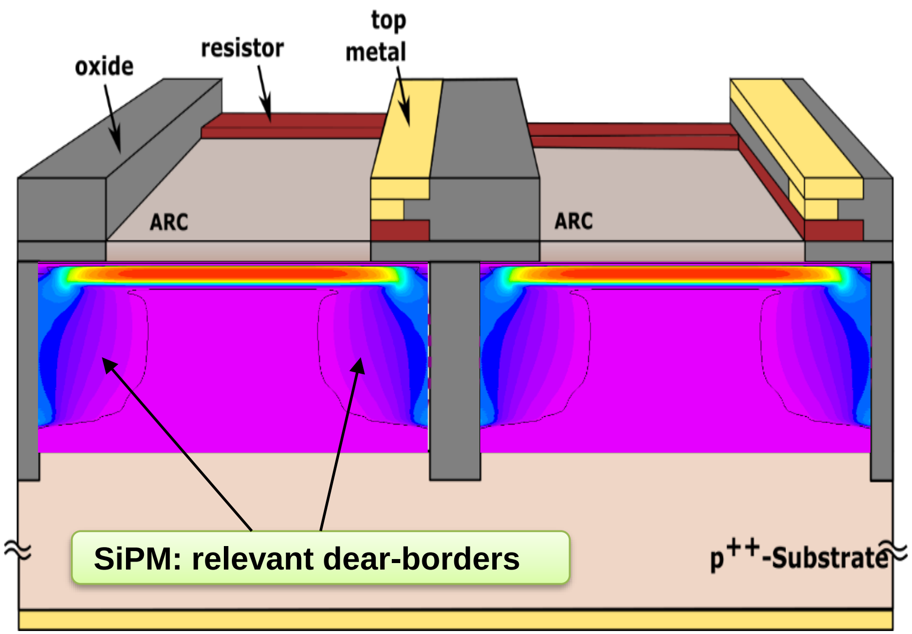
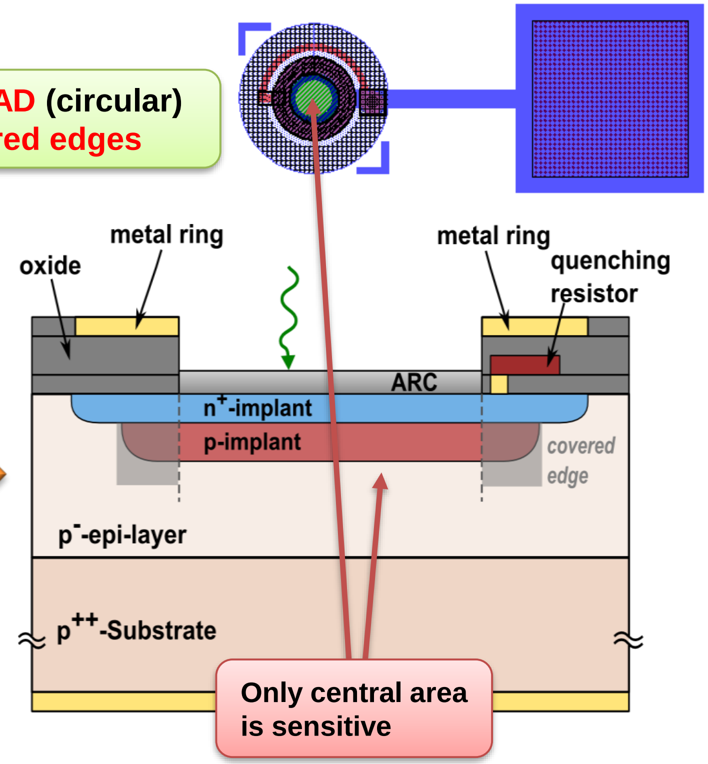
https://iris.fbk.eu/silicon-photomultipliers

backup

Evaluation of the PDE limits

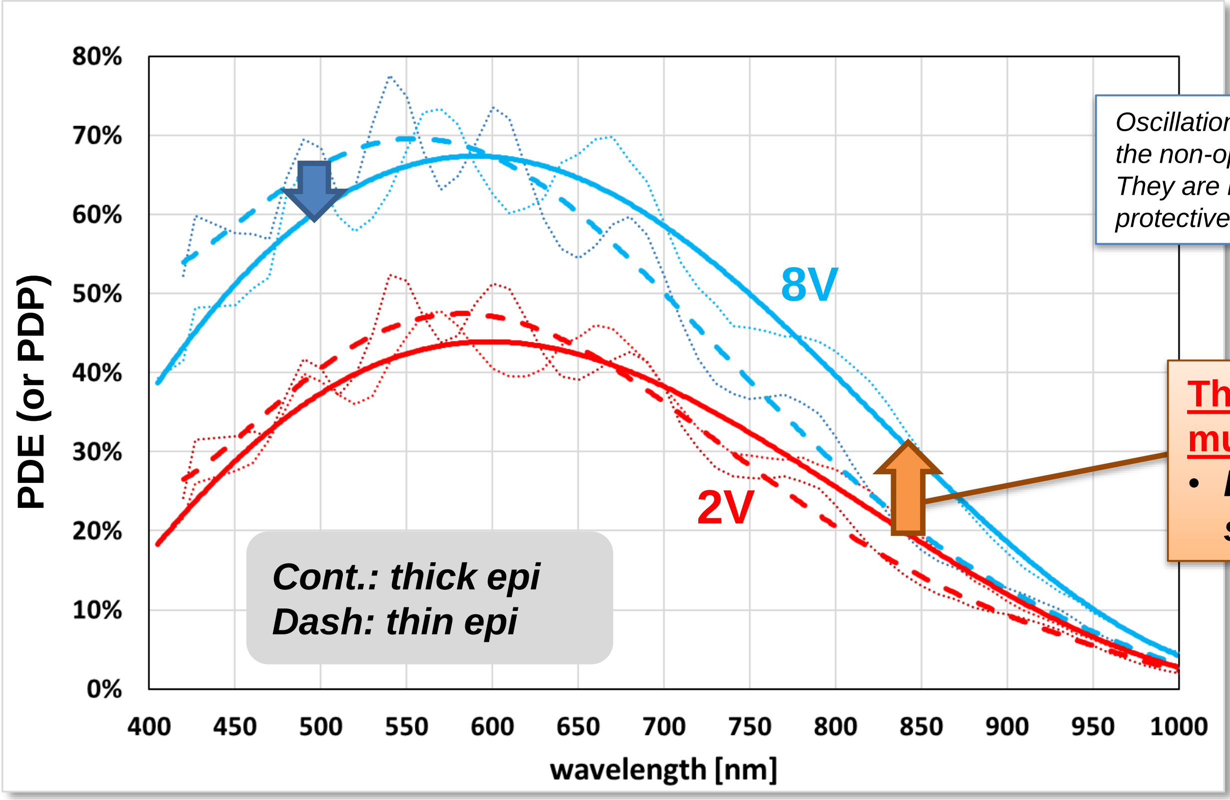


Single SPAD (circular) with covered edges



- *The border effect → still the limiting effect in PDE improvement (especially in small cells)*
- **maximum PDE achievable ?**
  - We employ a circular SPAD with covered edges
  - Only central region detect lights → Comparison: SPAD thin epi, SPAD thick epi

PDE comparison: thin vs think epi-layer



Oscillations in the PDE due to the non-optimized dielectric. They are removed when using protective resin on the top

Thick-epi:
much higher PDE !
- ***Despite the slower Pt rise***

- **Comparison: PDE of circular SPAD (covered edges) → thin vs thick epi**
  - Significantly higher PDE at long wavelength… despite the slower Pt rise

- **PDE: from 20% to ~30% at 850nm**
  from ~12% to ~18% at 900nm

PDE achievable without border effect