3D integration approaches for SiPM: from BSI to TSV

L. Parellada-Monreal, F. Acerbi, A. Ficorella, A. Franzoi, A. G. Gola, S. Merzi, A. Nawaz, M. Ruzzarin and G. Paternoster

Fondazione Bruno Kessler

lparelladamonreal@fbk.eu
www.fbk.eu

Outline

01 FBK SiPM technology

FBK SiPM technology roadmap and motivation for 3D integration

02 BSI SiPM for NIR

03 TSV interconnections for VUV/NUV SiPM

04 Conclusions

Outline

01 FBK SiPM technology
FBK SiPM technology roadmap and motivation for 3D integration

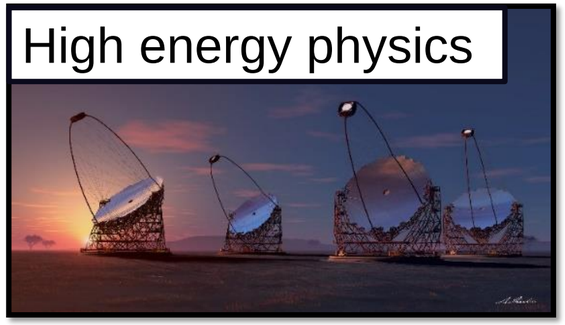
02 BSI SiPM for NIR

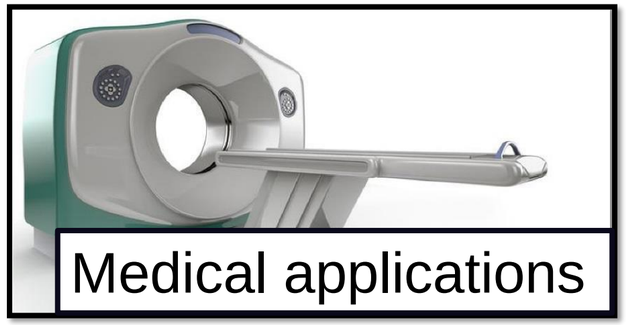
03 TSV interconnections for VUV/NUV SiPM

04 Conclusions

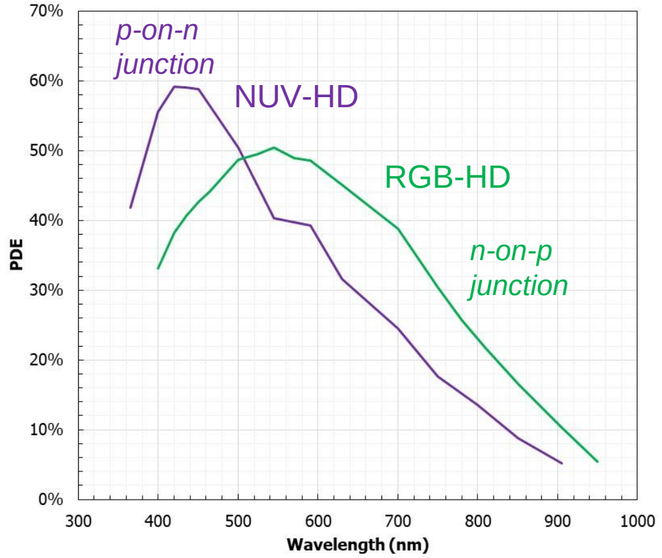
FBK SiPM technology

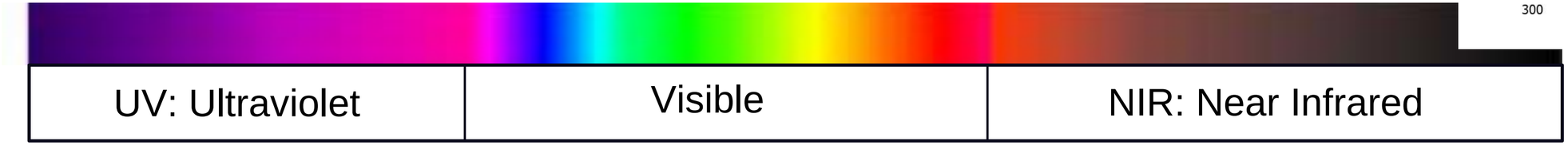
High energy physics





Medical applications





UV: Ultraviolet	Visible	NIR: Near Infrared

Electric field engineering

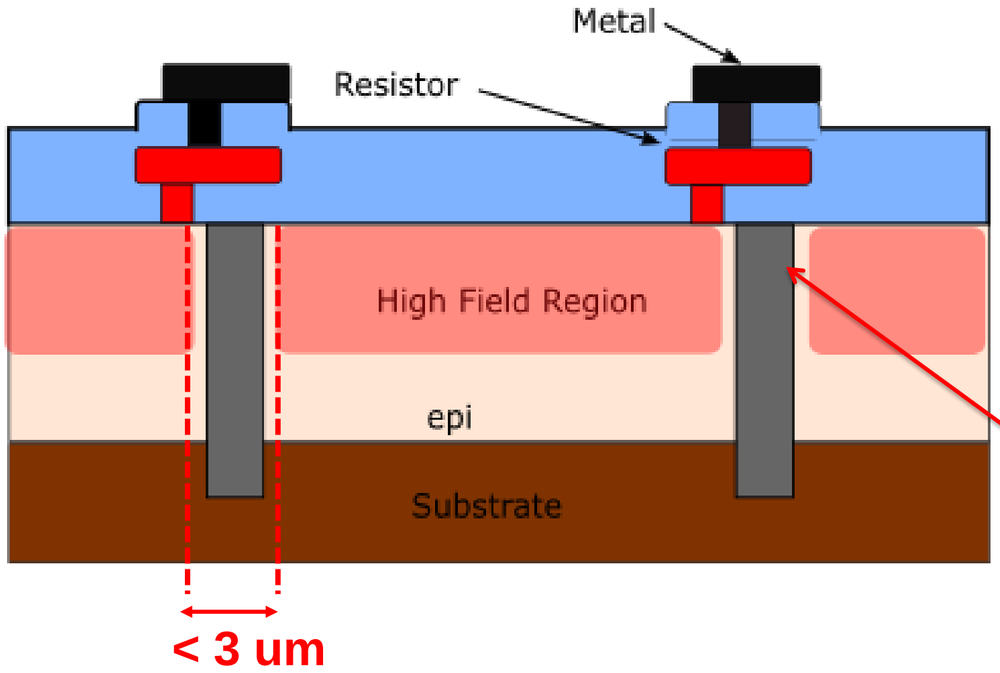
New cell border (trenches)

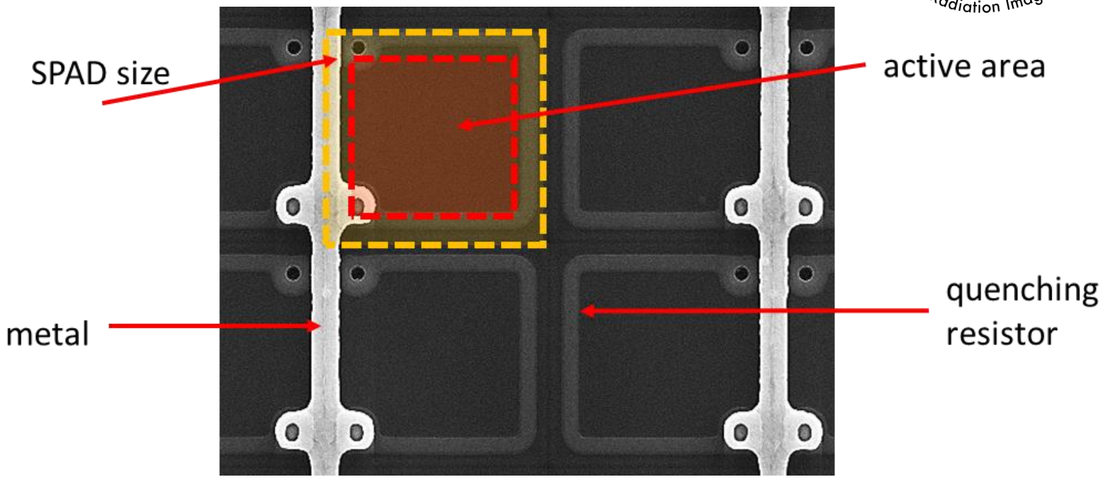
2005 **2010** **2012** **2015**

RGB **NUV** **NUV-HD**

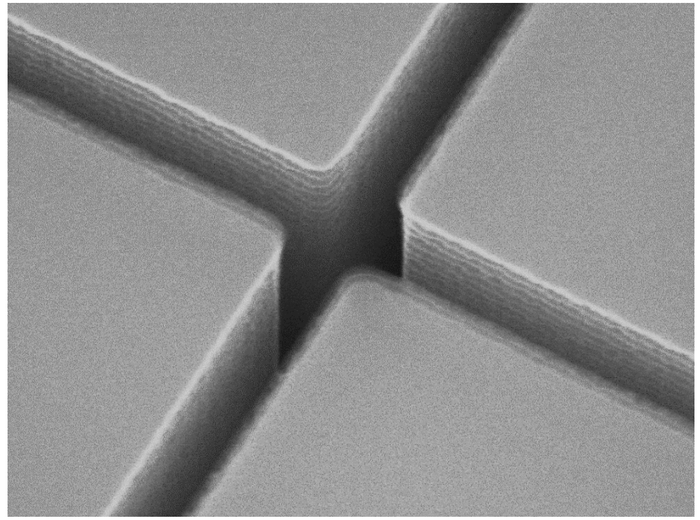
RGB-HD

HD Silicon Photomultiplier Technology





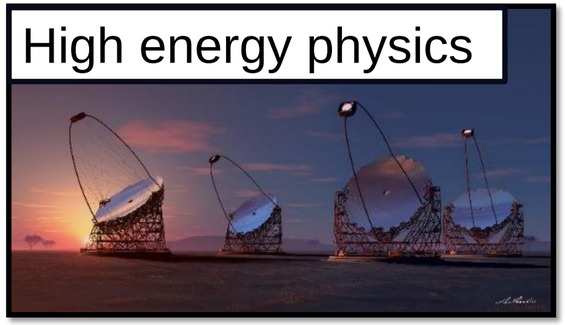
Deep Trench

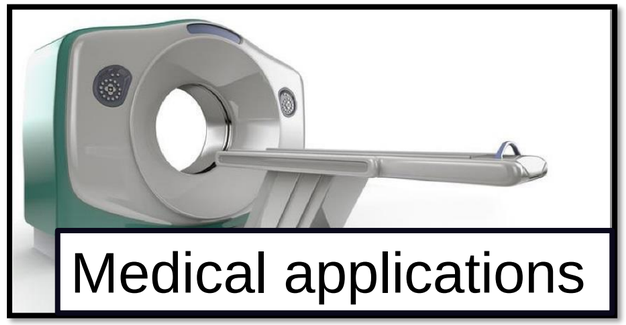


- Trenches between cells → Lower Cross-Talk
- Cell pitch: 15 – 40 um
- Narrow dead border region → Higher Fill Factor (>80%)
- Make it simple: 9 lithographic steps

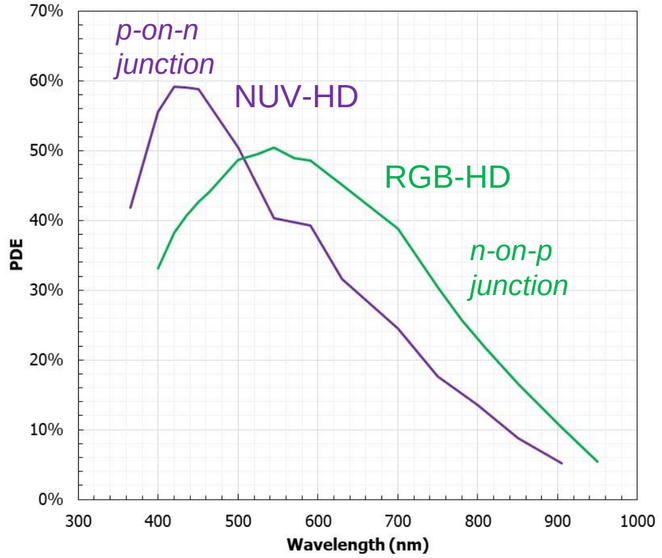
FBK SiPM technology

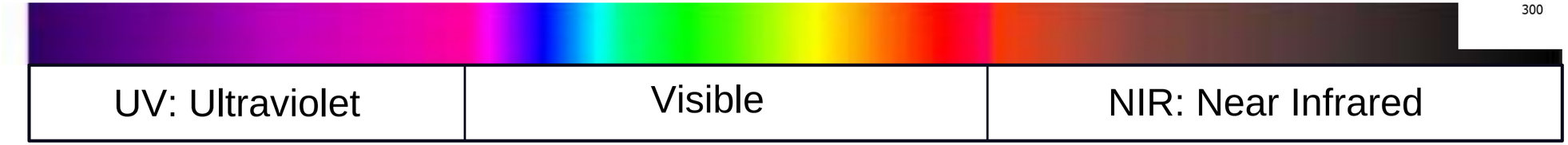
High energy physics





Medical applications





UV: Ultraviolet	Visible	NIR: Near Infrared

Electric field engineering

New cell border (trenches)

2005 — **RGB**

2010 — **RGB-HD**

2012 — **NUV**

2015 — **NUV-HD**

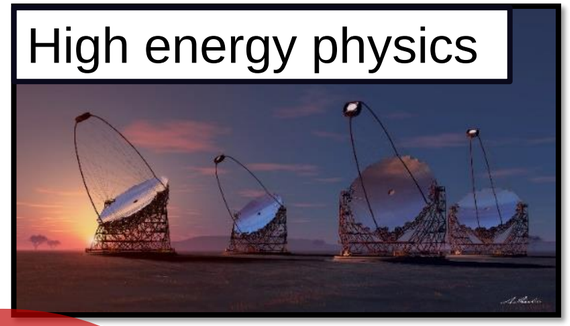
2016 — **NUV-HD-Cryo**

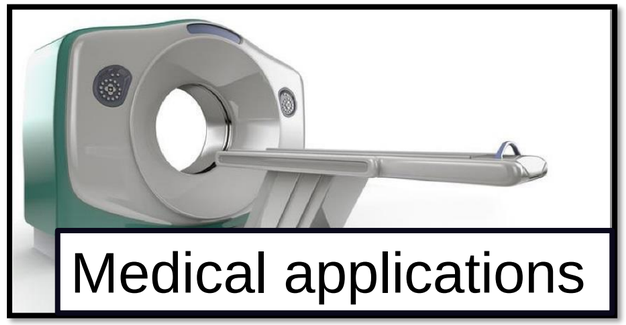
2017 — **RGB-UHD**

Ultra high cell density (very small cells)

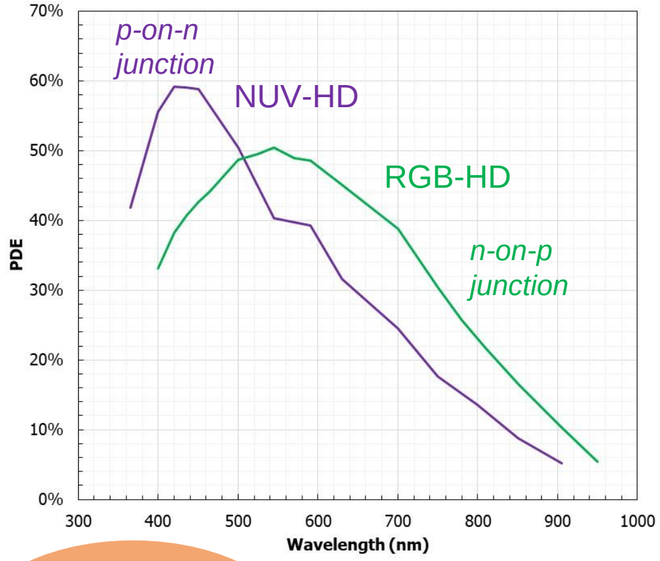
FBK SiPM technology

High energy physics





Medical applications



VUV

UV: Ultraviolet | Visible | NIR: Near Infrared

NIR

Electric field engineering

New cell border (trenches)

2005 RGB

2010

2012 NUV

RGB-HD

2015 NUV-HD

2016

NUV-HD-Cryo

2017 RGB-UHD

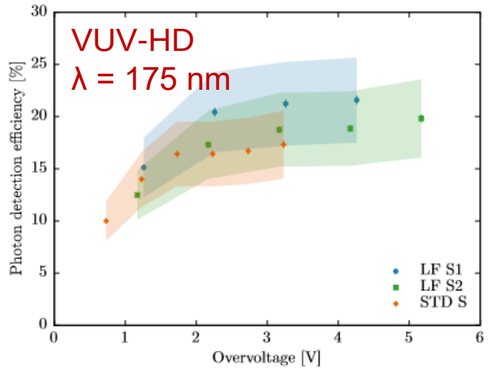
Ultra high cell density (very small cells)

NIR-HD

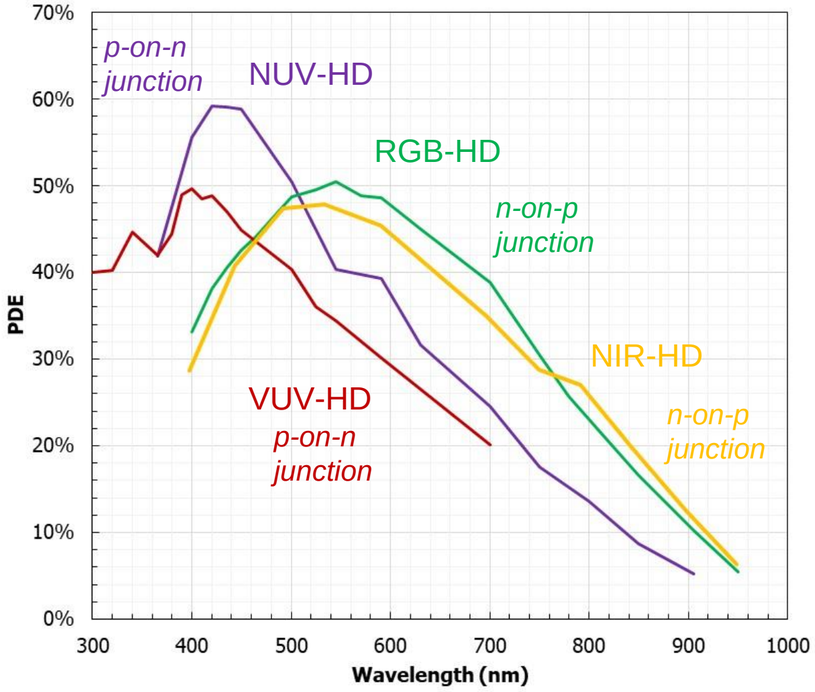
2018

2019 VUV-HD

FBK SiPM technology



Jamil, A., et al. "VUV-sensitive silicon photomultipliers for xenon scintillation light detection in nEXO." IEEE Transactions on Nuclear Science 65.11 (2018): 2823-2833



Electric field engineering

New cell border (trenches)

2005 — 2010 — 2012 — 2015 — 2016 — 2017 — 2018 — 2019

RGB

NUV

RGB-HD

NUV-HD

NUV-HD-Cryo

RGB-UHD

NIR-HD

VUV-HD

Ultra high cell density (very small cells)

Ongoing Developments

3D integration

Hybrid SPAD arrays/SiPM

BSI NIR-HD

TSV VUV-HD

3D Integration: Hybrid SPAD array/SiPM

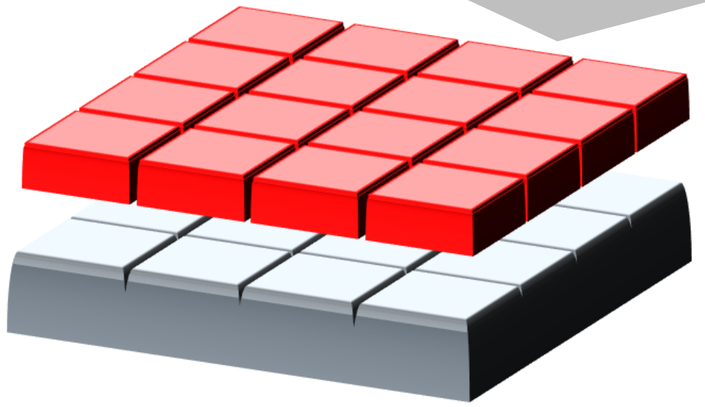
In the Framework of IPCEI project, FBK proposed an R&D aimed at developing an **hybrid sensor** integrating:

- SPAD in Custom Technology
- CMOS read-out electronics

Main Advantages:

- Preserving the performance in terms of PDE and DCR of SPADs in custom technology
- Adding some functionality at pixel level and further electronics at chip level

CUSTOM SPAD array/SiPM



CMOS read-out electronics

NUV-HD

RGB-UHD

NIR-HD

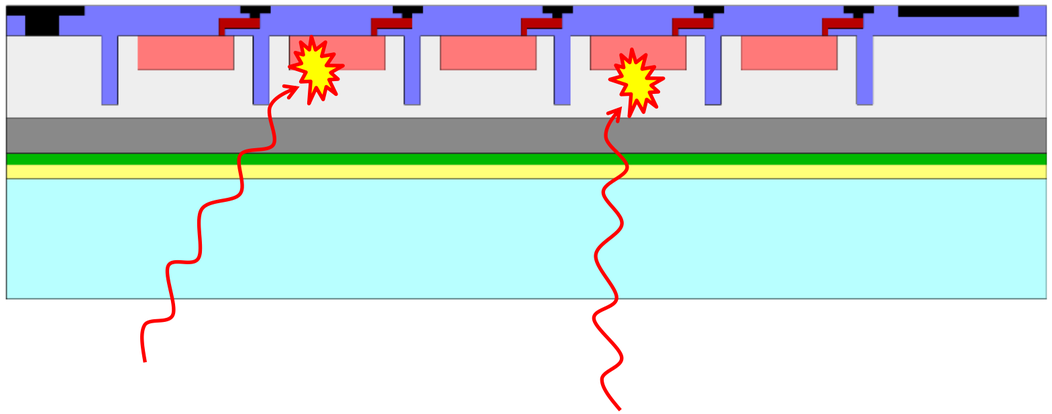
VUV-HD

NUV-HD Cryo

- Ultra-Versatile Technology platform
- It combines all the advantages of a sensor in custom technology with the advantages of an integrated CMOS readout

3D Integration schemes

Back Side illumination for Visible/NIR



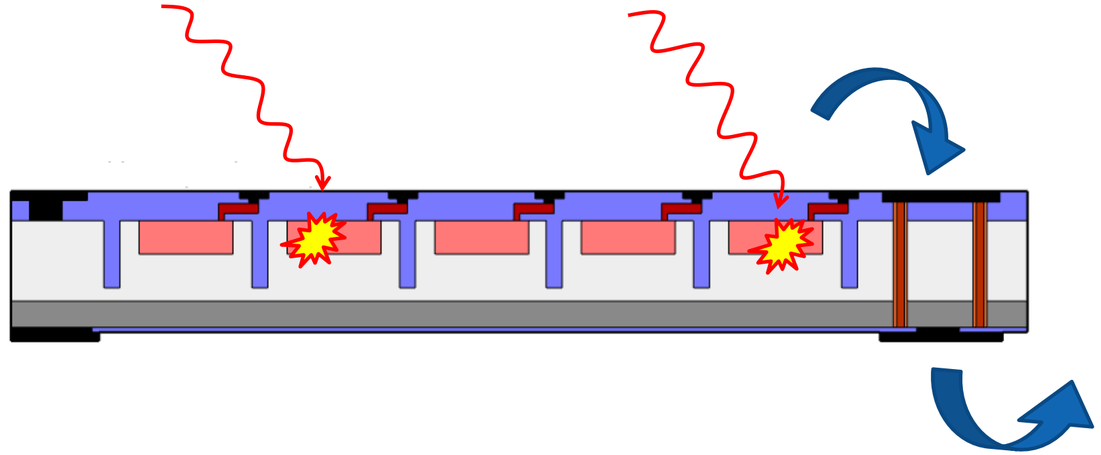
Pro:

- 100% FF
- TSV-free

Cons:

- Very thin sensor devices

Front Side Illumination for NUV/VUV



Pro:

- Much shallower junction depth
- Unaffected device performance

Cons:

- TSV connections
- FF losses due to TSV and BEOL

Outline

01 FBK SiPM technology

FBK SiPM technology roadmap and motivation for 3D integration

02 BSI SiPM for NIR

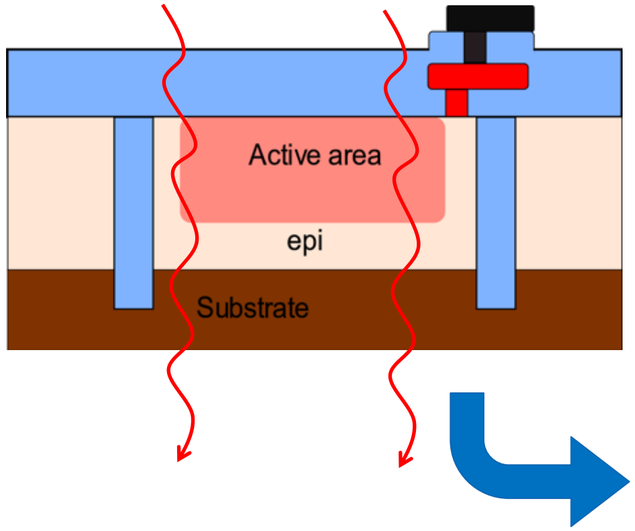
03 TSV interconnections for VUV/NUV SiPM

04 Conclusions

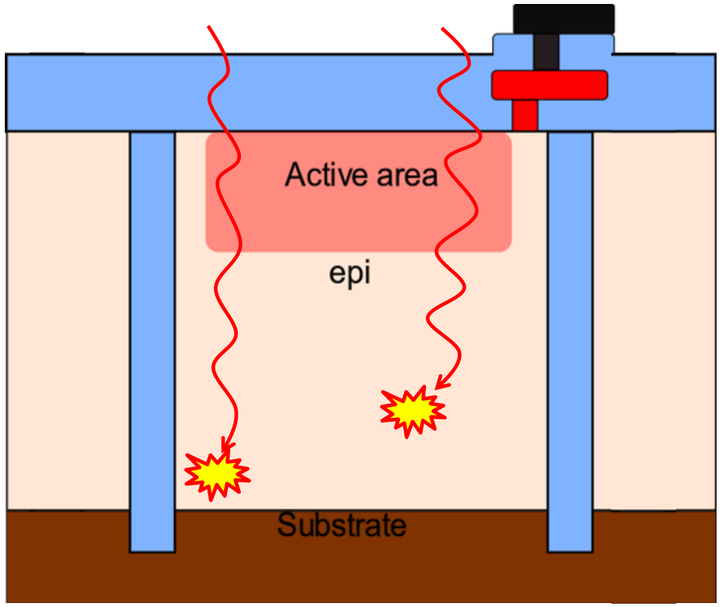
FSI vs BSI NIR SiPM

NIR light with energy close to the Si bandgap interacts deeper in the substrate

FSI-1



FSI-2

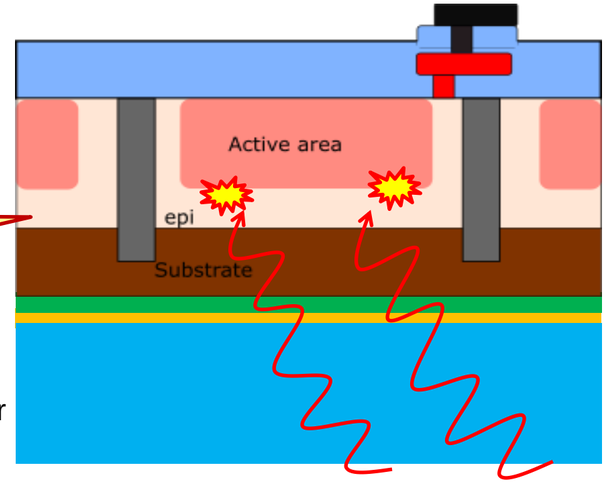


BSI

THINNED SUBSTRATE

ARC

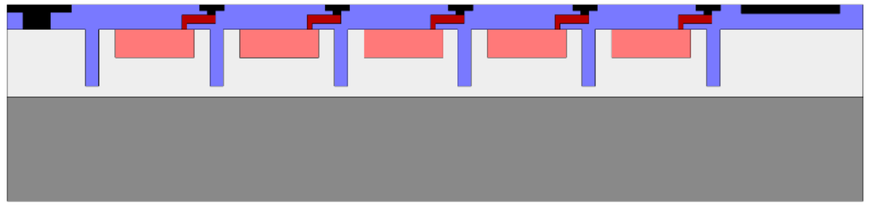
Glass support wafer



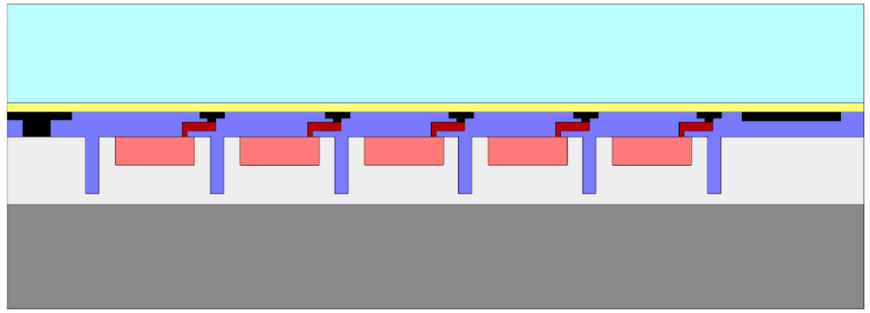
Thicker epi-Silicon is used to increase absorption

BSI NIR SiPM process flow

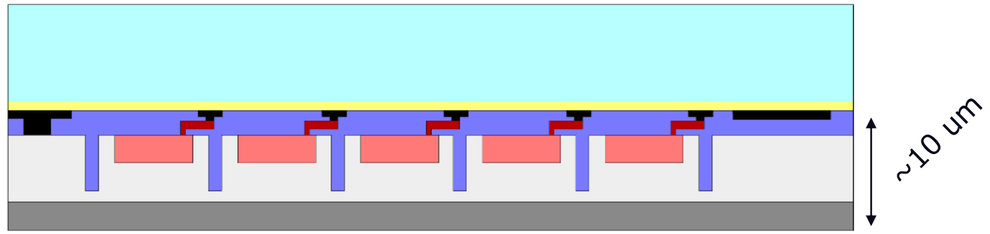
1. SiPM Wafer



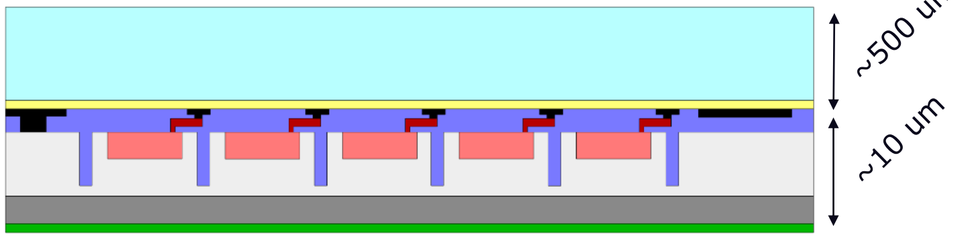
2. Temporary Bonding



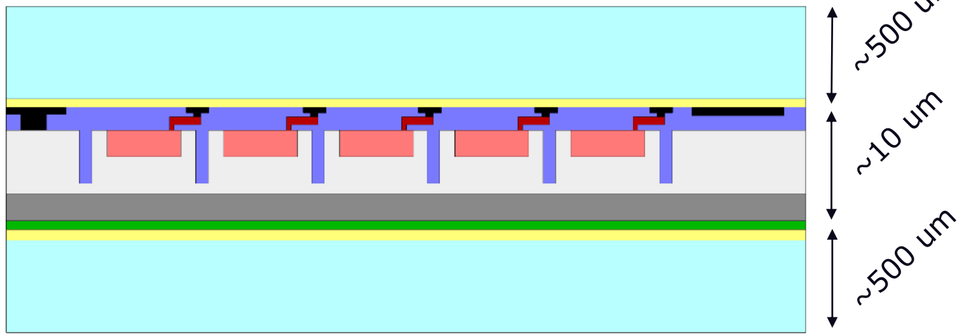
3. Grinding & Polishing



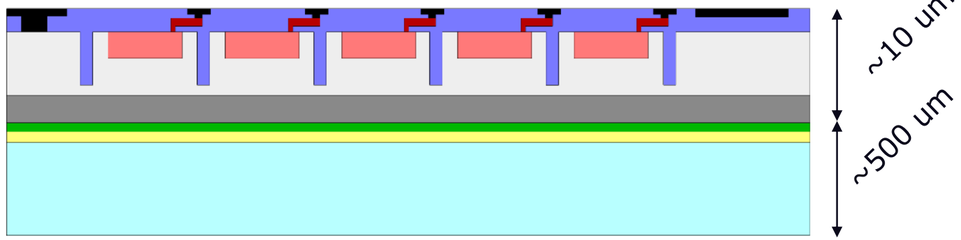
4. Backside processing



5. Permanent Wafer Bonding



6. Wafer Debonding



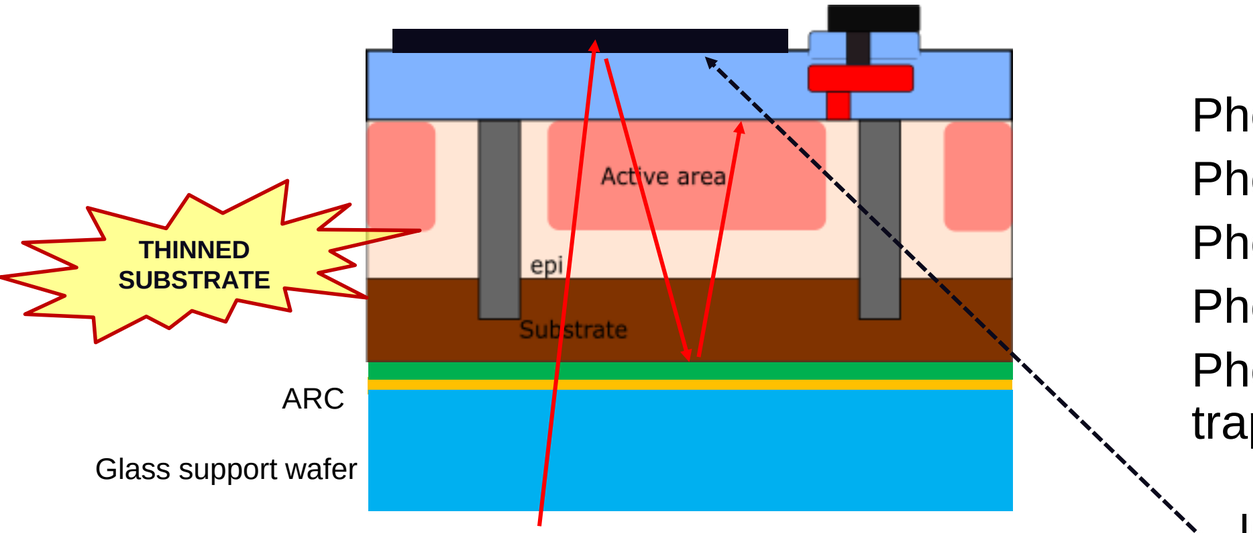
BSI NIR SiPM

Advantages

- 100% FF
- Increase the absorption thanks to light trapping
- Ready to be 3D integrated

Challenges

- Absorption depth of NIR photons in silicon ~30 um



Photons reflected at the entrance surface
Photons absorbed in the residual substrate
Photons escaping from the front surface
Photons absorbed in the active area
Photons back reflected at the front surface (light trapping)

lost
counted

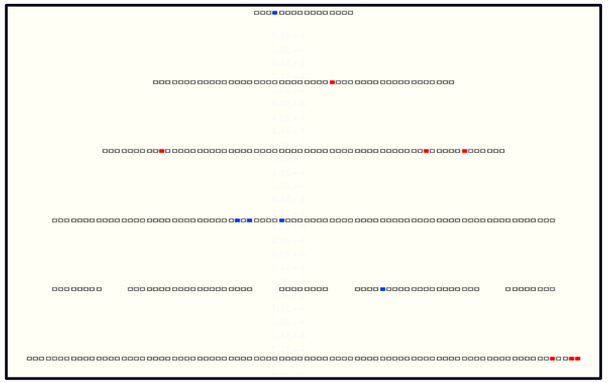
Including metal plate on the top surface can enhance the light trapping

Results on BSI SiPM for NIR

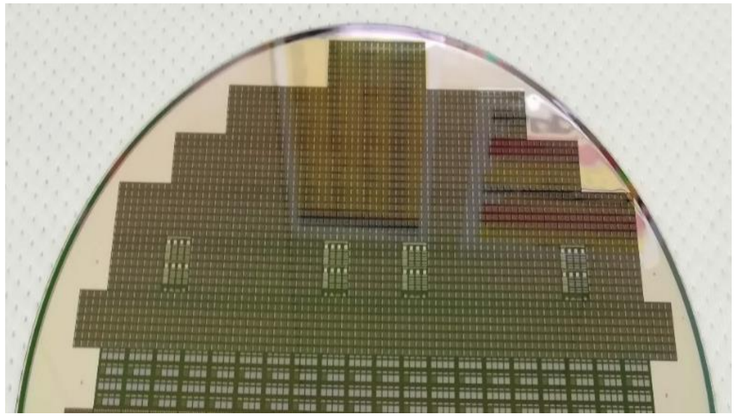
THINNED SUBSTRATE

Electrical characterization

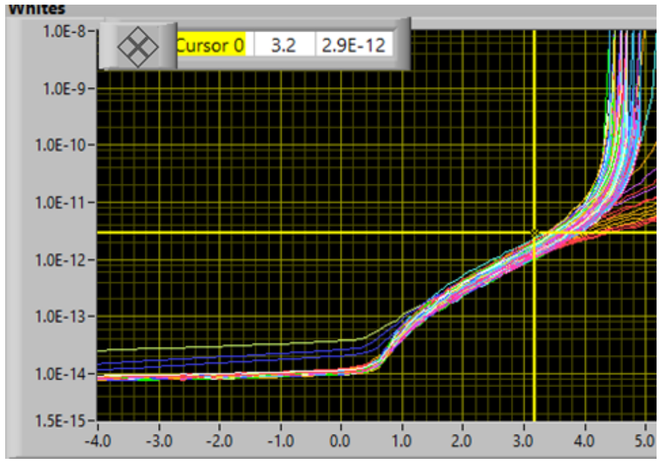
- Automatic I-V measurements after ultra-thinning
- 180 SiPMs (1 mm^2) have been measured on a 6'' wafer
- 169 working SiPMs (~ 95% yield).



Ultrathin substrate (~ 10 um)



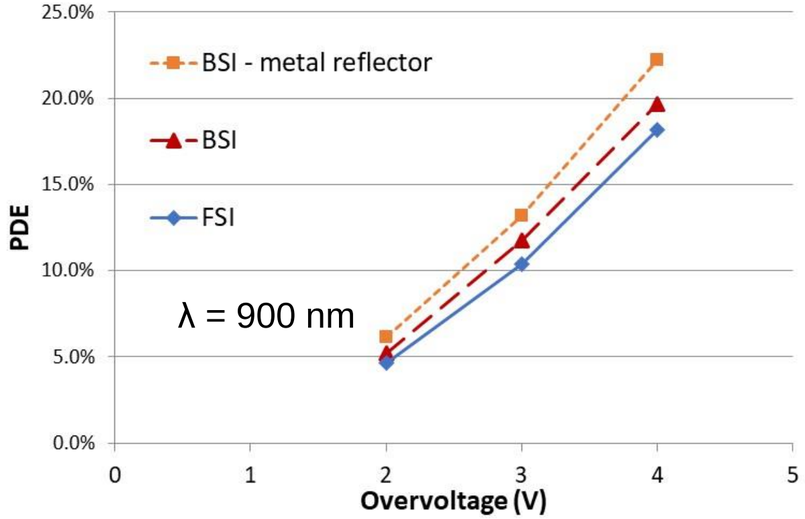
- Compilation of I-V curves from a single back-thinned wafer
- Same BD voltage and same dark current w/o and with thinning

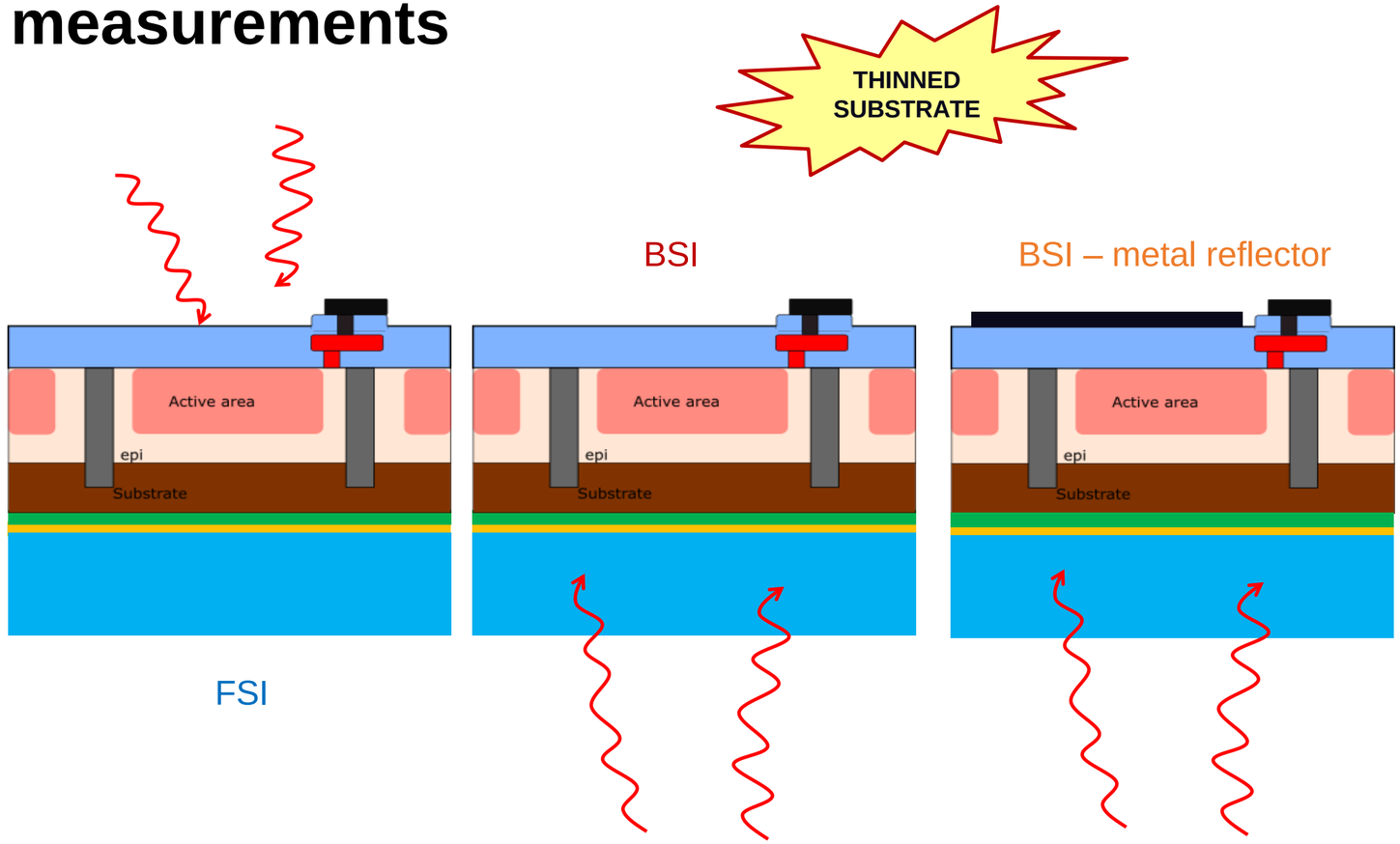


- The thinning process does not degrade the electrical and noise performance of the device at a low excess bias voltage

Results on BSI SiPM for NIR

Photon detection efficiency measurements





Outline

01 FBK SiPM technology

FBK SiPM technology roadmap and motivation for 3D integration

02 BSI SiPM for NIR

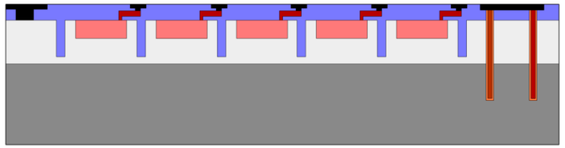
03 TSV interconnections for VUV/NUV SiPM

04 Conclusions

Through Silicon Vias

Via Mid

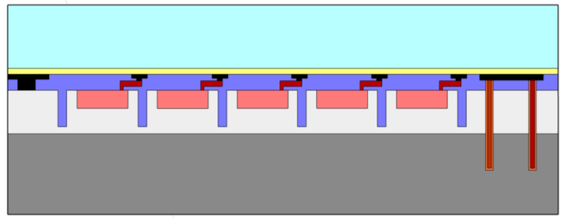
- SiPM fabrication + TSV formation



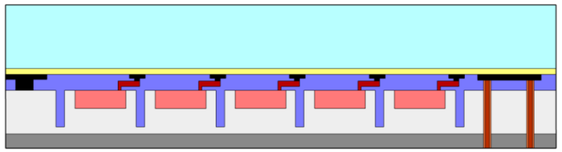
High thermal budget allowed (high quality and conformal material deposition)

Necessity to adapt the device process flow ➔ Critical lithography needs to be carried out after the TSV fabrication

- Edge Trimming + BONDING

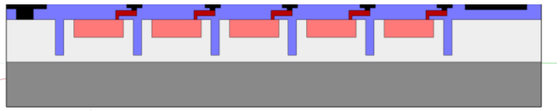


- THINNING



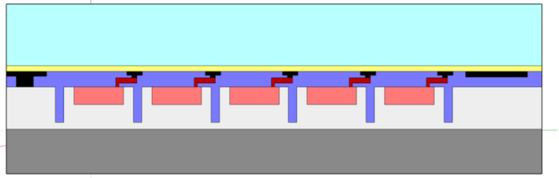
Via Last

- SiPM fabrication

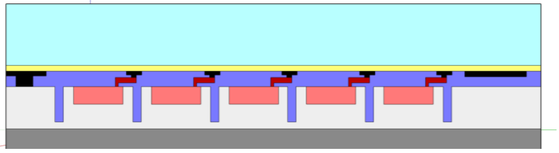


Front end of line is unchanged

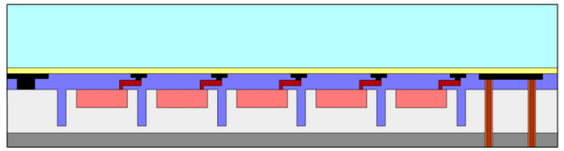
- Edge Trimming + BONDING



- THINNING

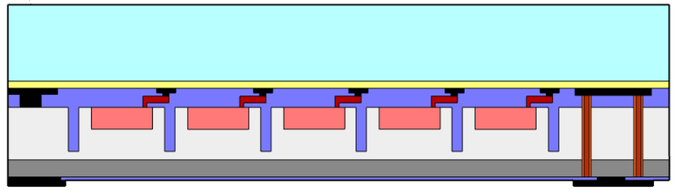


- TSV formation

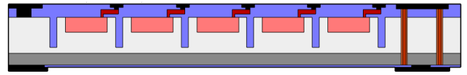


Low thermal budget allowed during the TSV formation at the back end of line

- Contacts formation

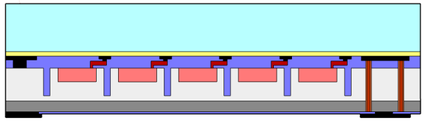


- DEBONDING

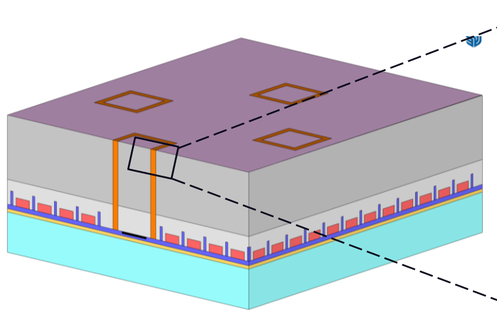


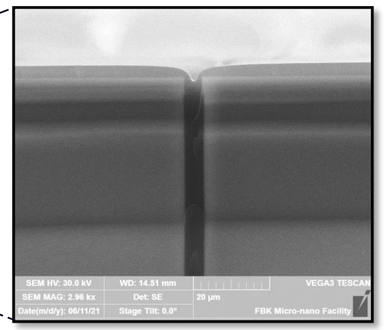
Thickness at least 150 um

- NO-DEBONDING



Thickness 10-50 um

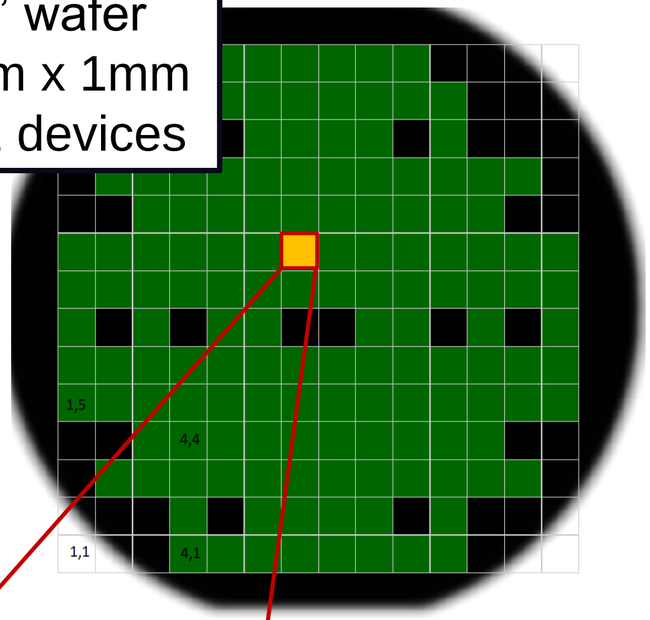


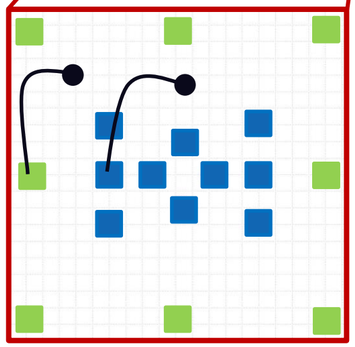


SiPM with TSV for VUV/NUV – Via Mid

Silicon thickness: 150 um

6'' wafer
1 mm x 1mm
142 devices

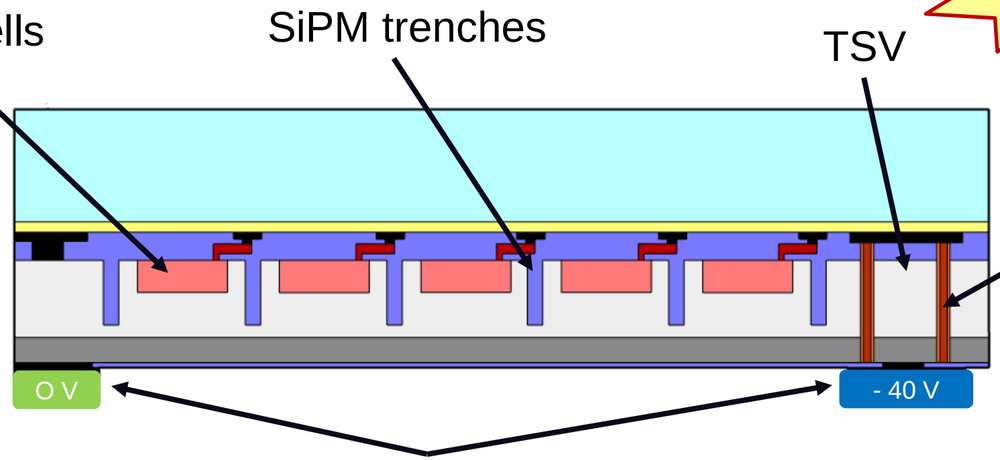


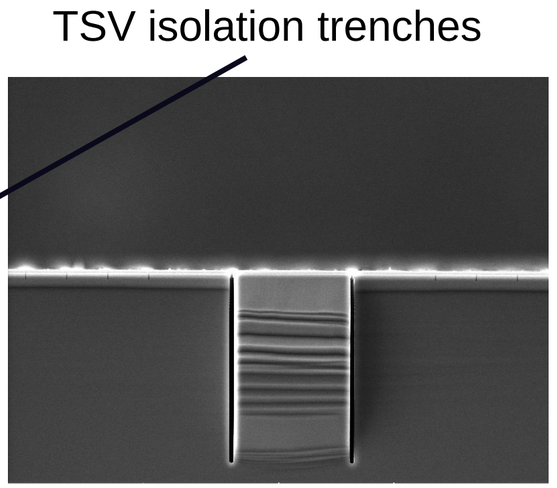


Back side of the SiPM

Silicon bulk pad

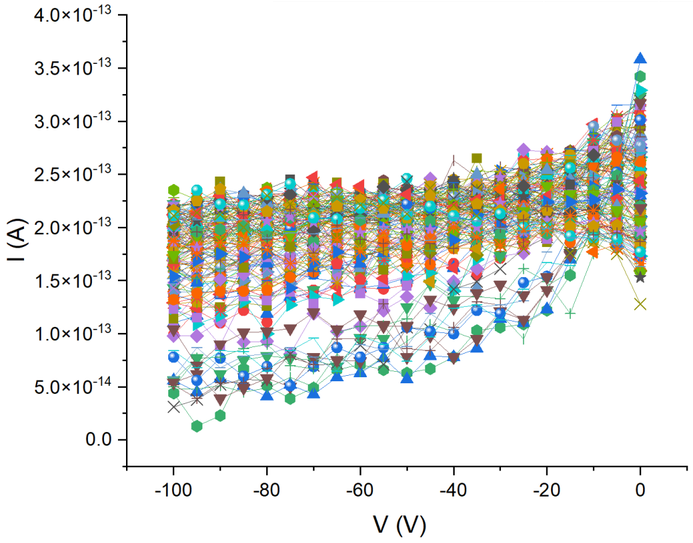
TSV pad





At **-100 V** of bias applied the intensity varies from **30 to 200 fA**

Trough Silicon Vias – Via Mid are isolated from the bulk silicon contact



Outline

01 FBK SiPM technology

FBK SiPM technology roadmap and motivation for 3D integration

02 BSI SiPM for NIR

03 TSV interconnections for VUV/NUV SiPM

04 Conclusions

Conclusions

- FBK is working on 3D-integration approaches to develop **Hybrid SPAD arrays/SiPM** in the framework of IPCEI Microelectronic project

Back Side Illuminated SiPM for NIR detection

- **95% of yield** for SiPM with **10 um silicon thickness** were realized and an increase of the PDE at 900 nm for BSI NIR SiPM with metal reflectors compared with the FSI technology was measured

Trough Silicon Vias interconnections for VUV/NUV SiPM

- Preliminary results on the **Via Mid** approach show good quality and yield regarding the TSV isolation

- Thanks to the no limitation on thermal budget we have been able to use high quality and conformal materials for a proper TSV isolation leading to a very **robust process flow**

Ongoing and future work

- Improved SiPM BSI for NIR detection are currently being fabricated with new p-n junction configurations and new bonding process

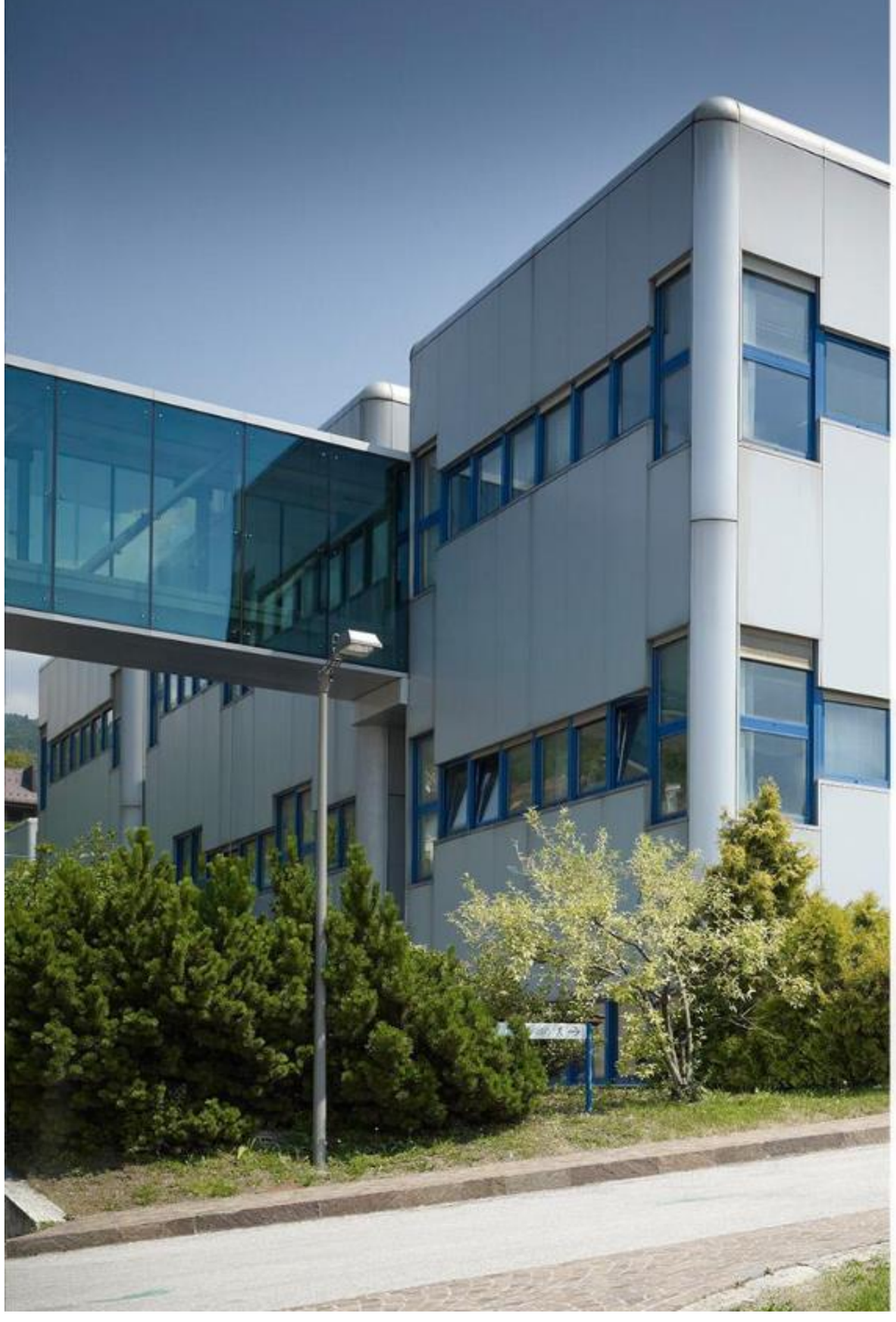
- TSV Via Last are being realized and the TSV resistance will be measured

FONDAZIONE BRUNO KESSLER

FUTURE BUILT ON KNOWLEDGE

Thank you

lparelladamonreal@fbk.eu
www.fbk.eu

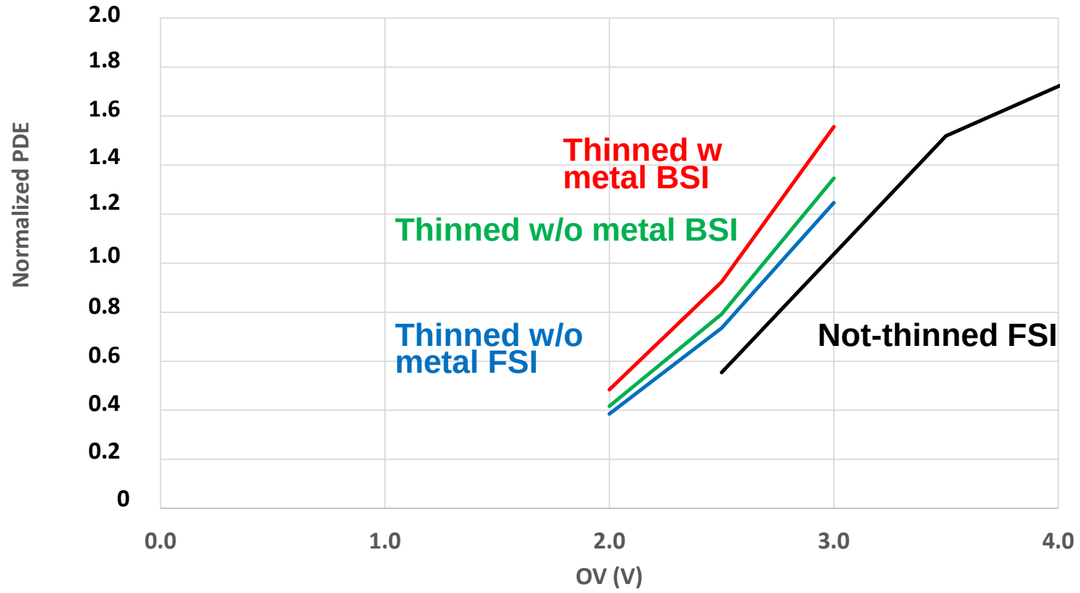


FONDAZIONE
BRUNO KESSLER

FUTURE BUILT
ON KNOWLEDGE

Results on BSI SiPM for NIR

PDE measurements



Type	Normalized PDE @ 905 nm 3V OV
Ref. not thinned	1 (normalized)
Thinned no metal FSI	+ 24%
Thinned no metal BSI	+ 34%
Thinned metal BSI	+ 50%