Surface passivation of single-photon avalanche diodes for enhanced sensitivity in the vacuum ultraviolet range for liquid noble gas experiments

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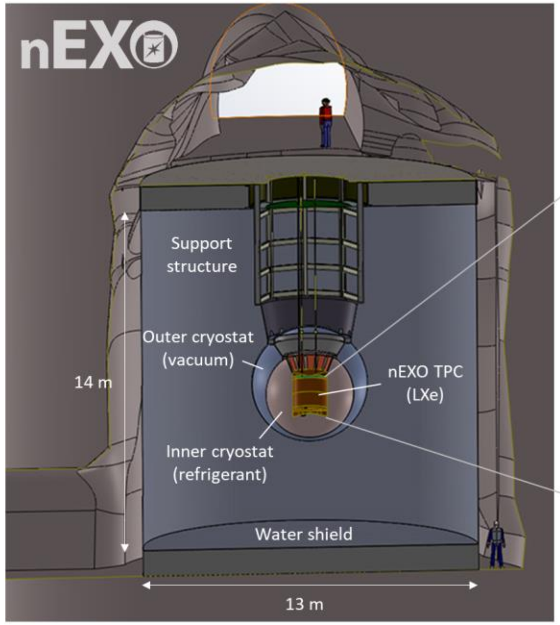
GRAMS

Outline

- Sherbrooke's contribution in the nEXO experiment
- Challenges of VUV direct detection for silicon-based detectors
- Single-photon avalanche diode and improving photon detection efficiency in UV
- Process modification to allow delta-doping on Sherbrooke's SPAD
- Characterization of first SPAD with delta-doping at Sherbrooke

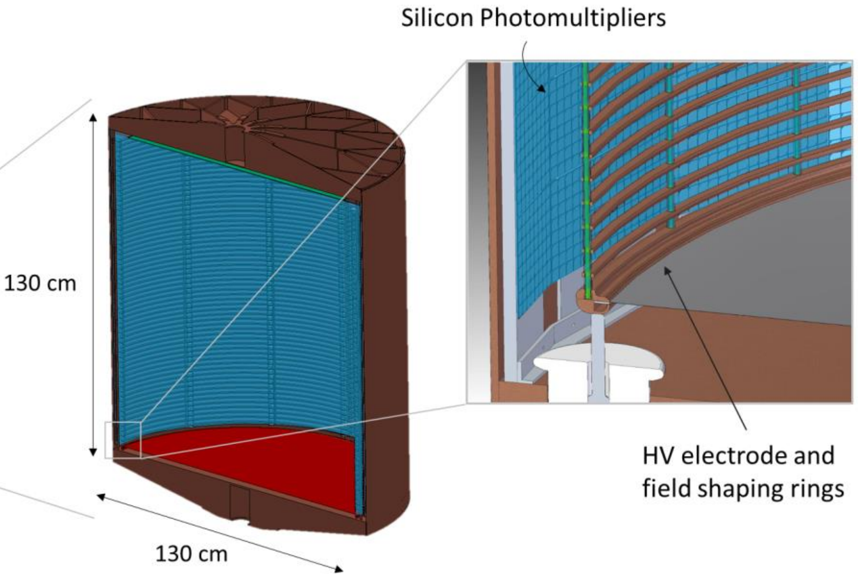
nEXO and the need for VUV-sensitive Silicon Photomultiplier (SiPM)

- nEXO: next generation neutrinoless double beta decay experiment *Kharusi, S. Al, et al. "nEXO pre-conceptual design report." arXiv preprint arXiv:1805.11142 (2018).*
- Observation of ^{136}Xe decay: 5 tonnes liquid xenon time projection chamber ➞ collection of scintillation light and ionization charges
- Photodetection module: 4.5 m² of analog SiPMs (or *3D Photon-to-Digital Converter by Sherbrooke* "high risk, high reward" plan)



Source : nexo.llnl.gov

Cryopit at SNOLAB, Subdbury ON (Canada)

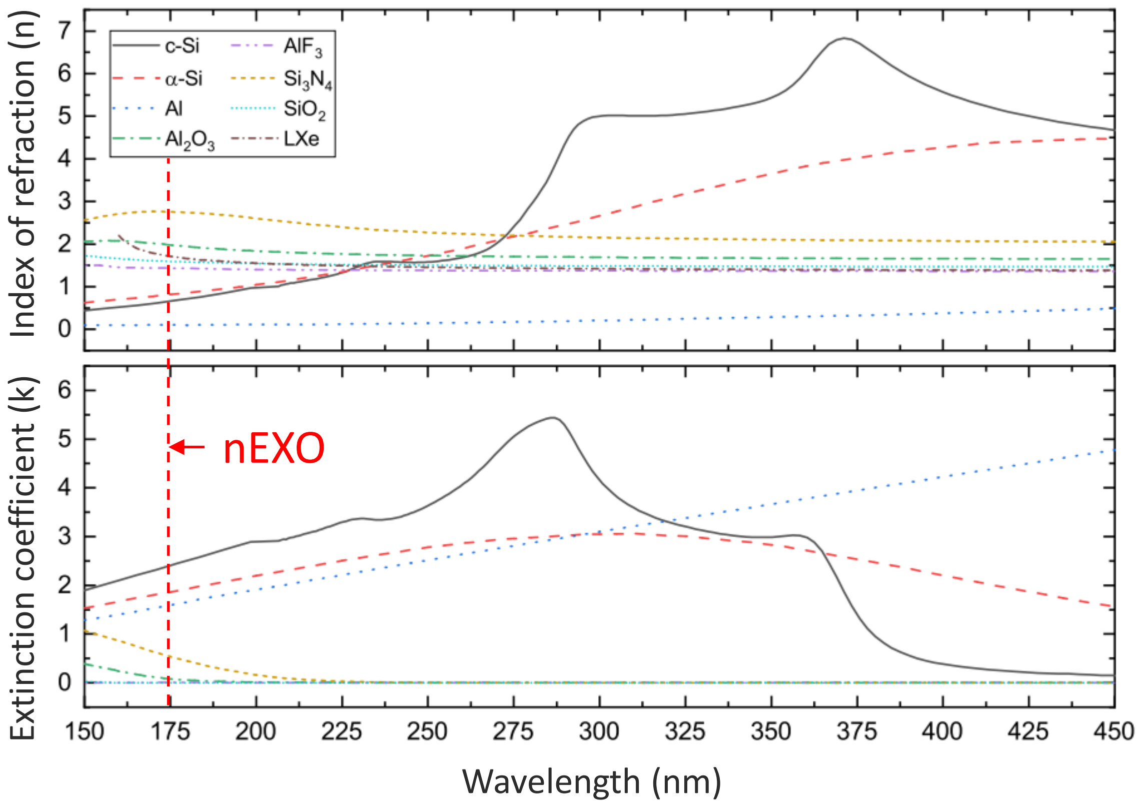


nEXO Time Projection Chamber with 4.5 m² SiPM surface coverage

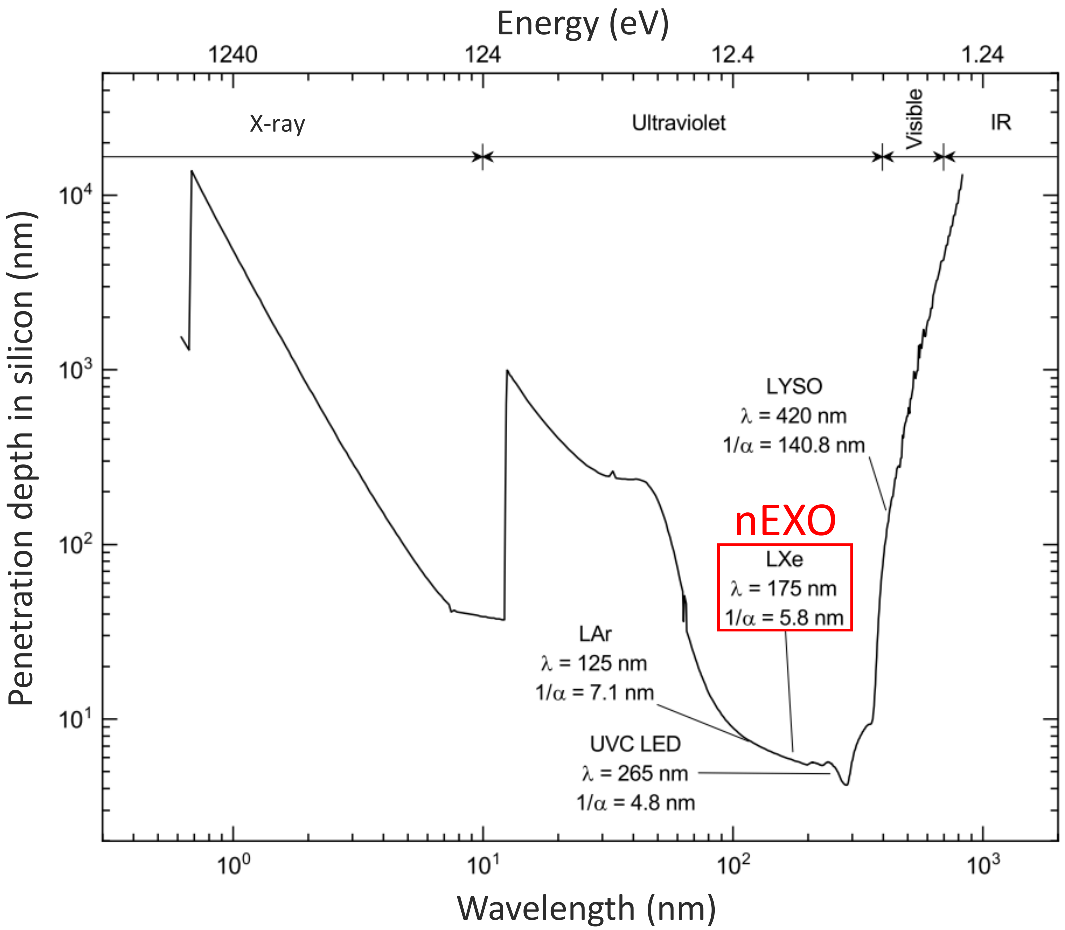
SiPM requirements	
Dark noise at $3V_{ov}$	< 50 Hz/mm²
Correlated noise after 1µs	< 20 %
Timing resolution	< 10 ns
Reading node capacity	< 50 pF/mm²
Total power budget	2.2 mW/cm²
Radiopurity	< 10 µBq/kg
Operating temperature	167 K
Photon detection efficiency at 175 nm	> 15 %

Challenges of VUV direct detection for silicon-based detectors

Passivation materials are absorbent (*k*) and the index of refraction (*n*) varies rapidly in the UV



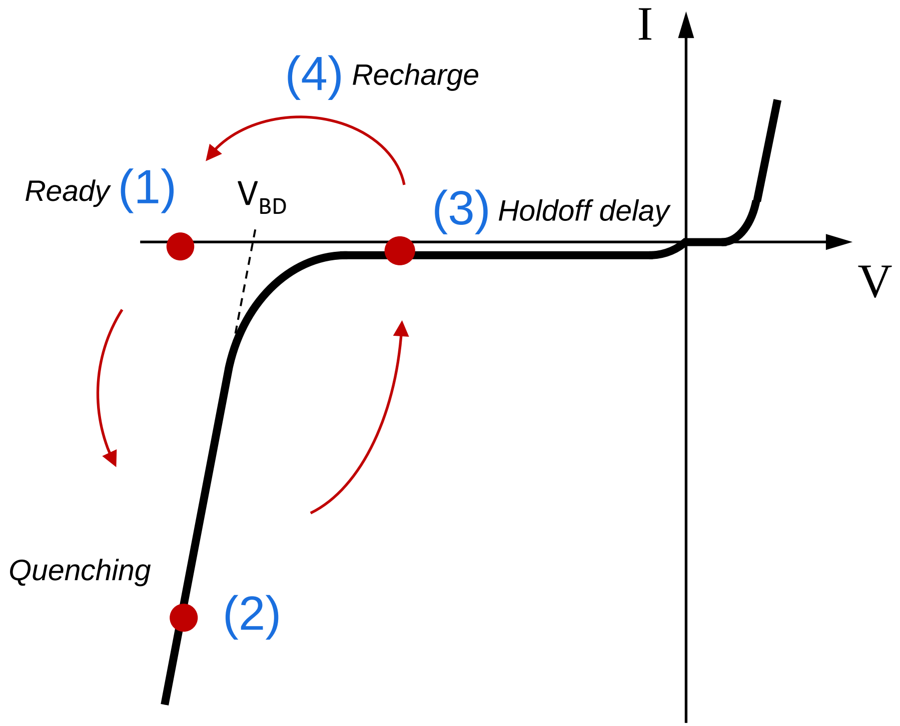
Short penetration depth of UV photons in silicon



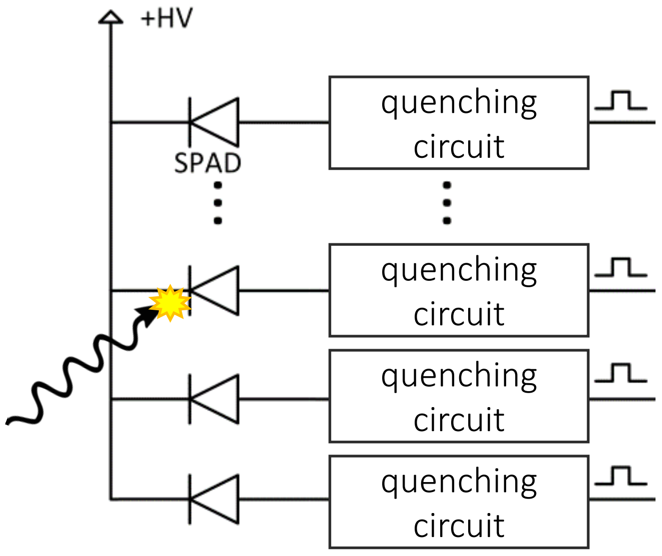
How to improve VUV sensitivity for silicon-based detectors ?

Digital single-photon avalanche diodes (SPAD)

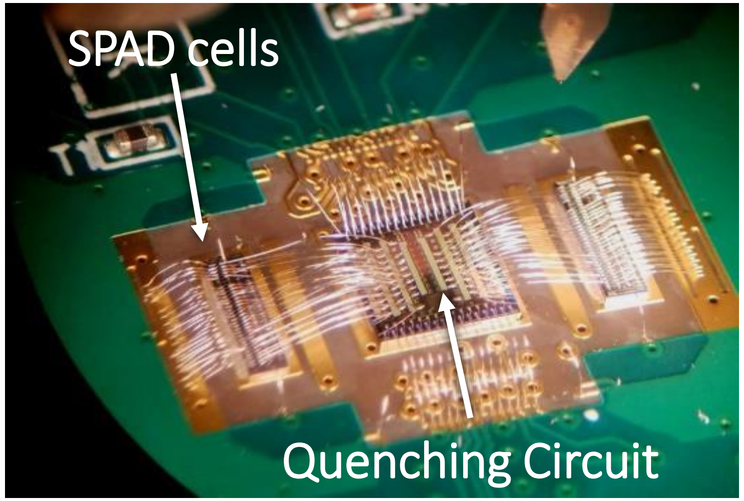
- SPADs are the single unit cell of silicon photomultiplier (SPAD array)
- Biased over their breakdown voltage to reach Geiger-mode (impact ionization)
- Digital SPAD ➞ SPAD + quenching circuit to control quenching time, holdoff delay and recharge time



SPAD array



SPAD testing platform



Parent, Samuel, et al. "Single photon avalanche diodes and vertical integration process for a 3D digital SiPM using industrial semiconductor technologies." 2018 IEEE Nuclear Science Symposium and Medical Imaging Conference Proceedings (NSS/MIC). IEEE, 2018. doi: 10.1109/NSSMIC.2018.8824571

Photon detection efficiency for FSI p⁺n SPAD in the UV spectrum

External quantum efficiency (EQE)

Main factors ➢ Reflection, Transmission, **Absorption**

SPAD critical properties ➢ Properties of the entry interface (materials, thickness, etc.)

Solution studied ➢ Tailored antireflective coating

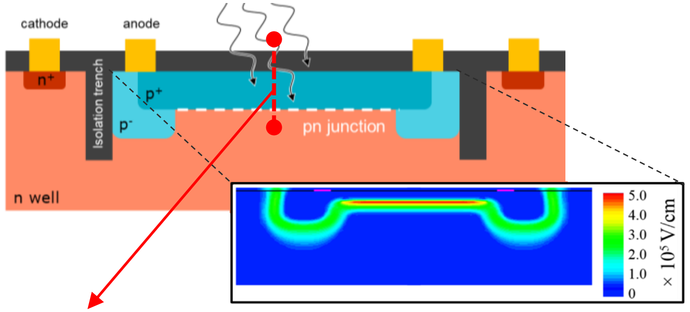
Internal quantum efficiency

Main factors ➢ Energy bands, **Surface traps**

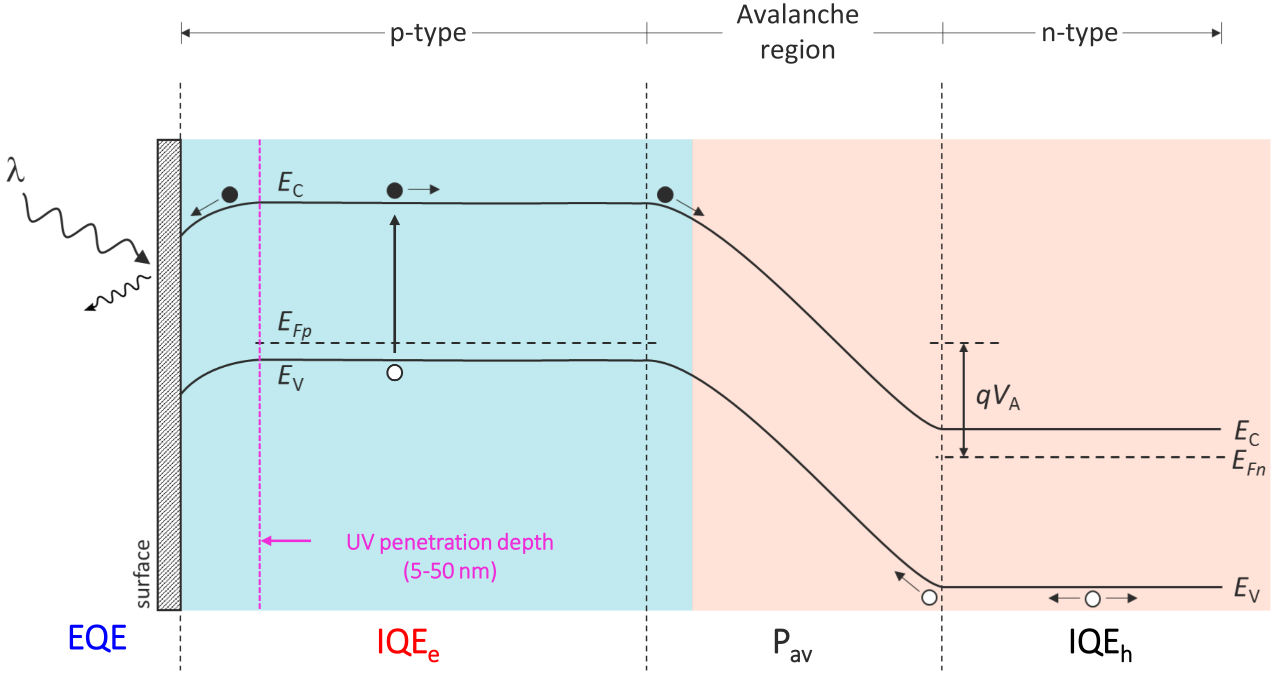
SPAD critical properties ➢ Charge collection by drift or diffusion towards the avalanche region

Solution studied ➢ Proper design of internal energy band structure

Front-side illuminated p⁺n SPAD side view

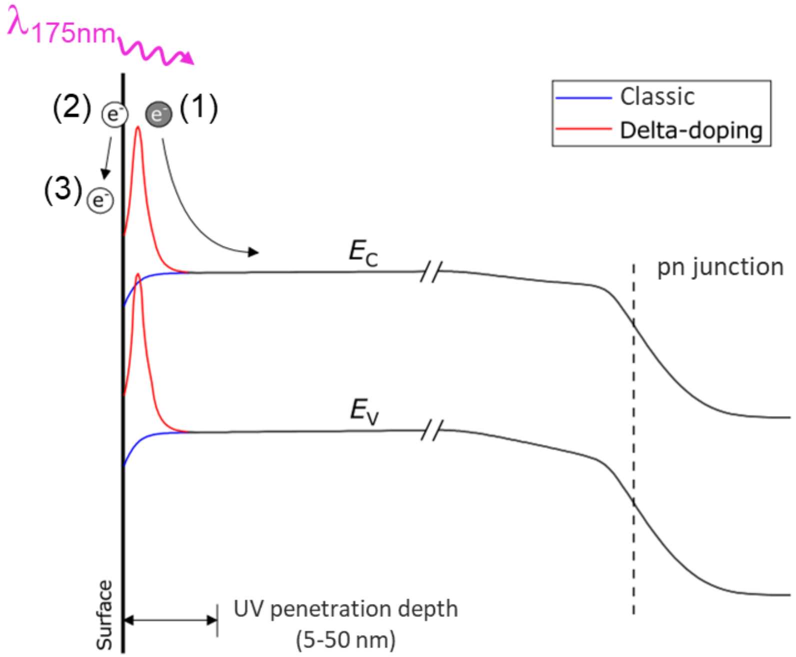


Energy band diagram

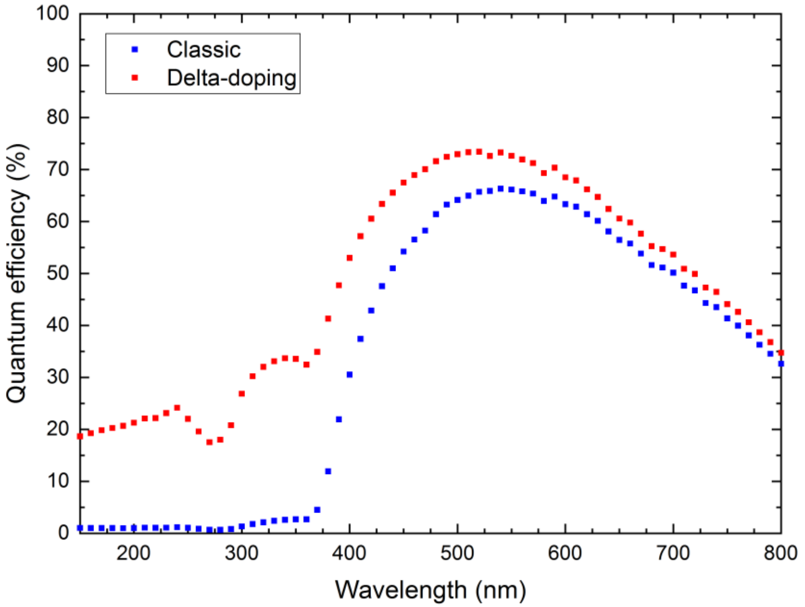


Surface energy band engineering for charge collection efficiency

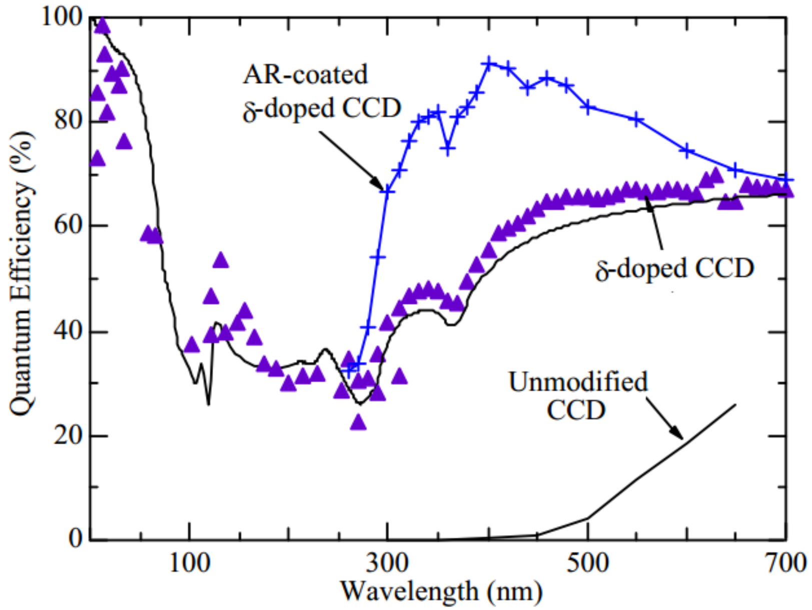
Delta-doping principle



Simulation of SPAD QE with delta-doping



Quantum efficiency of the "δ-doped CCD"



Hoenk, Michael E., et al. "Growth of a delta-doped silicon layer by molecular beam epitaxy on a charge-coupled device for reflection-limited ultraviolet quantum efficiency." Applied Physics Letters 61.9 (1992): 1084-1086. doi: 10.1063/1.107675

Growth of an very thin and highly doped layer at the surface of the SPAD

1. Electrons photogenerated over the delta-doping barrier drift towards the pn junction
2. Only electrons absorbed too close to the surface are lost
3. Electrons in interface states are trapped at the surface and do not contribute the dark noise

Post-processing of Teledyne Dalsa SPADs

Growth of the delta-doping layer by molecular beam epitaxy (MBE) in partnership with Lawrence Berkeley National Laboratory (LBNL)

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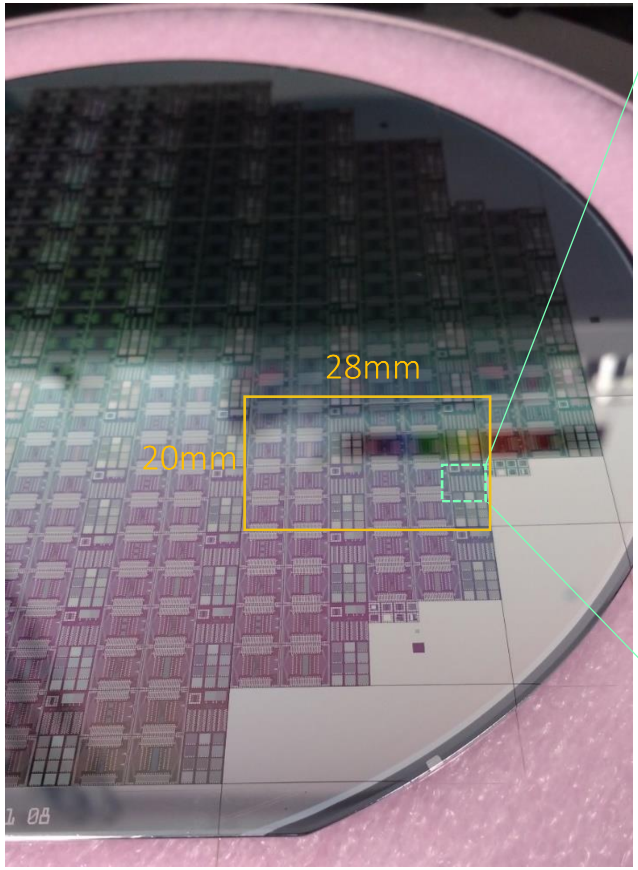
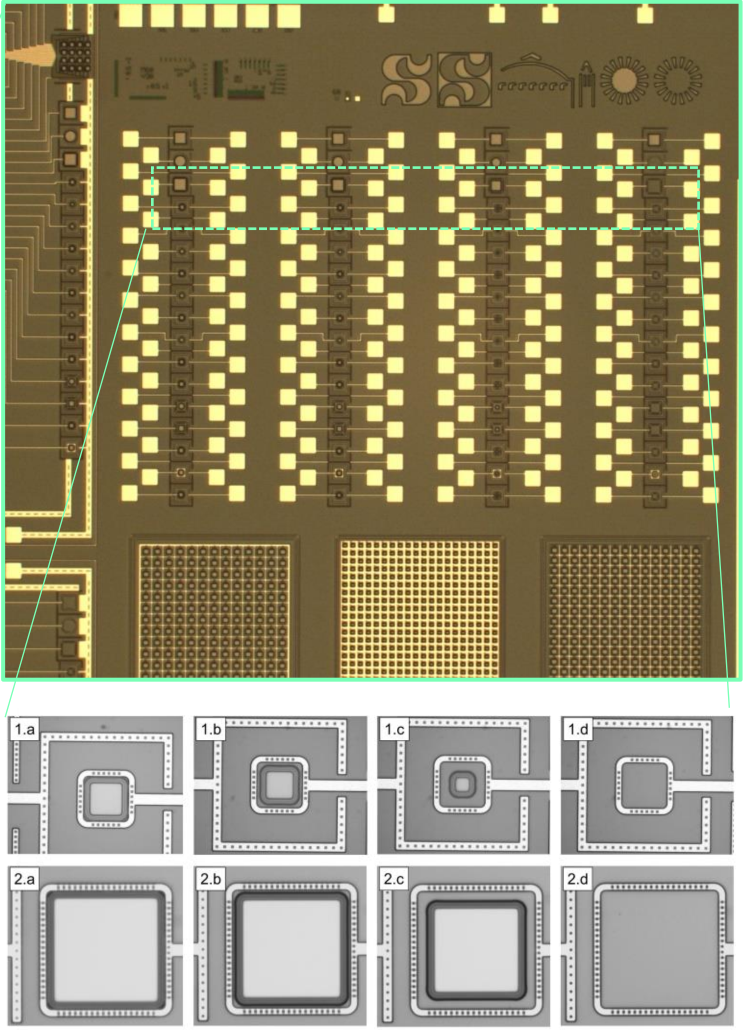
Berkeley Lab
Teledyne Dalsa Everywhereyoulook™

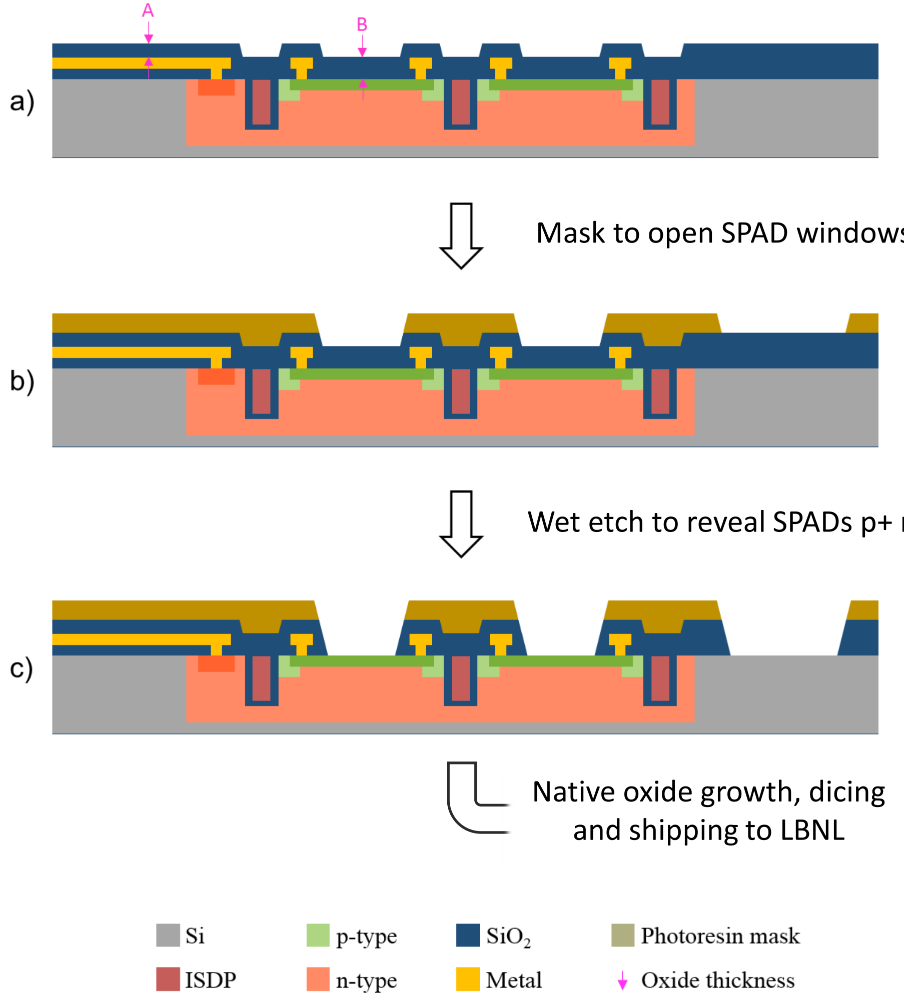
SPAD post-processing to allow front-side MBE growth



2D FSI p⁺n SPAD developed at Teledyne DALSA



*Wafers are removed from the production line before electrical contacts are opened



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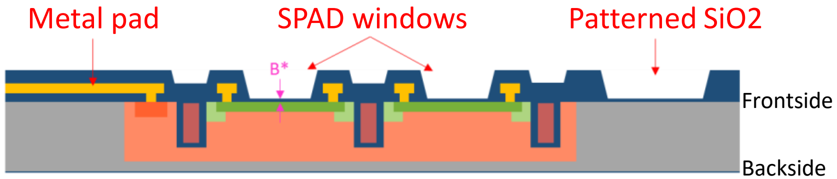
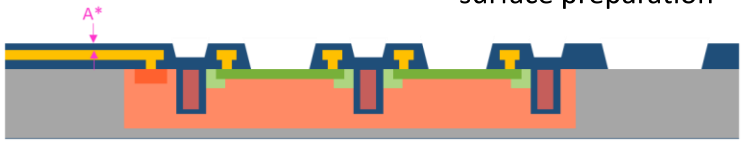
SPAD post-processing to allow front-side MBE growth

d)


⇩ Mask-less wet etch for surface preparation

e)


⇩ Mask-less delta-doping growth

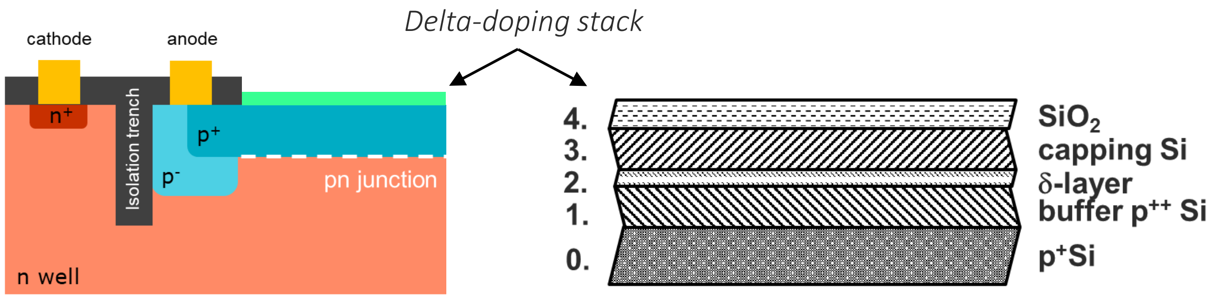
f)


⇩ Shipping to Sherbrooke for metal pad opening

g)

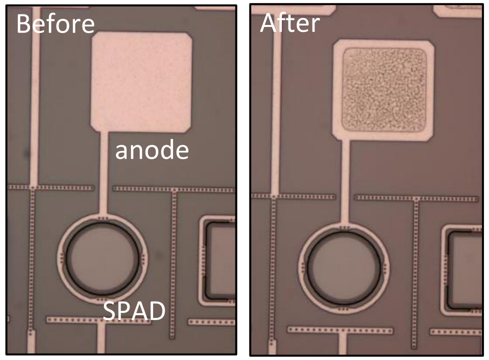

⇩ Laser dicing and SPAD+QC assembly

Low Temperature Molecular Beam Epitaxy (MBE) at LBNL

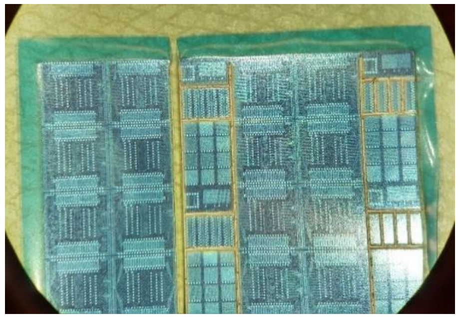


2 MBE runs (<450°C)	L0: SPAD	p-type Si(100)
MBEv1	L1: [1; 5] nm	boron-doped Si
MBEv2	L2: [2; 4] ML	monolayers of pure boron
	L3: 4 nm	Si capping layer
	L4:	native oxide

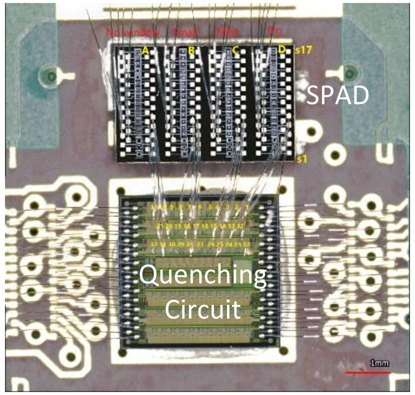
Metal pad opening



Laser dicing



SPAD+QC assembly



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Dark noise and photon detection efficiency characterization

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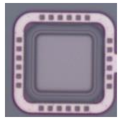
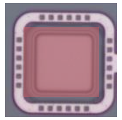
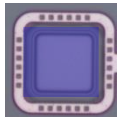
Dark noise characterization at various steps of the MBE process



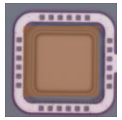
Control native oxide growth



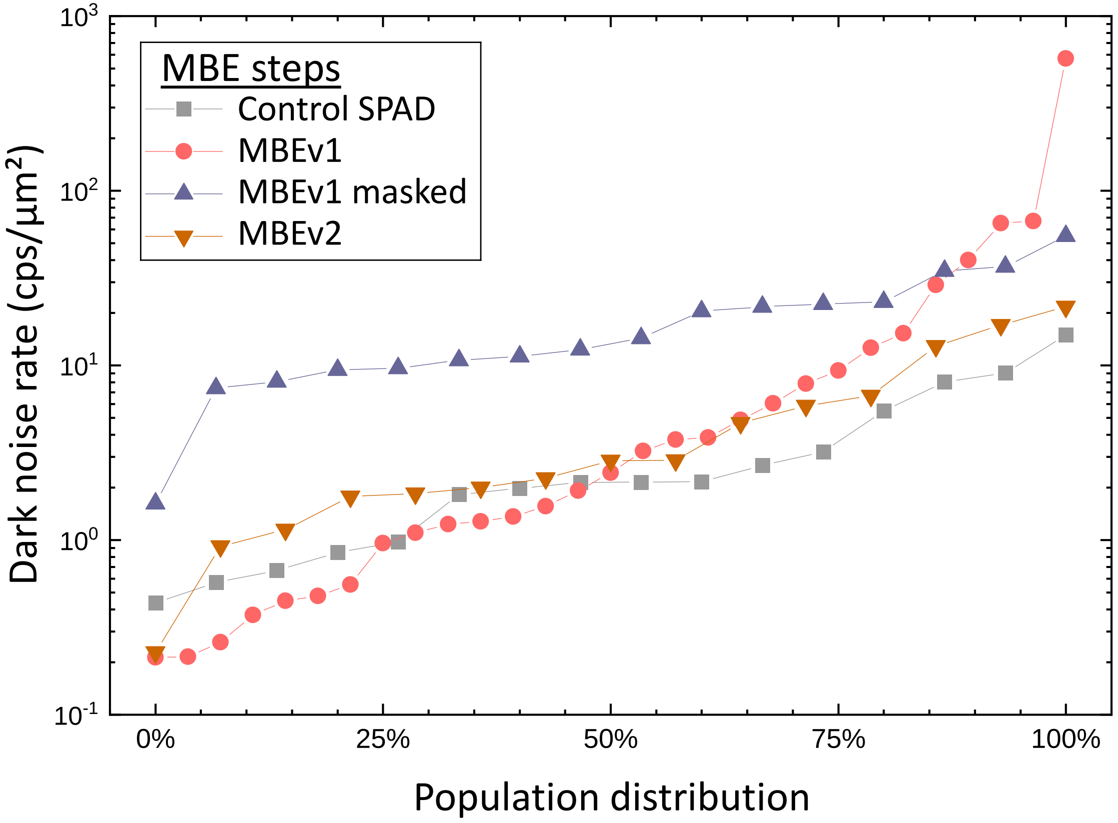
Surface preparation etch + MBEv1

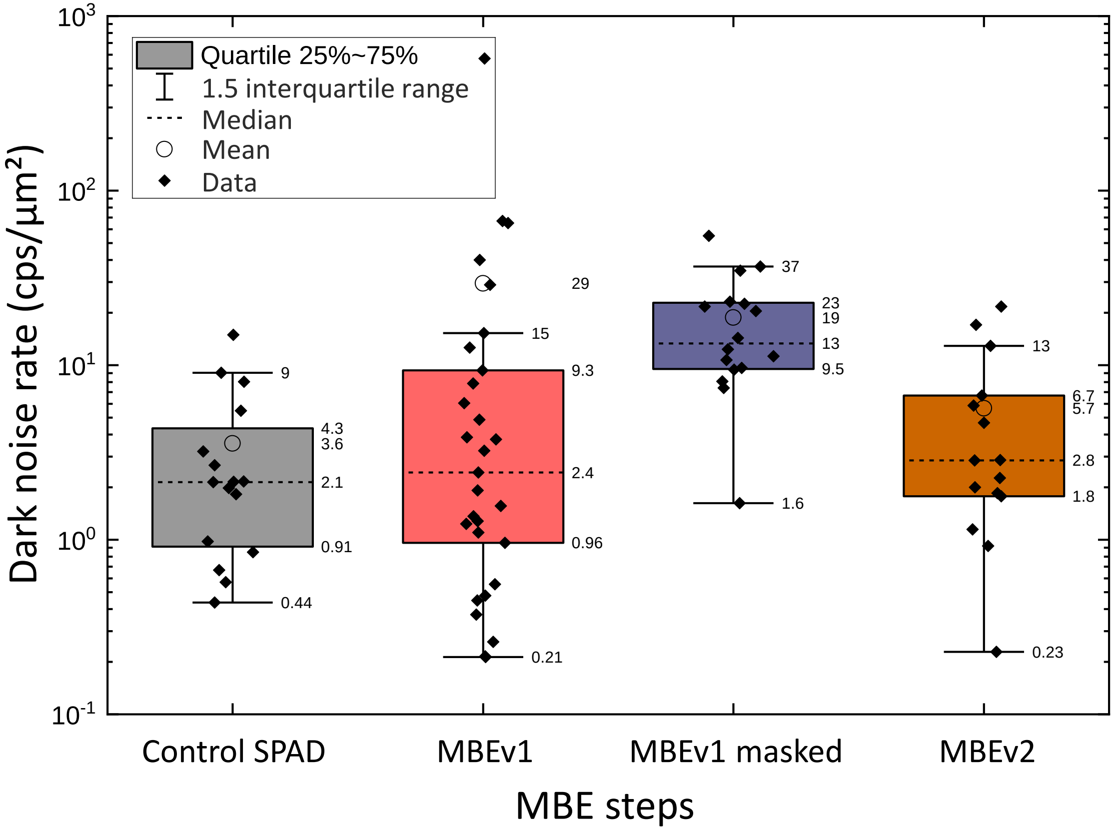


Surface preparation etch only



Surface preparation etch + MBEv2

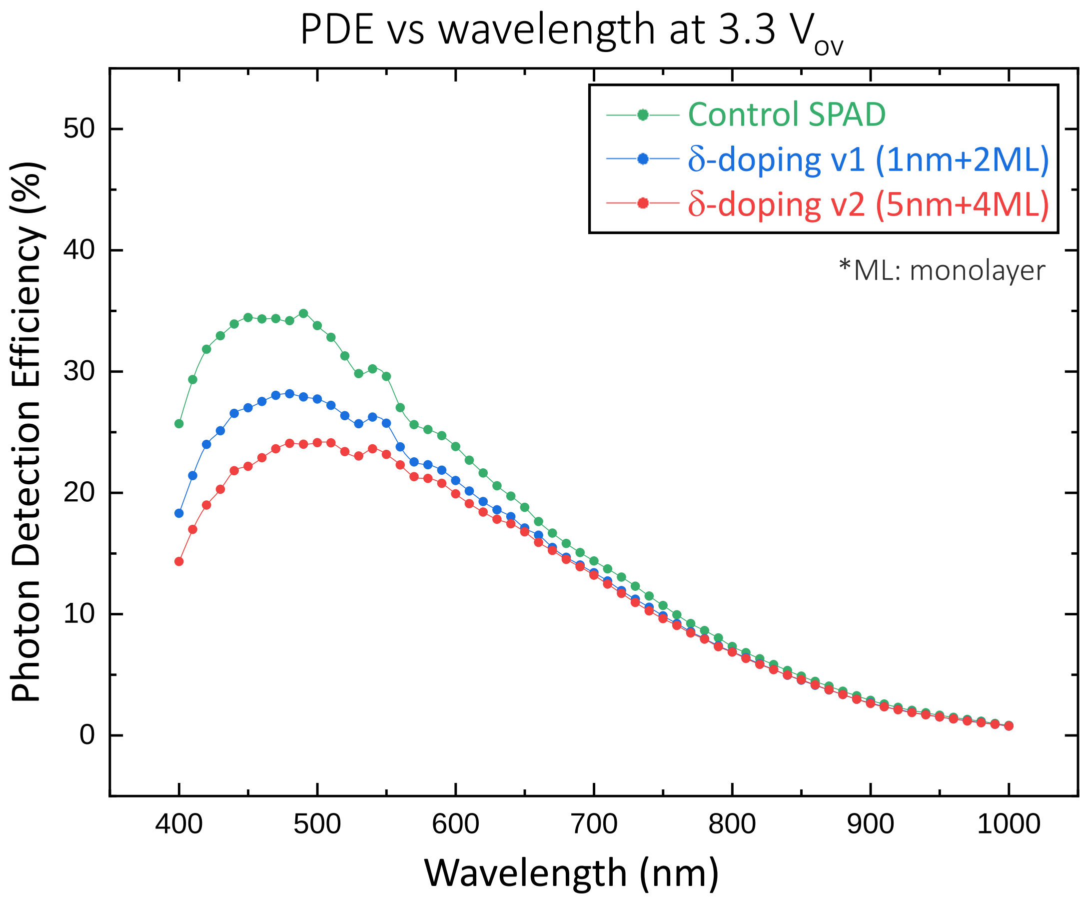


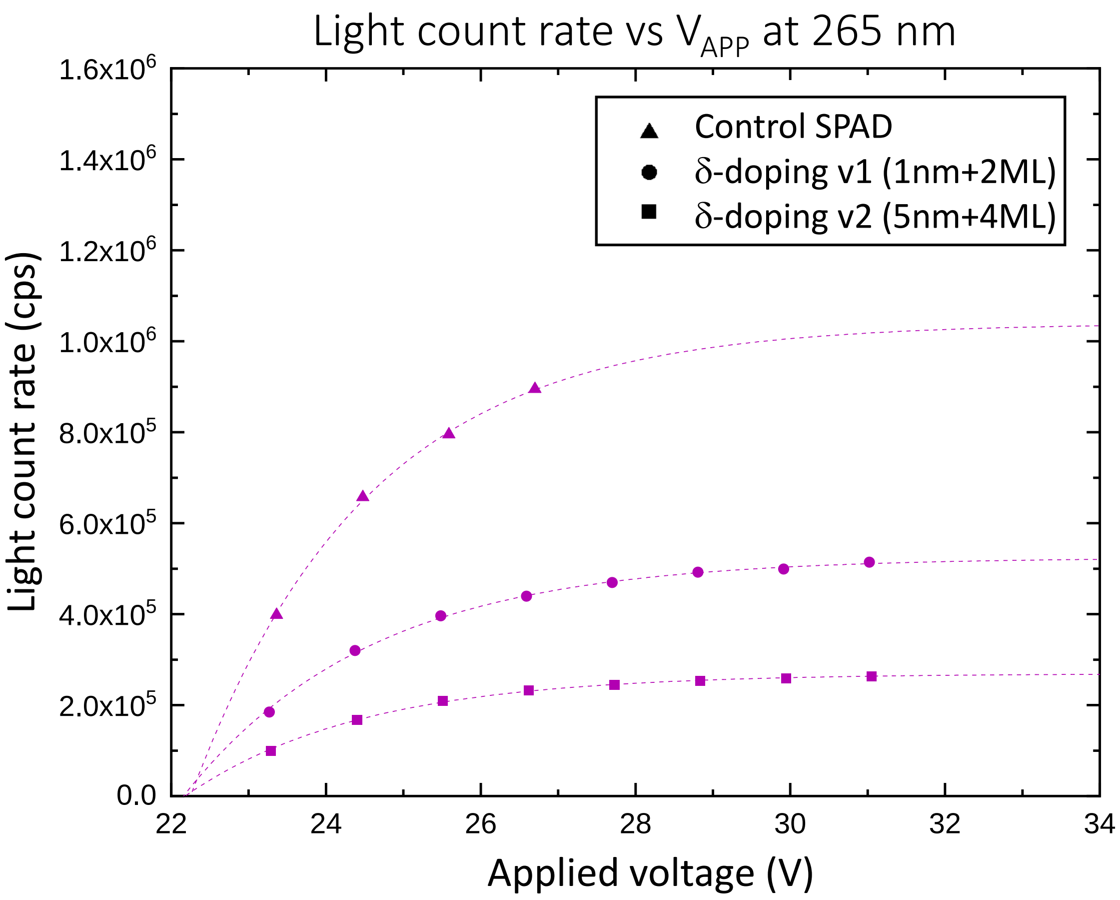


Photon detection efficiency (PDE) characterization

$$PDE = \frac{N_{measured\ photons}}{N_{impinging\ photons}}$$

Vachon, Frédéric, et al. "Measuring count rates free from correlated noise in digital silicon photomultipliers." Measurement Science and Technology 32.2 (2020): 025105. [doi: 10.1088/1361-6501/abba4b](https://doi.org/10.1088/1361-6501/abba4b)





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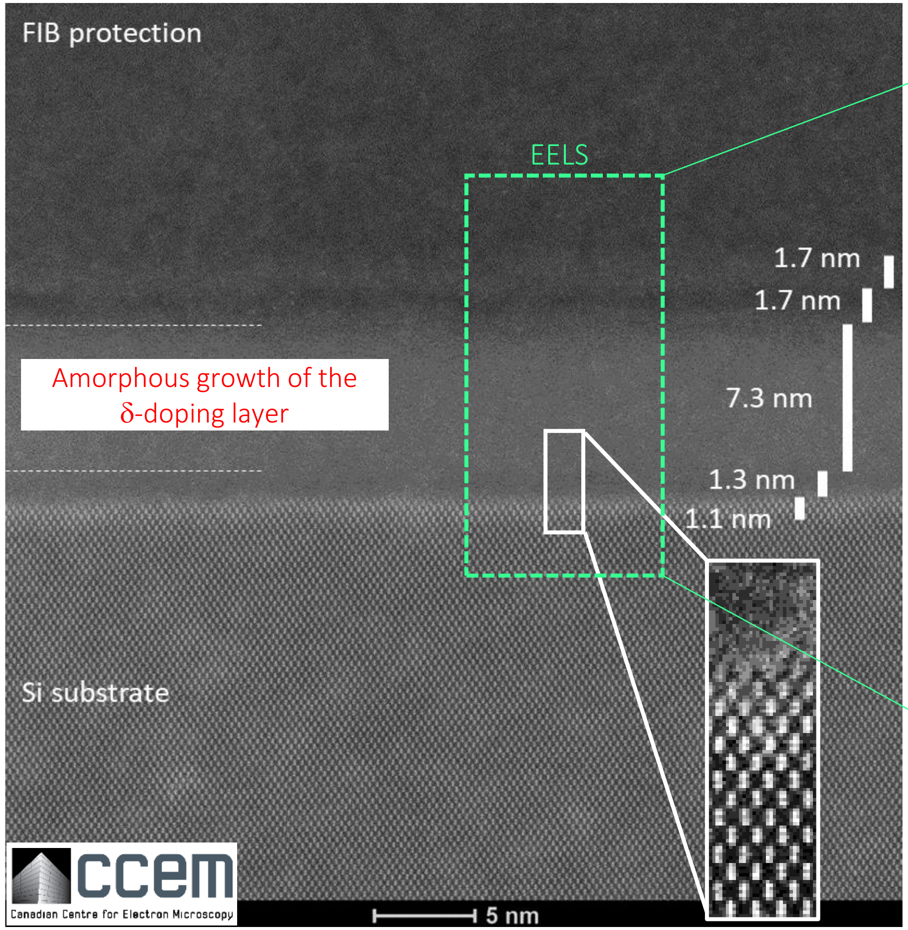
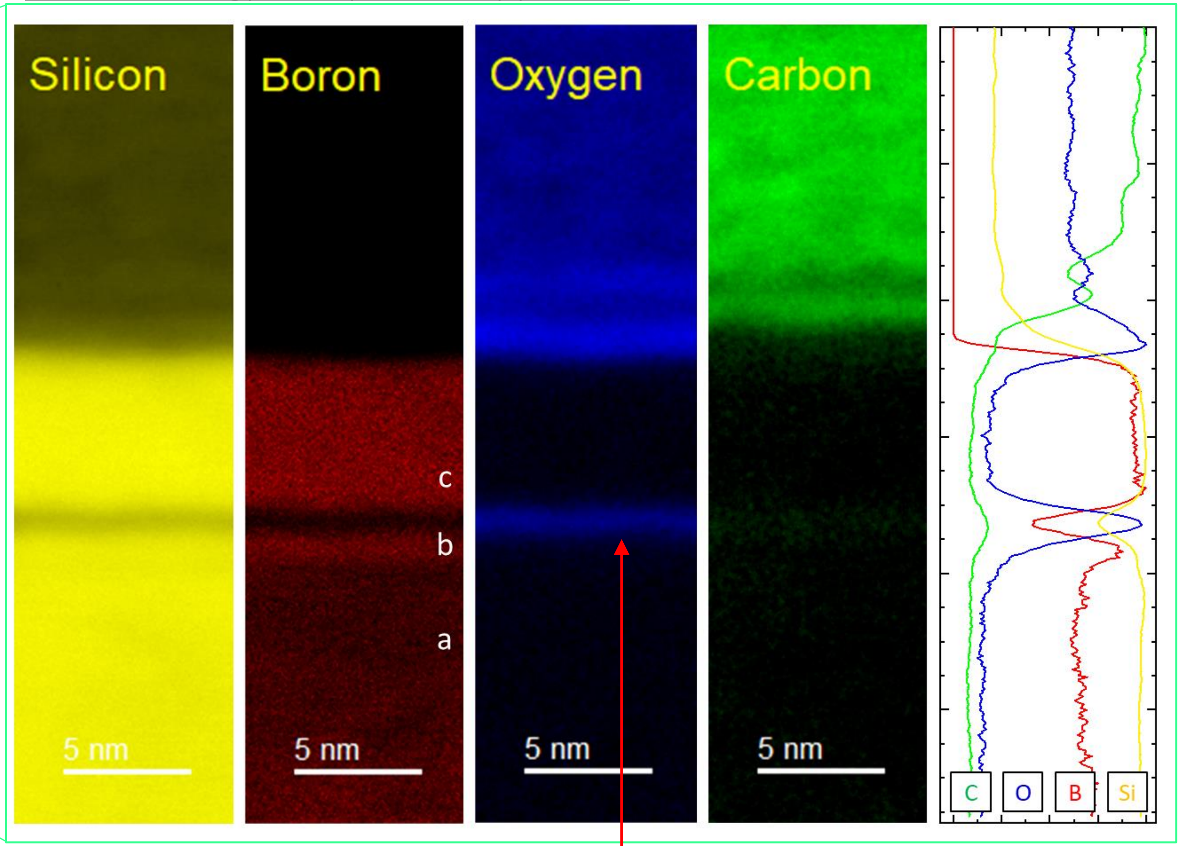
Close-up view of the delta-doping layer with TEM and EELS

Transmission electron microscopy (TEM)



Electron energy loss spectroscopy (EELS)



The presence of an oxide interlayer caused the amorphous growth

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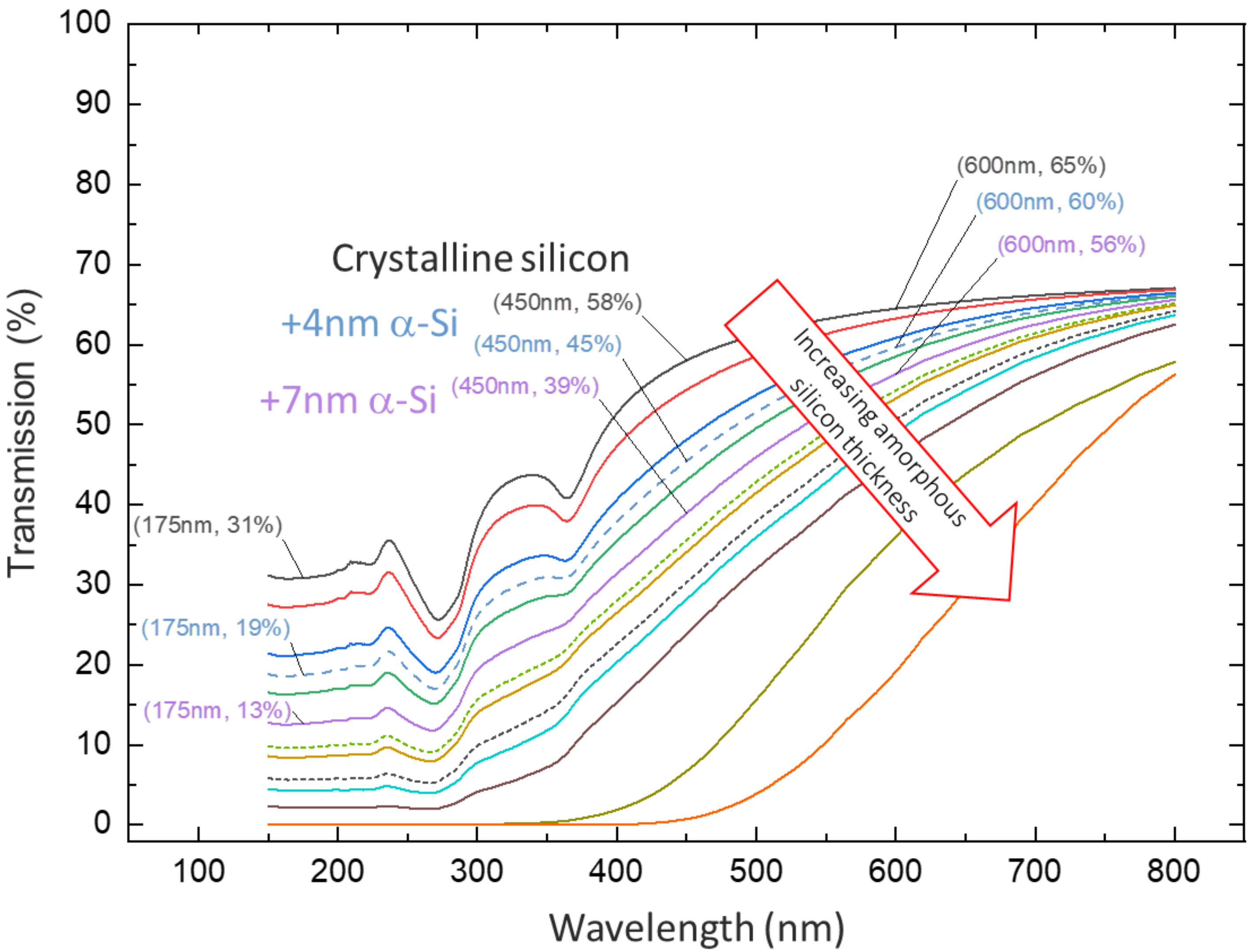
Effect of a highly-doped amorphous silicon layer on the SPAD surface

1. Electronics properties
   - Electrically active only if the dopants substitute silicon atoms at regular sites in the crystal lattice
   - Required to bend the energy bands

2. Optical properties:
   - Amorphous silicon is highly absorbent
   - Decreases transmission with increasing amorphous silicon (α-Si) thickness

3. The photon detection efficiency of the SPADs is reduced in the visible and even more in the UV



Conclusion

- FSI p+n SPAD process modification to allow low temperature MBE growth
- The MBE process does not affect the proper functionning of the SPADs *(i.e. breakdown voltage, dark noise, etc.)*

- However, our first try at MBE growth produced an amorphous layer which is highly absorbent
  - Low temperature MBE is required for back-end-of-line SPAD ➞ surface quality and the presence of contaminants is critical to a proper epitaxial growth

- Future works include:
  - Mounting a N2 purged glove blox on the MBE reactor's entry lock to limit exposure to oxygen and other contaminants
  - Surface preparation process tweaks to reach a perfectly H-terminated surface before MBE growth

- *Frédéric Vachon master's thesis (savoirs.usherbrooke.ca/handle/11143/18350)*

A team's work

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- Lorenzo Fabris (ORNL)
- Simon Viel (Carleton)
- nEXO Collaboration
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- Robert Groulx
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