ISSW2020

"The International SPAD Sensor Workshop"

June 8 – 10, 2020

POLITECNICO DI MILANO





Custom Silicon Technologies for High Detection Efficiency SPAD arrays

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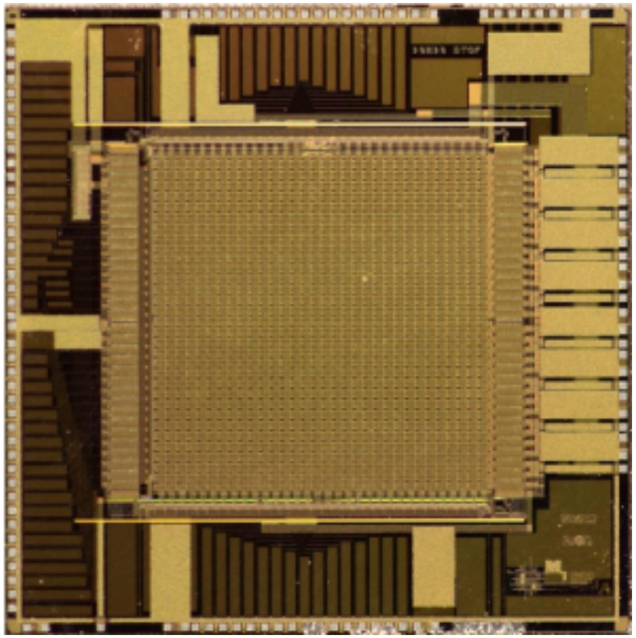
Our Idea

CMOS Technology

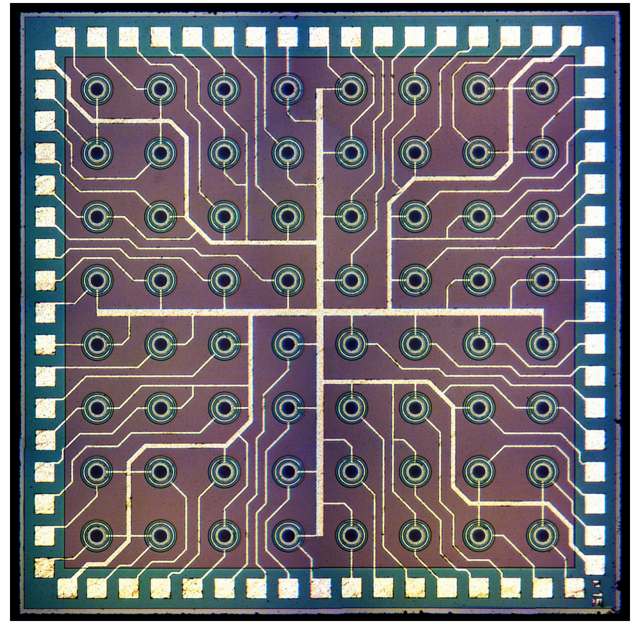


CMOS steps for SPAD fabrication

✔ Smart Pixels / Complex Systems

✖ No SPAD optimization

Custom Technology

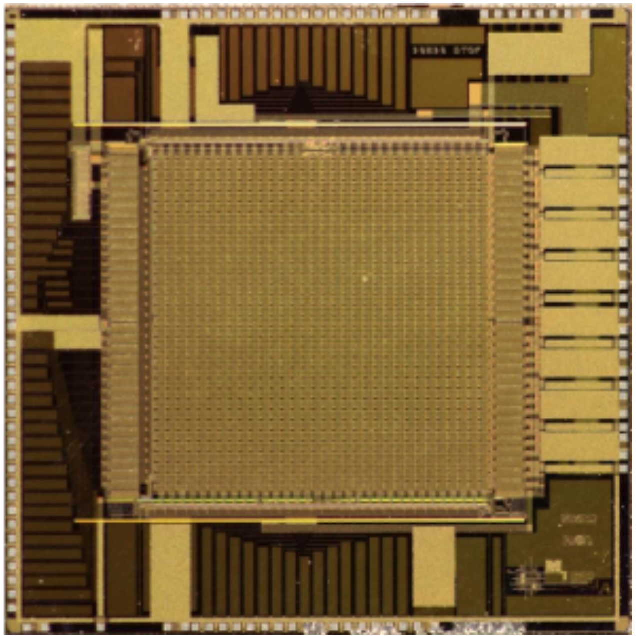


Special fabrication process

✔ SPAD optimization

✖ External electronics

CMOS Technology



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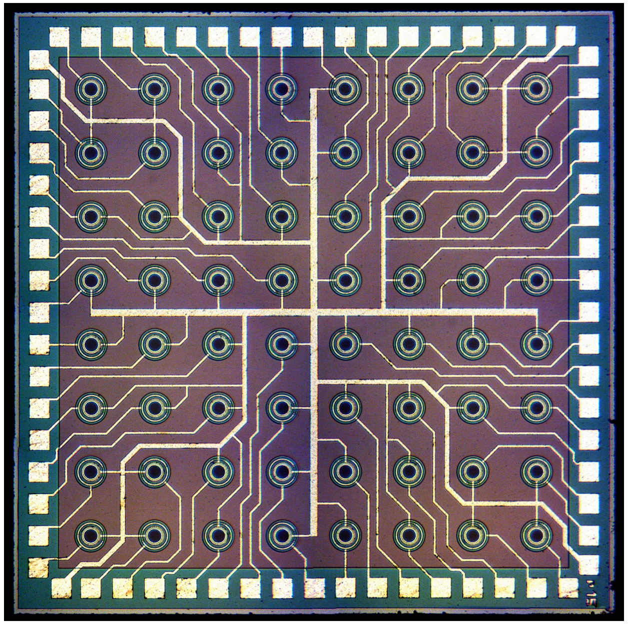

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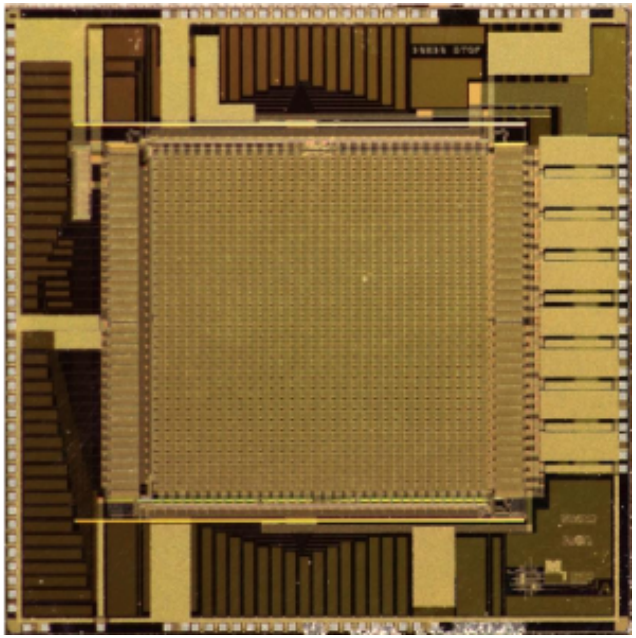
Two Approaches for Si-SPAD

CMOS Technology



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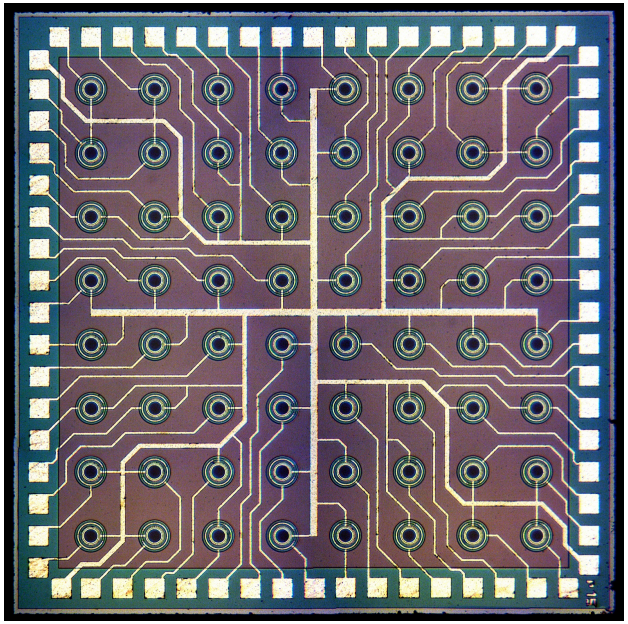

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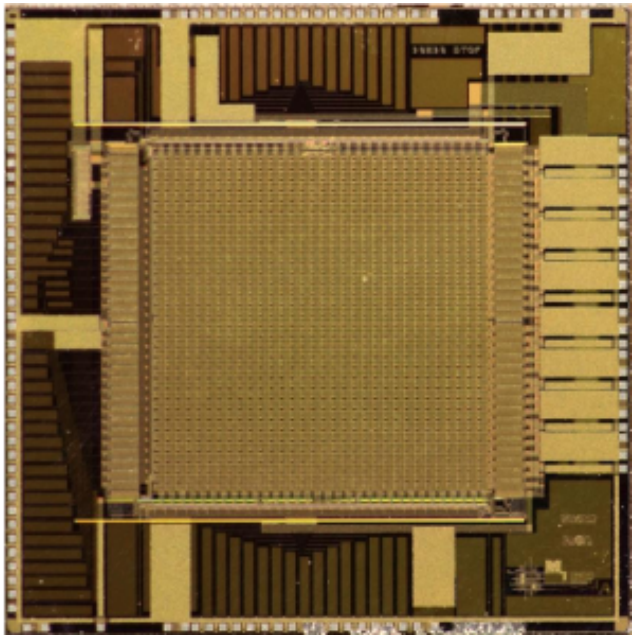

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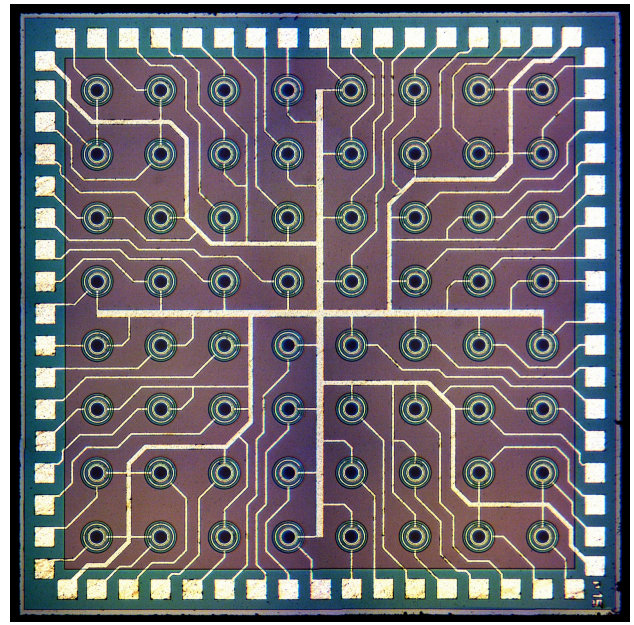

Special fabrication process

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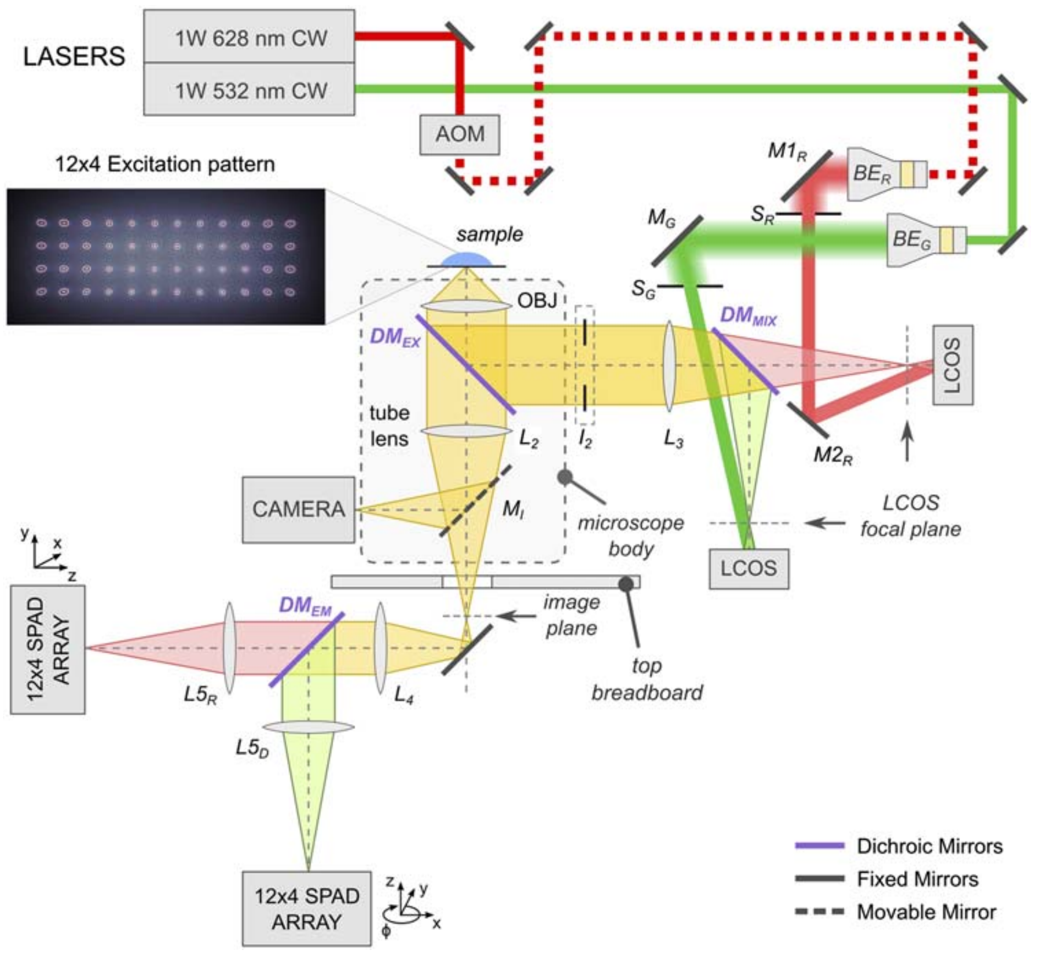
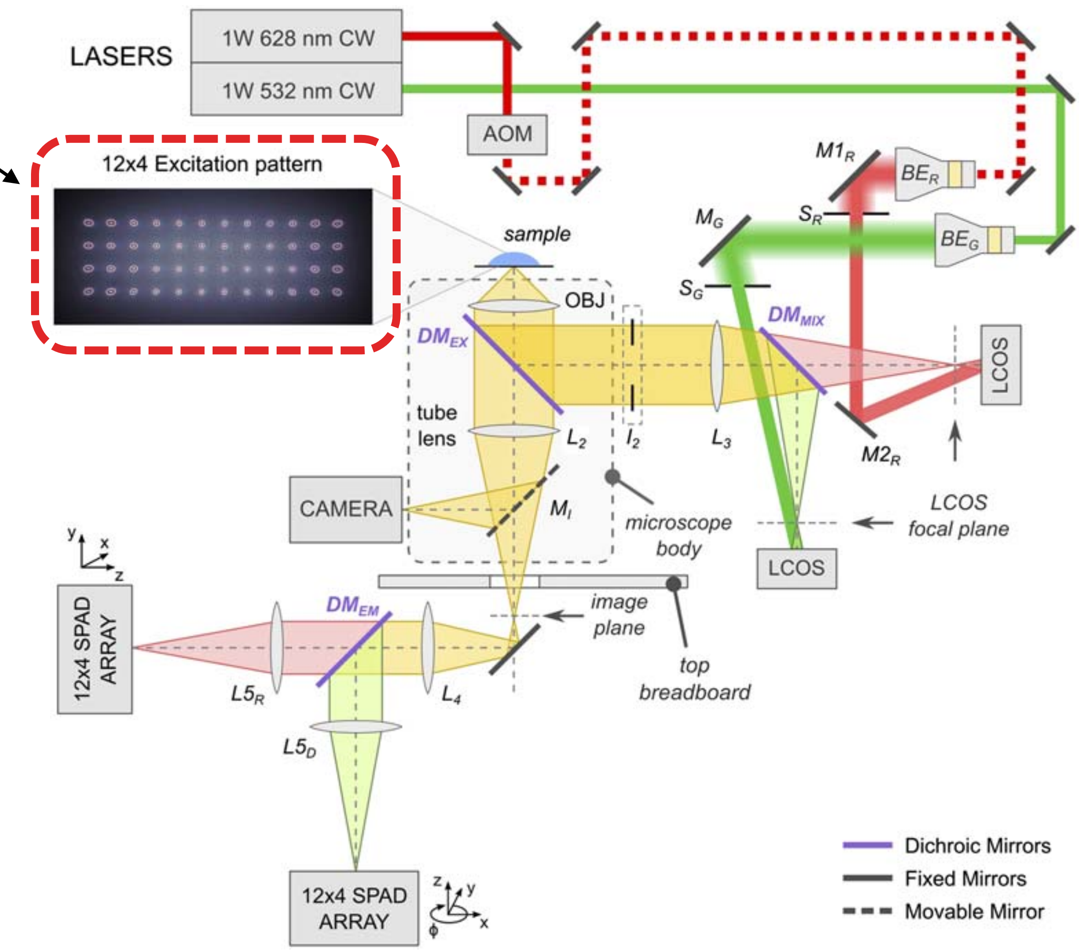
APPLICATIONS

Collaboration with Weiss & Michalet group at UCLA



Collaboration with Weiss & Michalet group at UCLA

Multiple Excitation Spots
- Parallel measurement
- 1 spot ➜ 1 detector



High-Throughput Single-Molecule Spectroscopy

Collaboration with Weiss & Michalet group at UCLA

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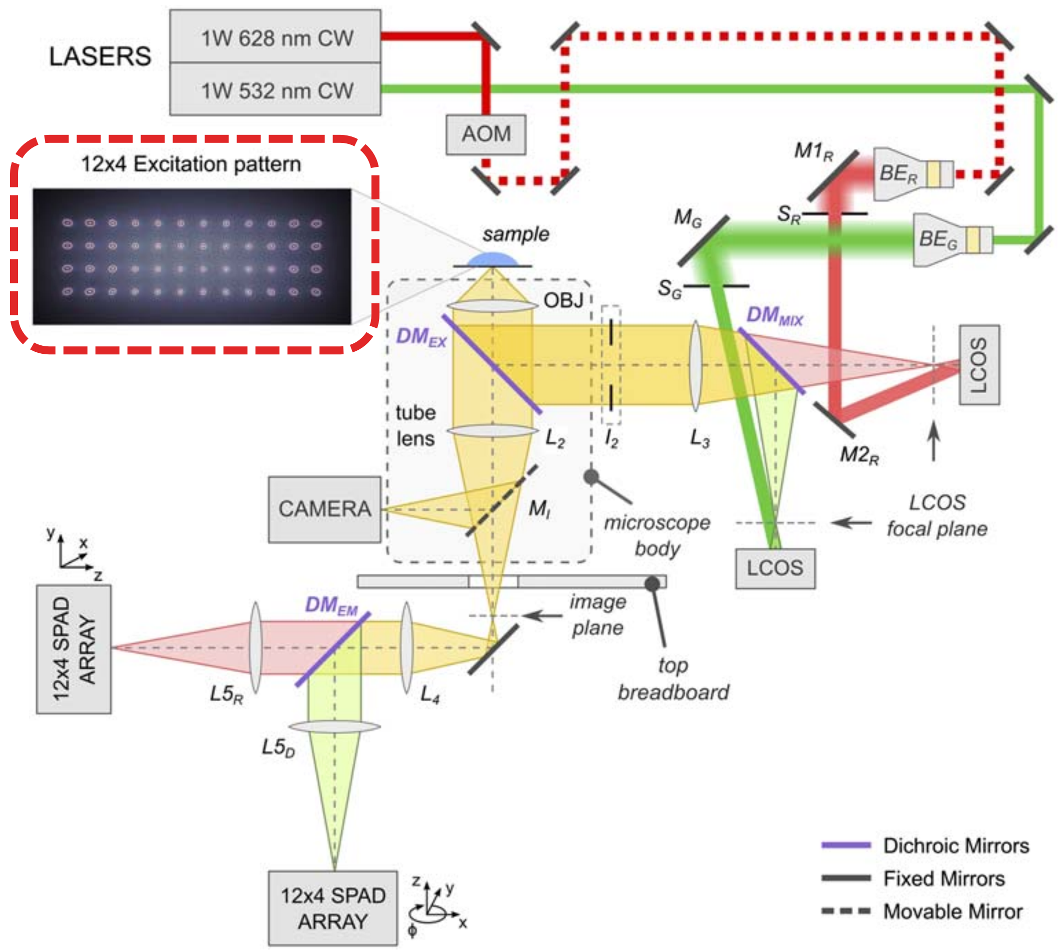


SPAD Requirements

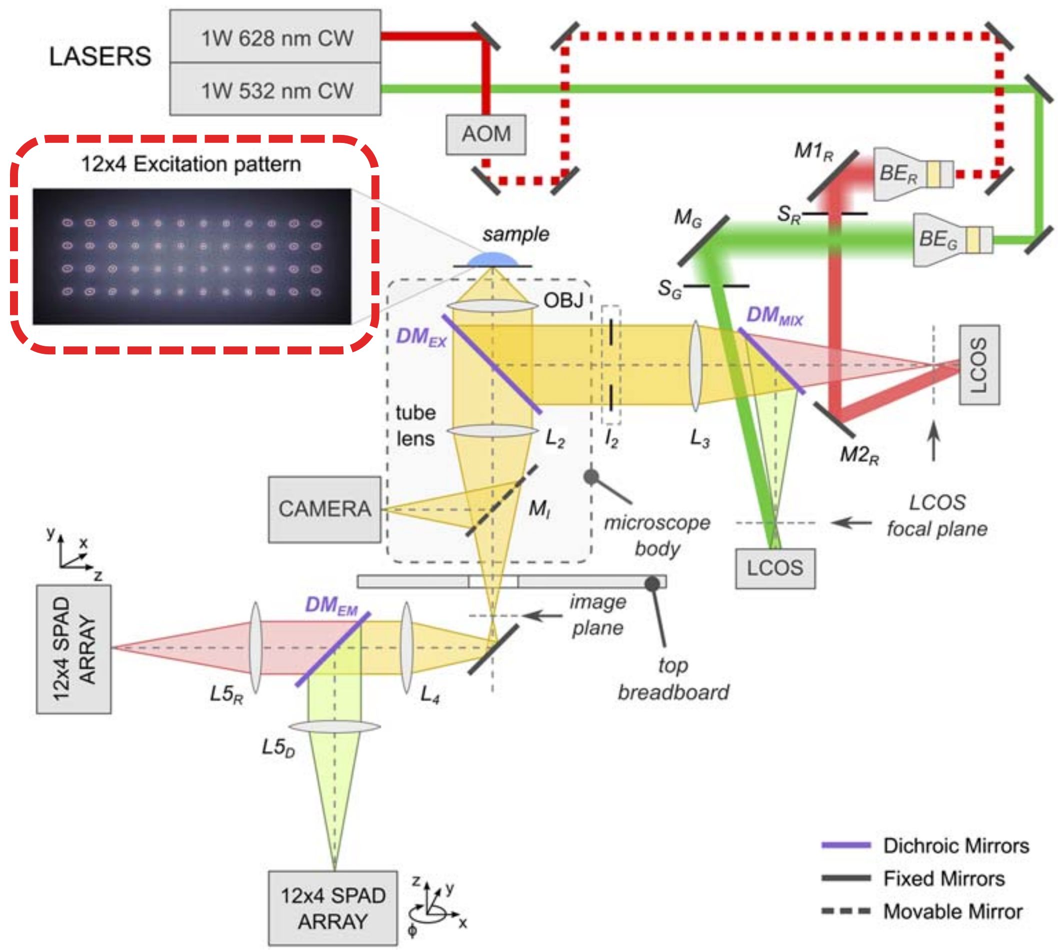
Collaboration with Weiss & Michalet group at UCLA

Multiple Excitation Spots

- Parallel measurement
- 1 spot ➜ 1 detector

SPAD Requirements

- Arrays
  - **10s' – 100's of pixels**
  - High fill factor not required



High-Throughput Single-Molecule Spectroscopy

Collaboration with Weiss & Michalet group at UCLA

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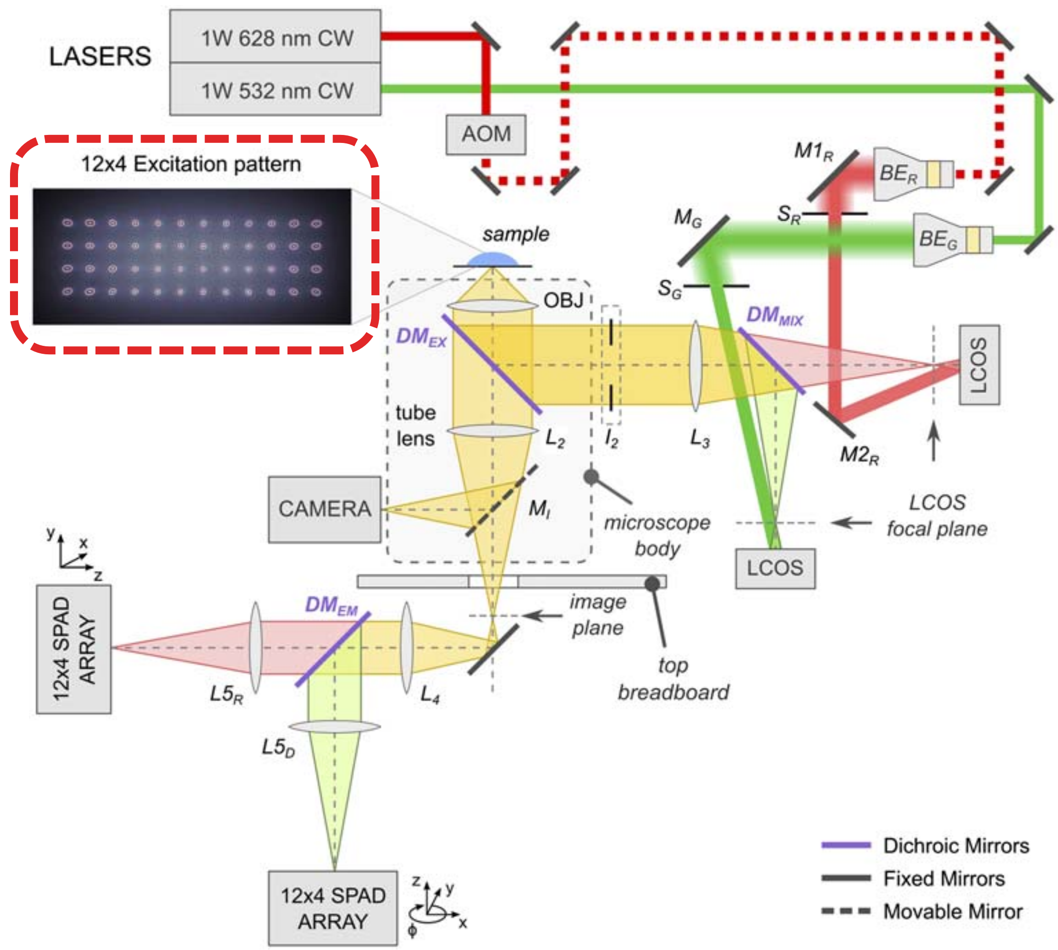

SPAD Requirements

- Arrays
  - **10s' – 100's of pixels**
  - High fill factor not required
- High detection efficiency
  - **Red and Near Infrared**
  - Limited measurement time

High-Throughput Single-Molecule Spectroscopy

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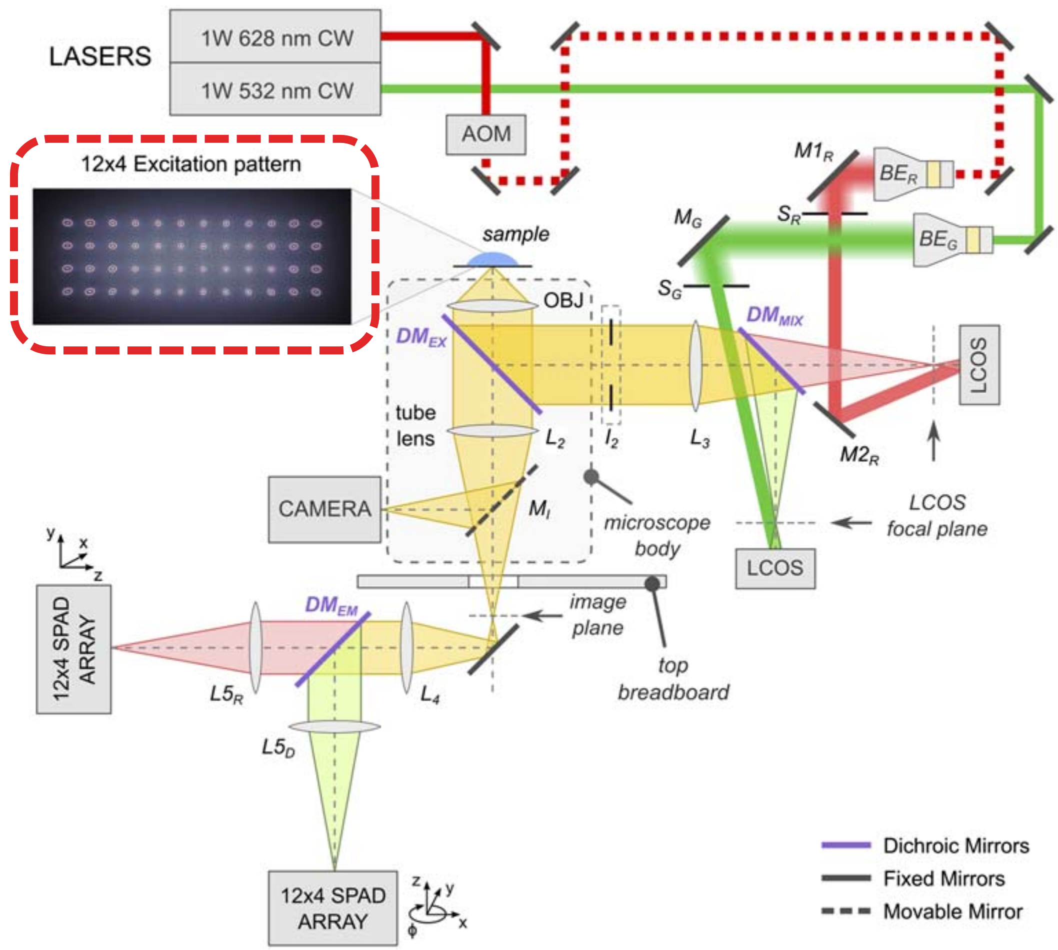


SPAD Requirements

- Arrays
  - **10s' – 100's of pixels**
  - High fill factor not required
- High detection efficiency
  - **Red and Near Infrared**
  - Limited measurement time
- Low timing jitter
  - **< 100 ps** FWHM
  - Small changes in lifetime

Many Applications…

Similar requirements in many other applications

- Quantum Key Distribution in free space
- Time Domain Diffuse Correlation Spectroscopy
- Super-Resolution Microscopy
- Quantum Information Processing
- …

Many Applications… No Suitable Detectors

Similar requirements in many other applications

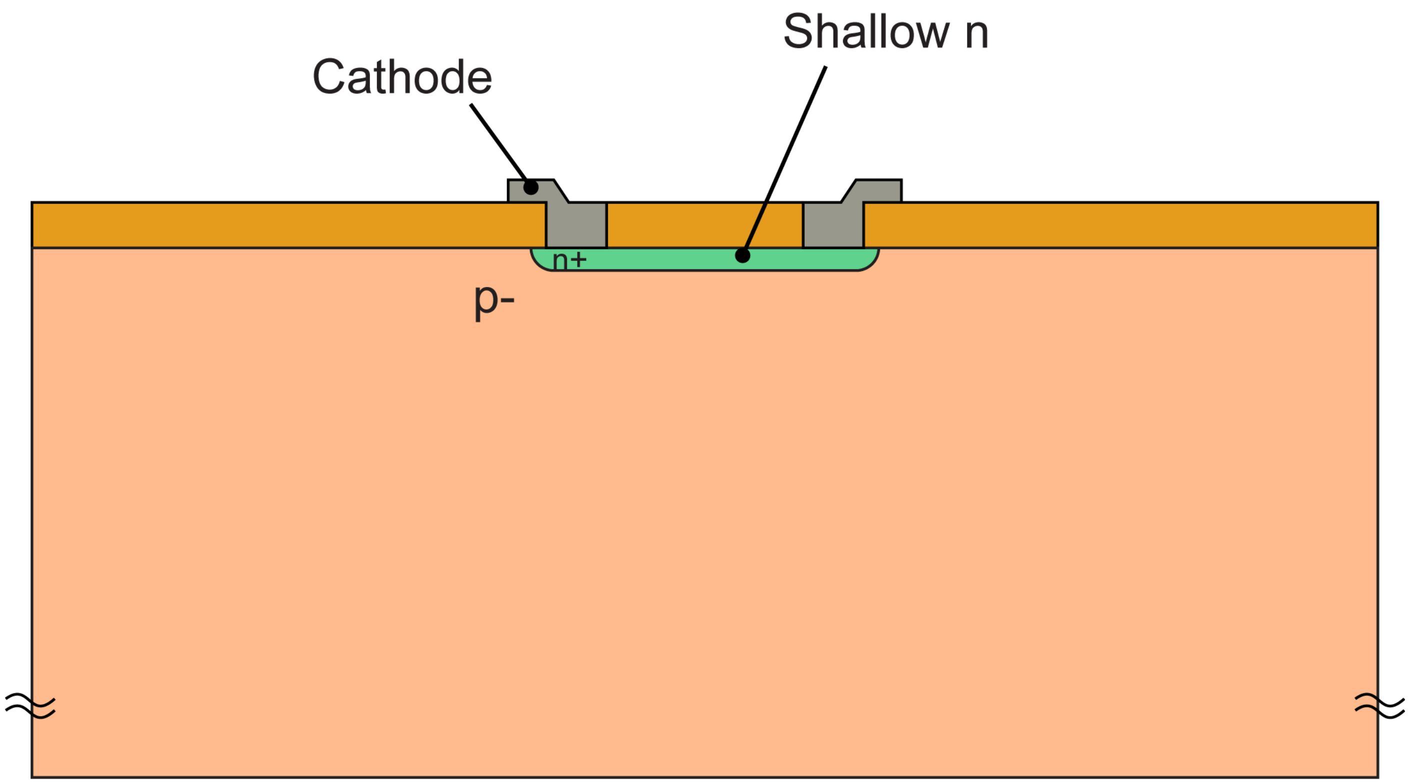
- Quantum Key Distribution in free space
- Time Domain Diffuse Correlation Spectroscopy
- Super-Resolution Microscopy
- Quantum Information Processing
- …

Lack of SPADs that combine:

- High **detection efficiency** in the red / near infrared
- Low **timing jitter**
- Availability of **arrays**

THIN SPAD IN CUSTOM TECHNOLOGY

Thin SPAD Structure



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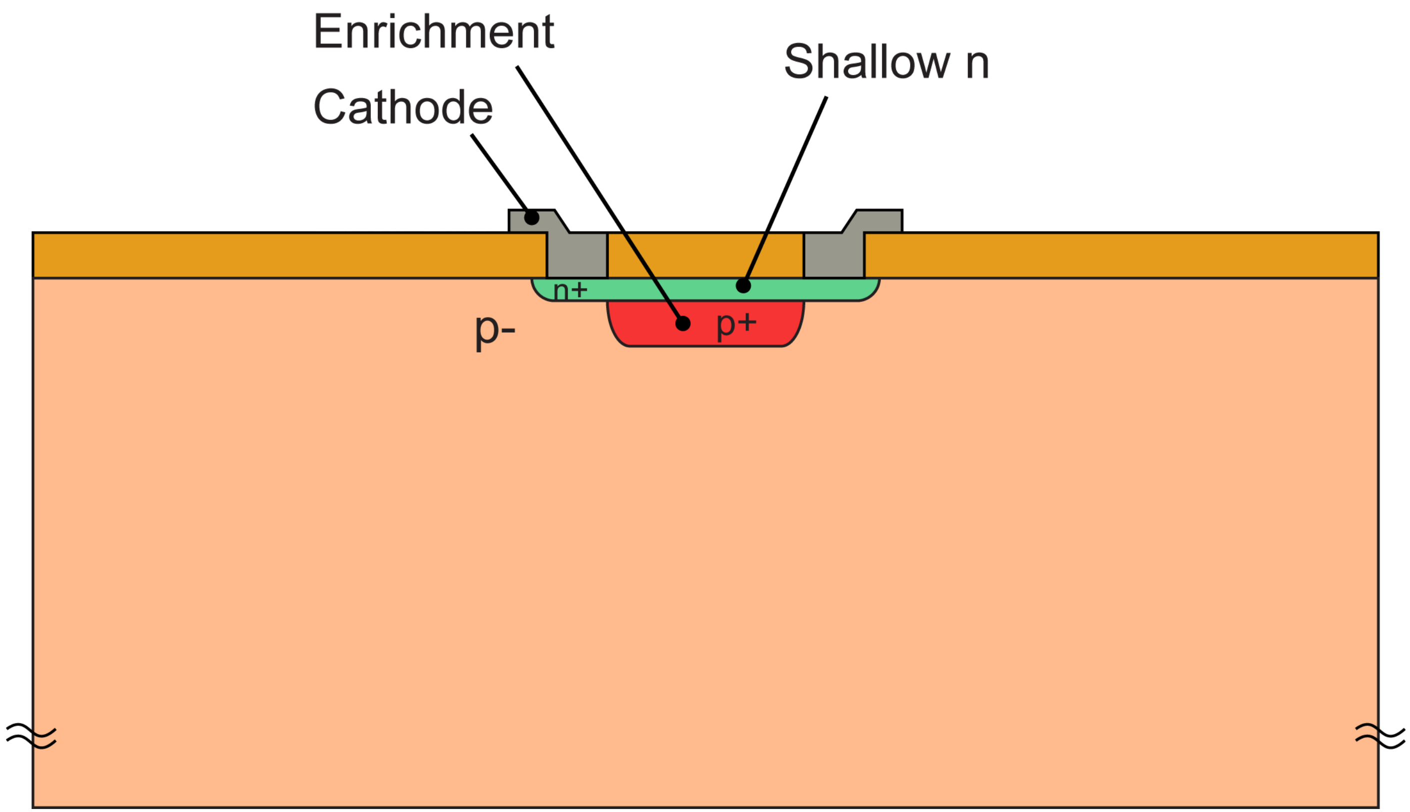

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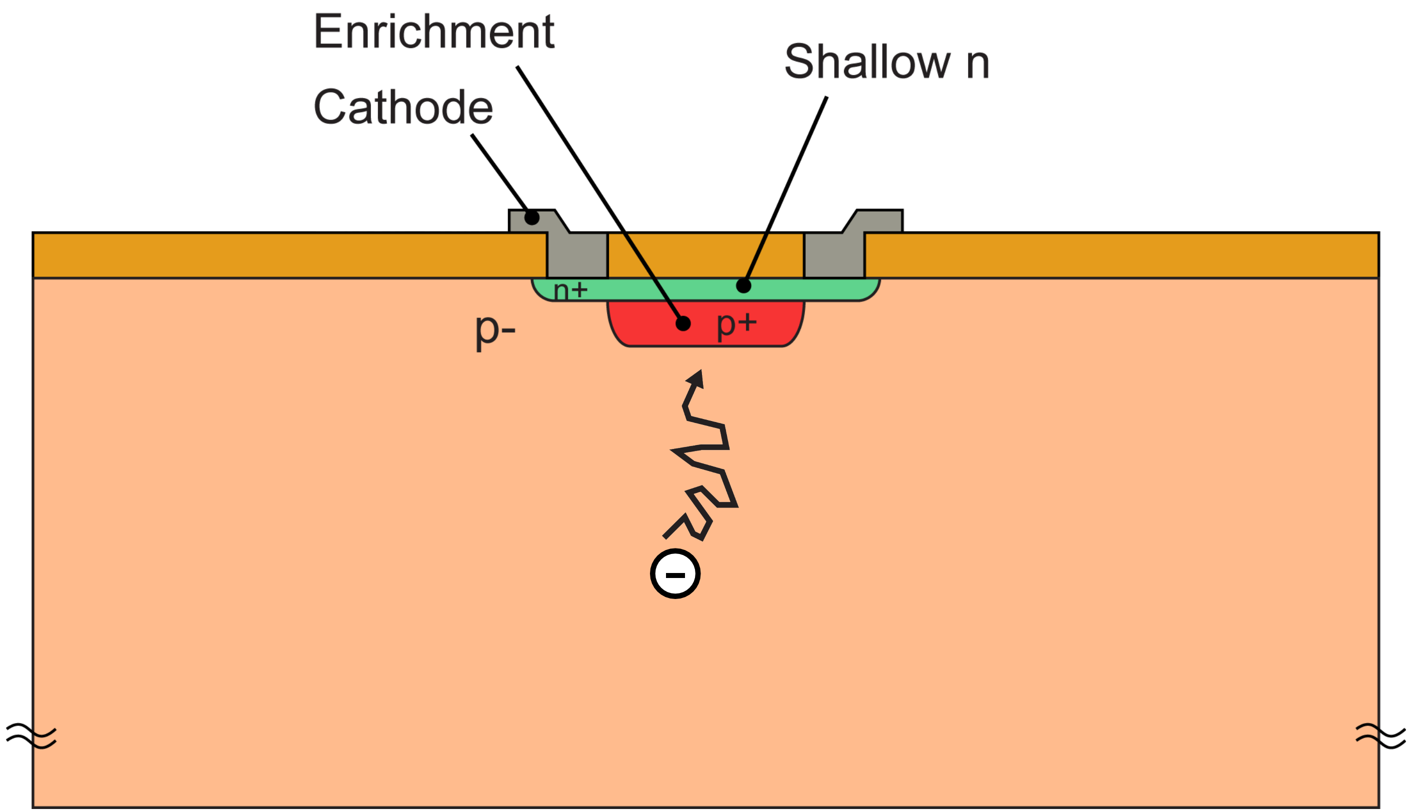
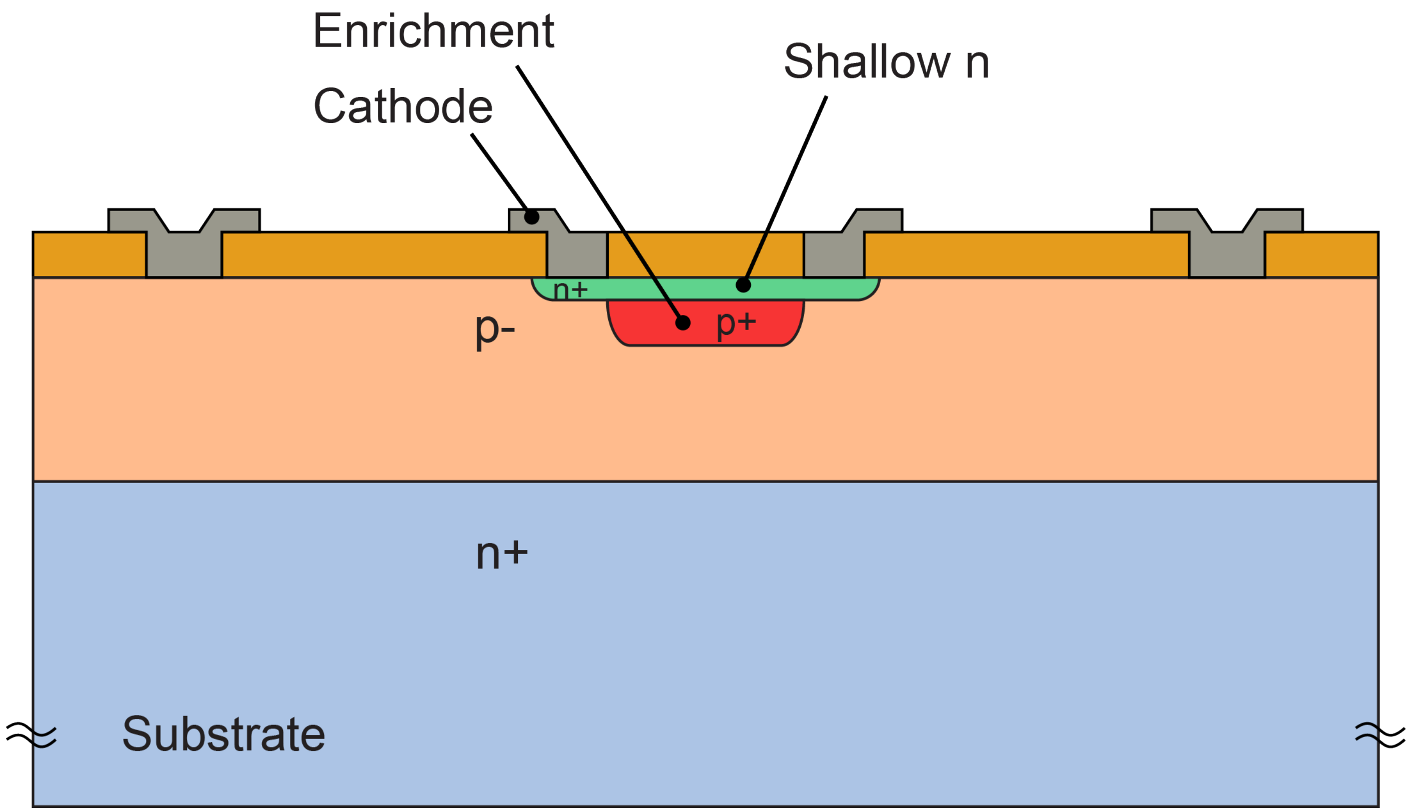


- Carriers generated in the substrate sometime trigger an avalanche
- **Very slow** diffusion tail in the **temporal response**

Thin SPAD Structure



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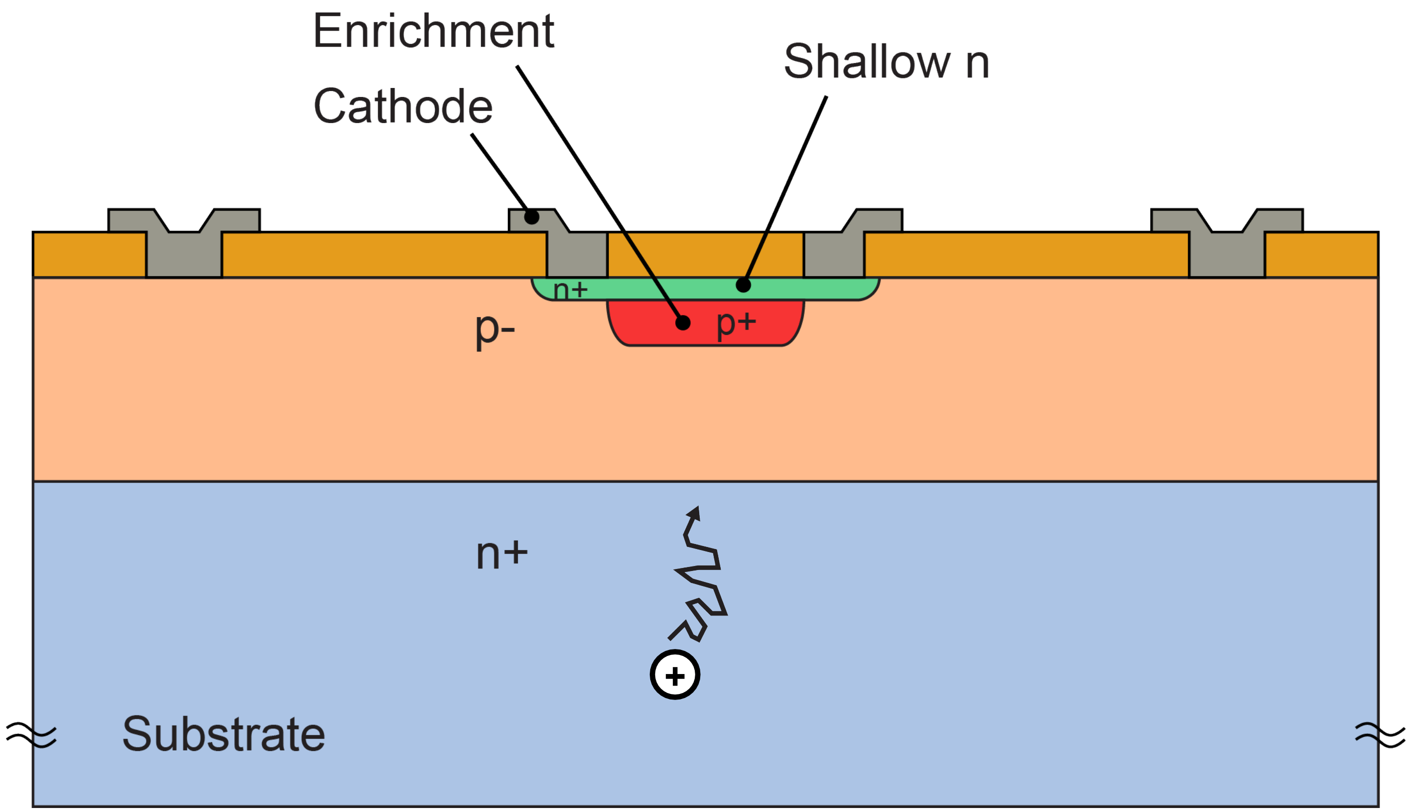
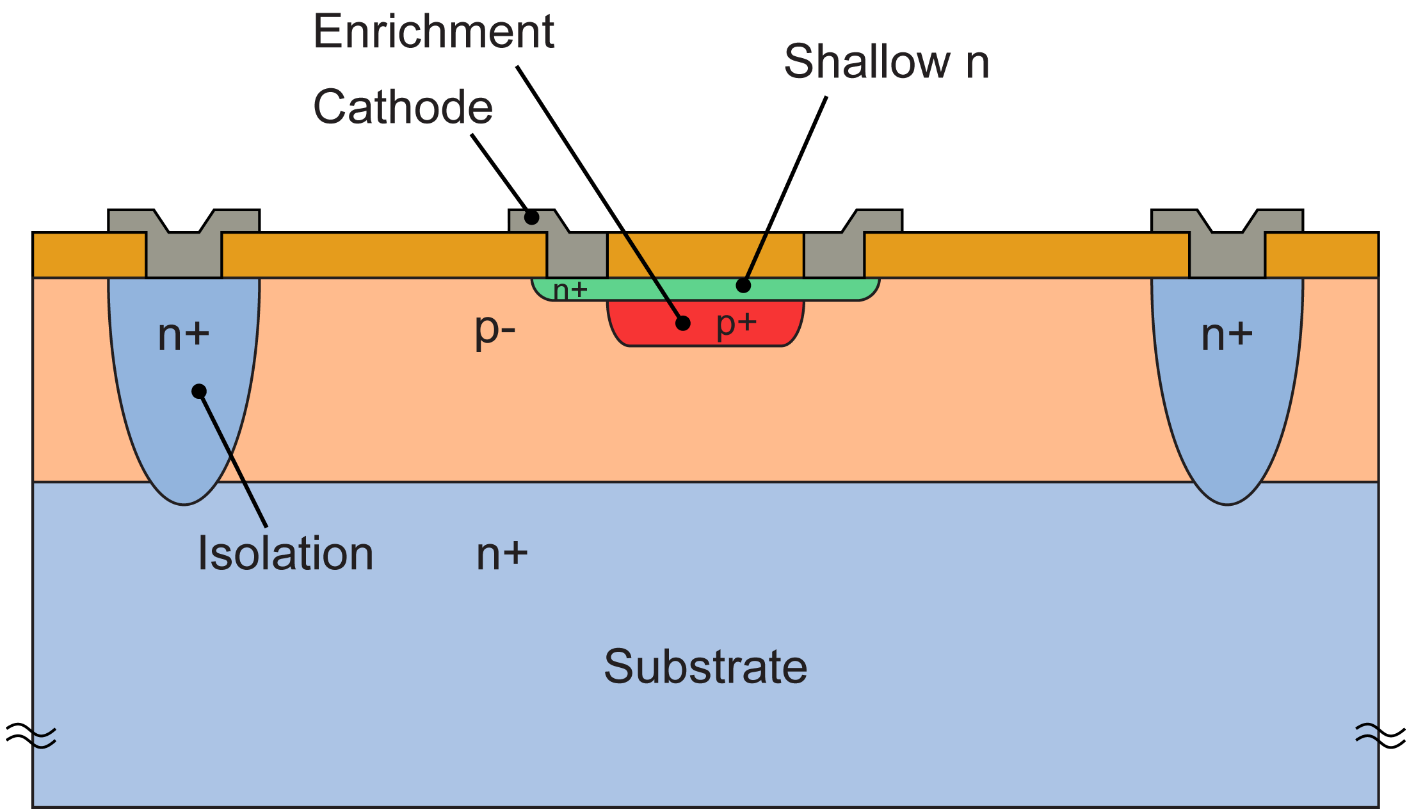


- Carriers generated in the substrate **cannot** trigger an avalanche
- **Short** diffusion tail in the **temporal response**

Thin SPAD Structure



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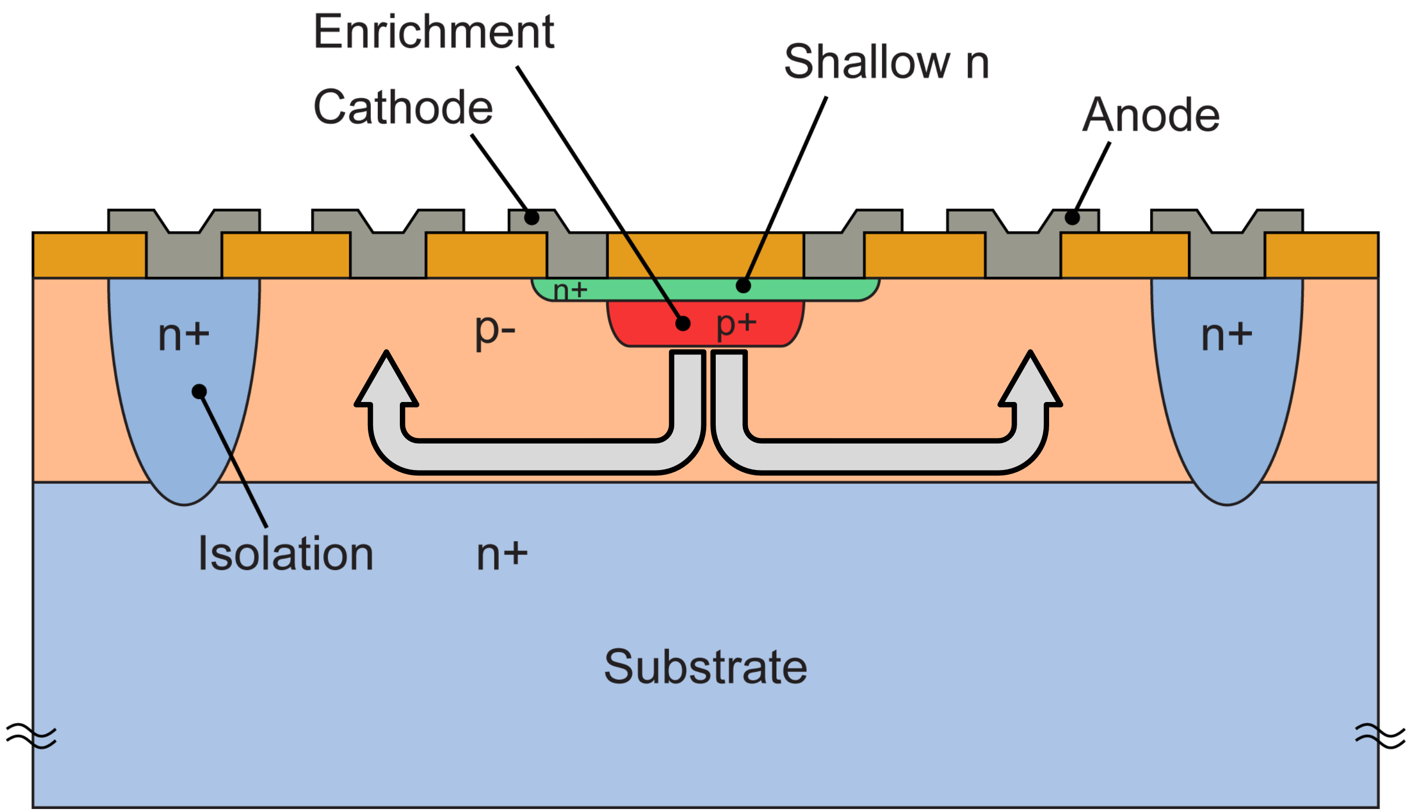

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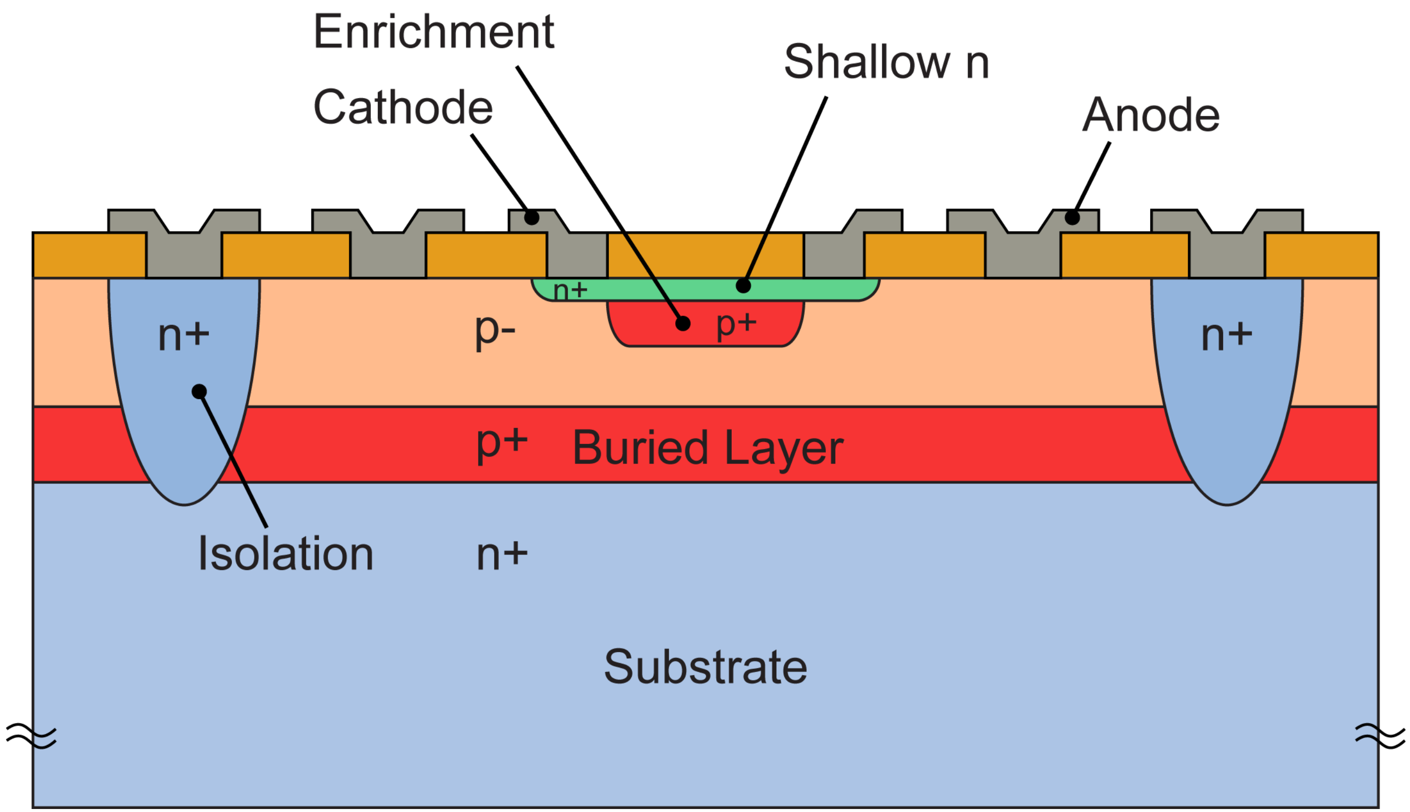

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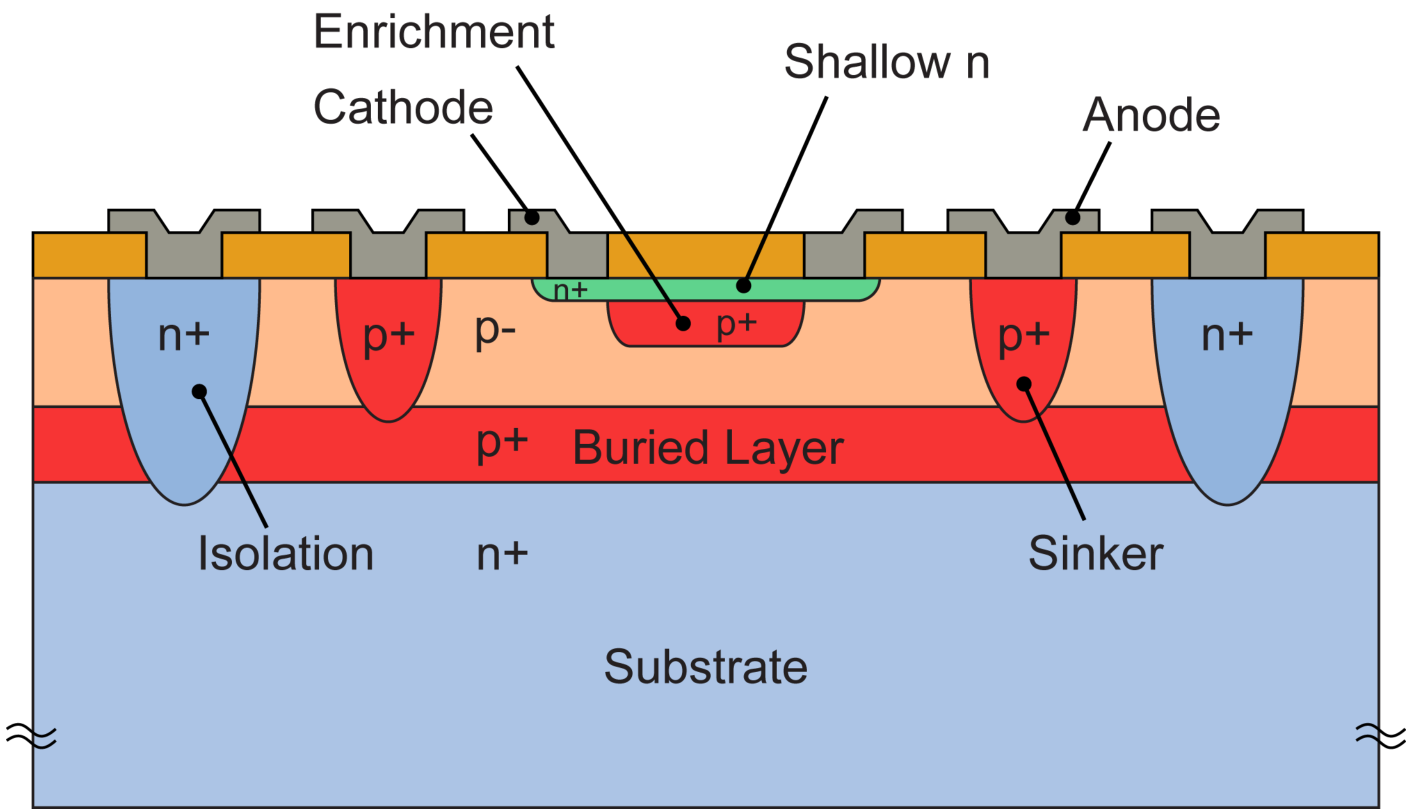
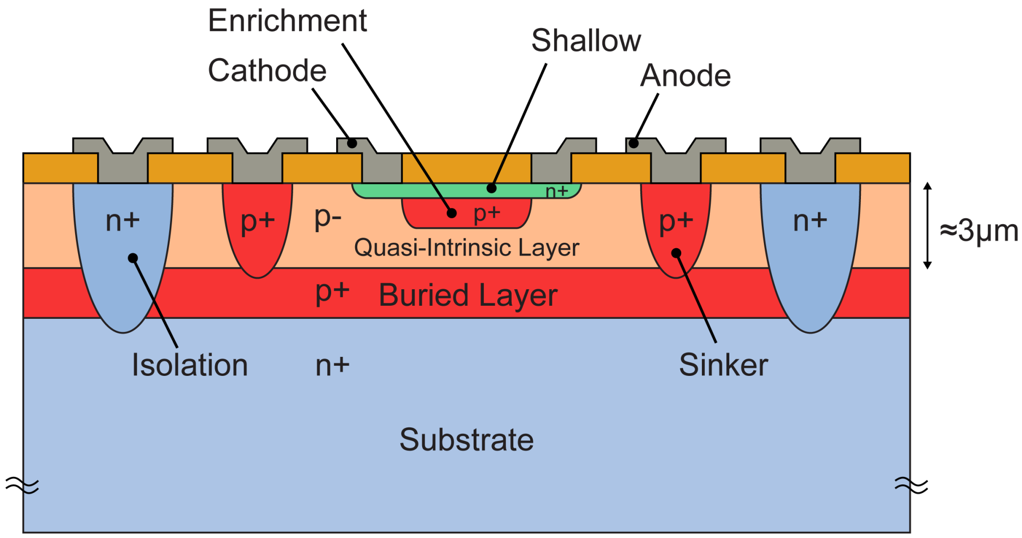


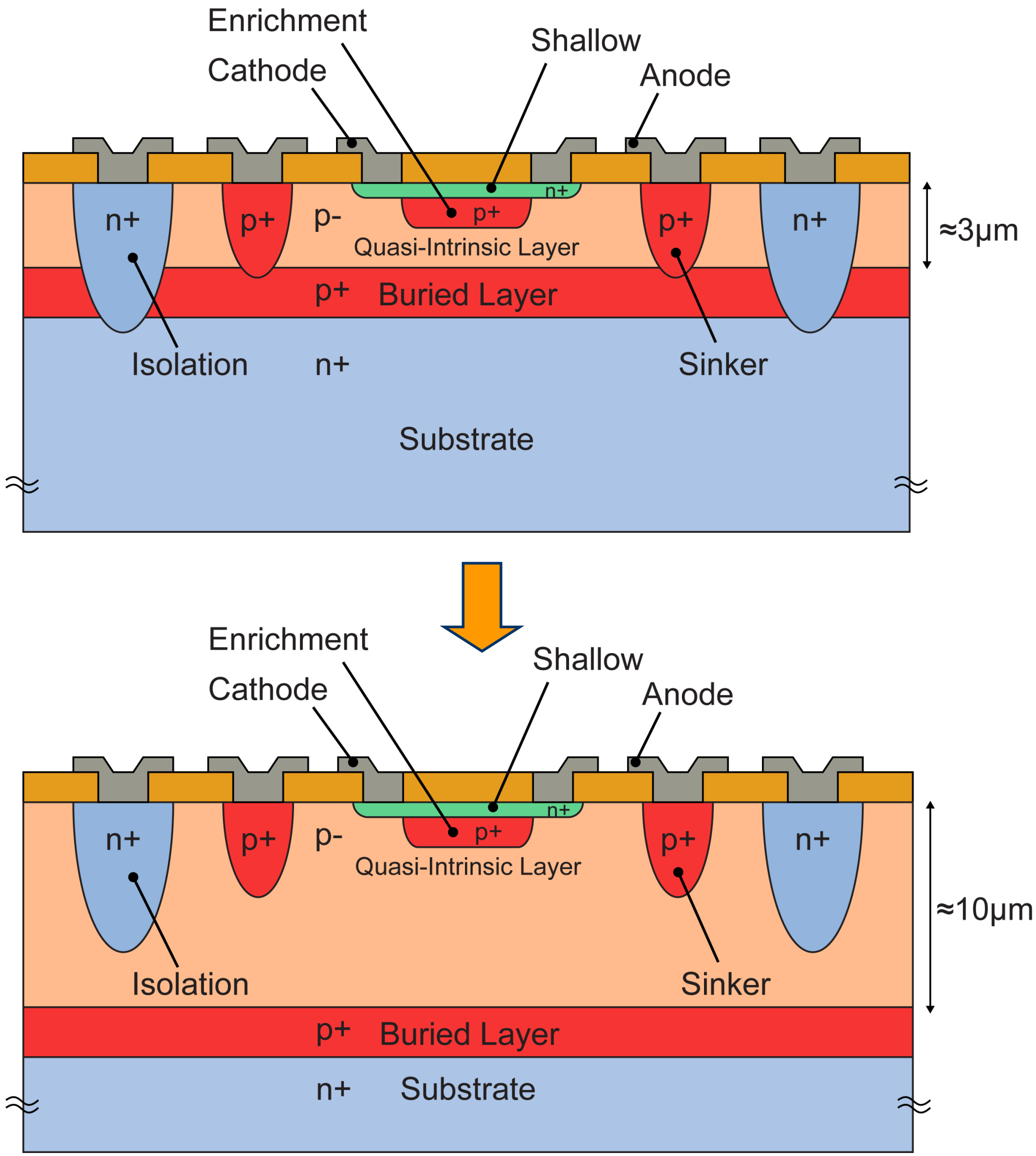
Enhancing the Detection Efficiency

Increasing the Detection Efficiency



- Only the photons absorbed in the upper layer can be detected
- Limited PDE at longer wavelengths

Increasing the Detection Efficiency



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- Thicker p- layer
- Not sufficient for good performance

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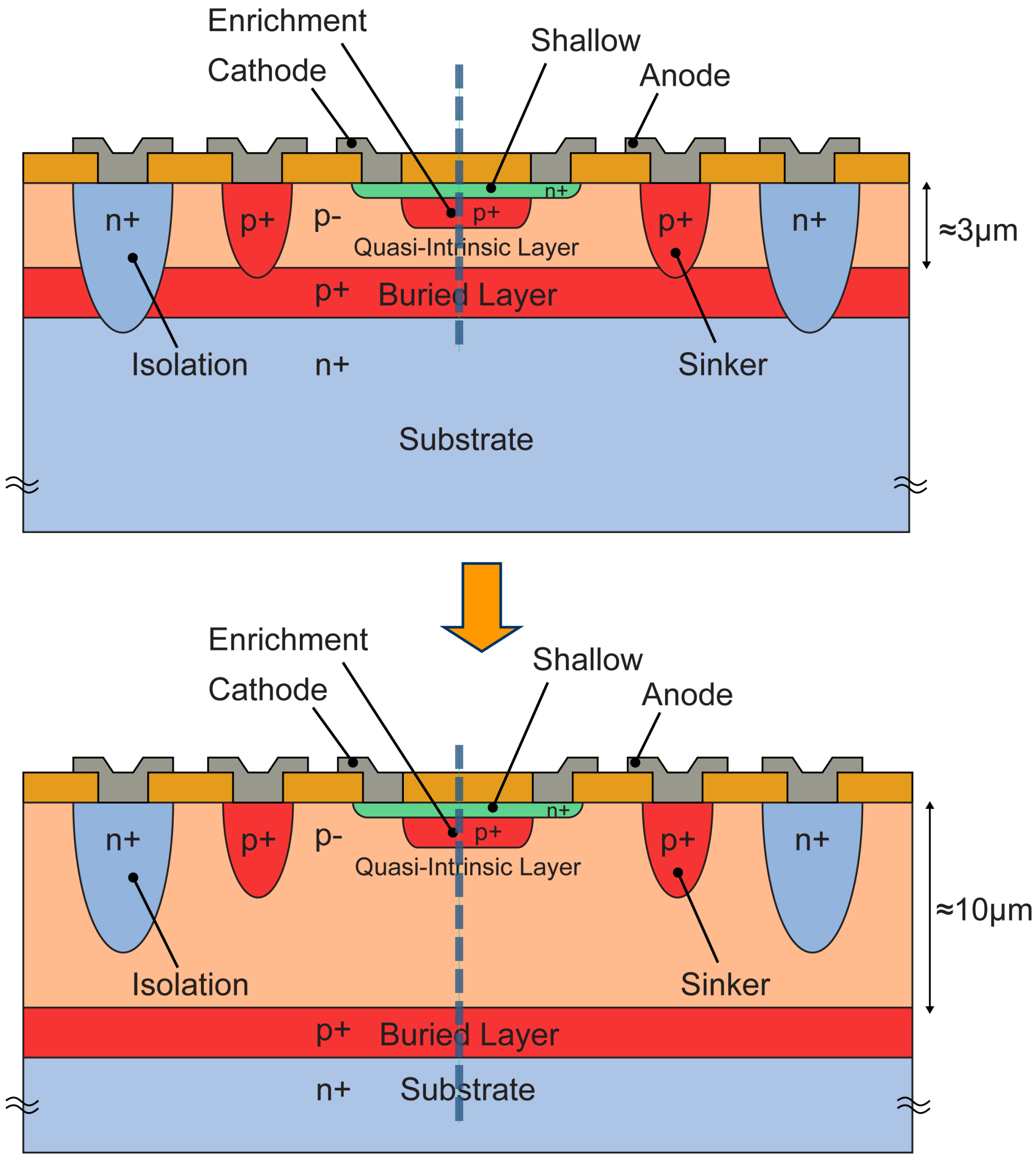

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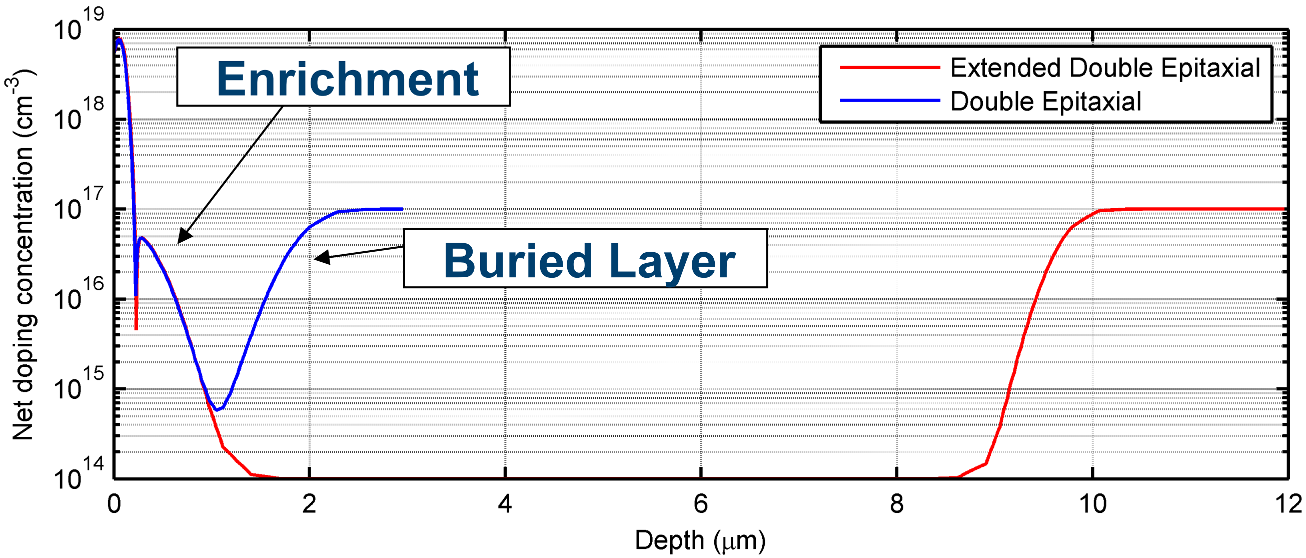
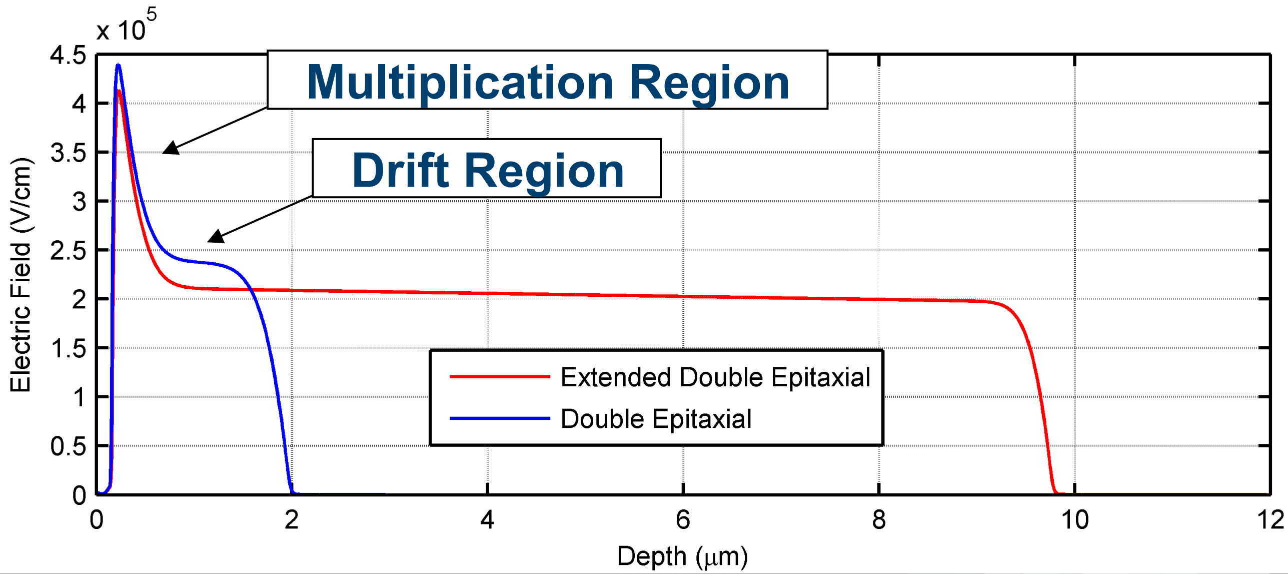
Extended Double Epitaxial SPAD





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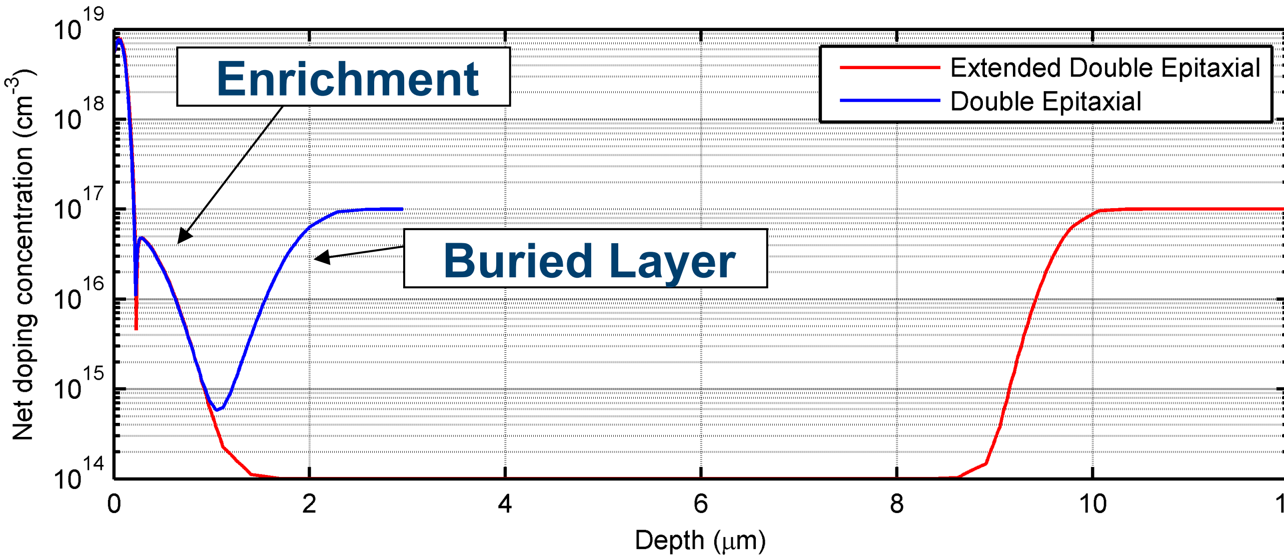
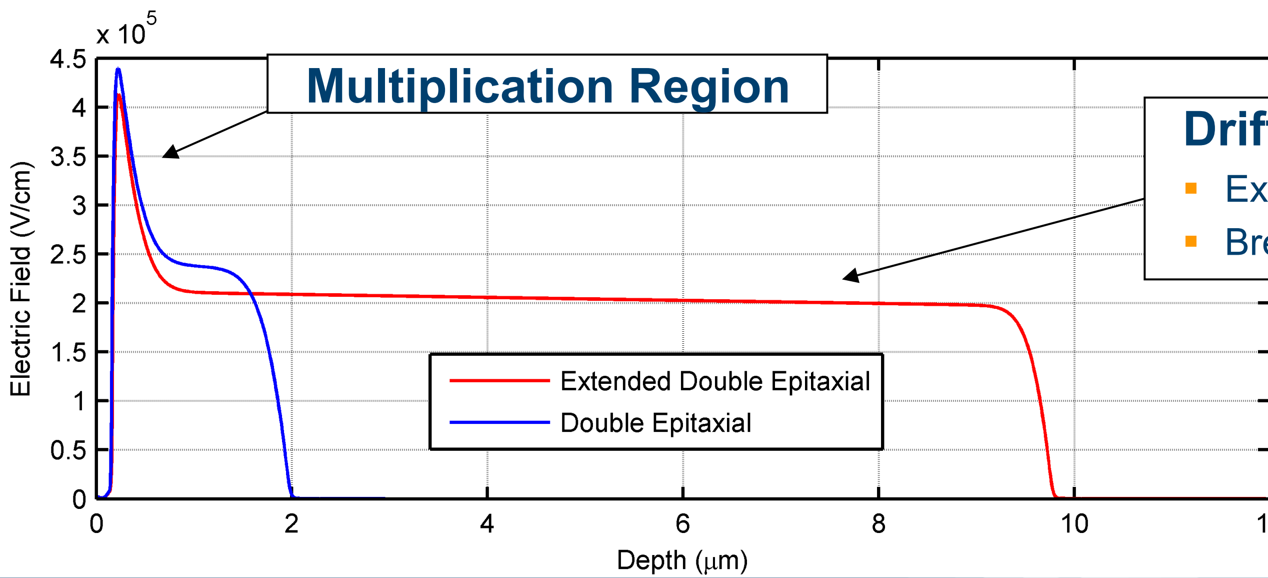
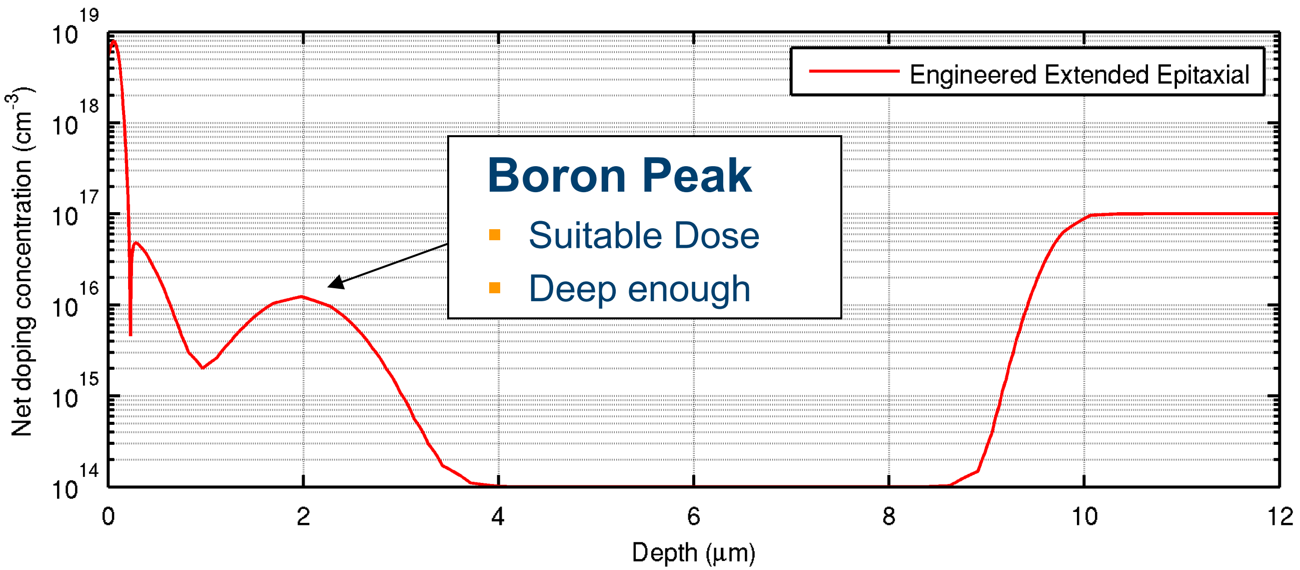


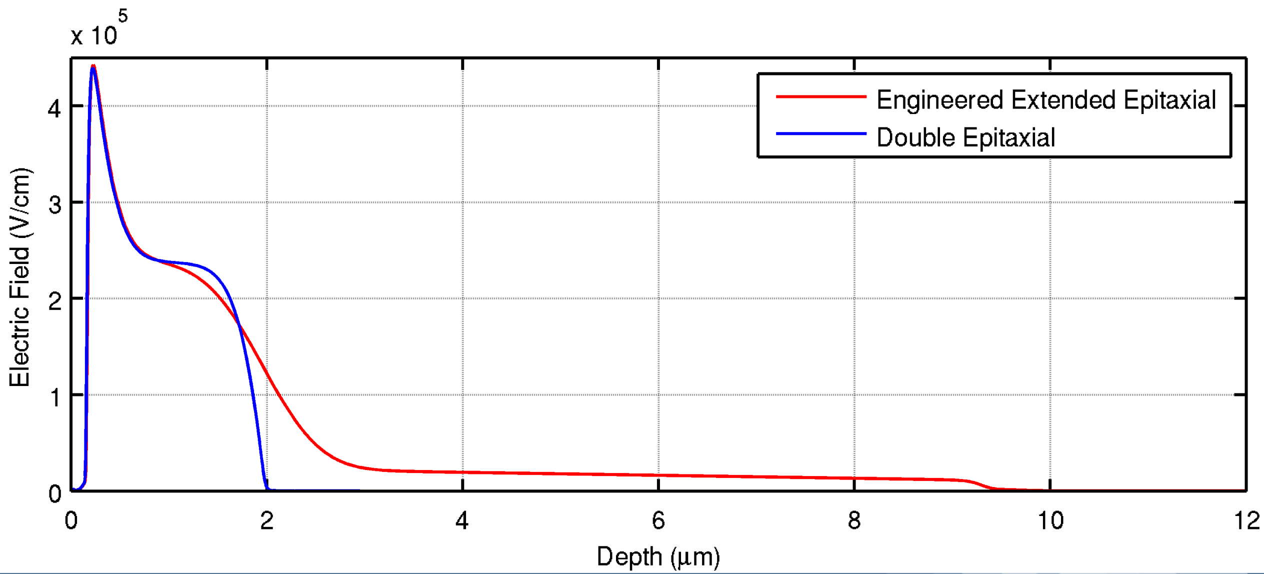


Drift Field

- Extremely high: $2 \cdot 10^5$ V/cm
- Breakdown Voltage: 197V

Engineered Extended Epitaxial SPAD





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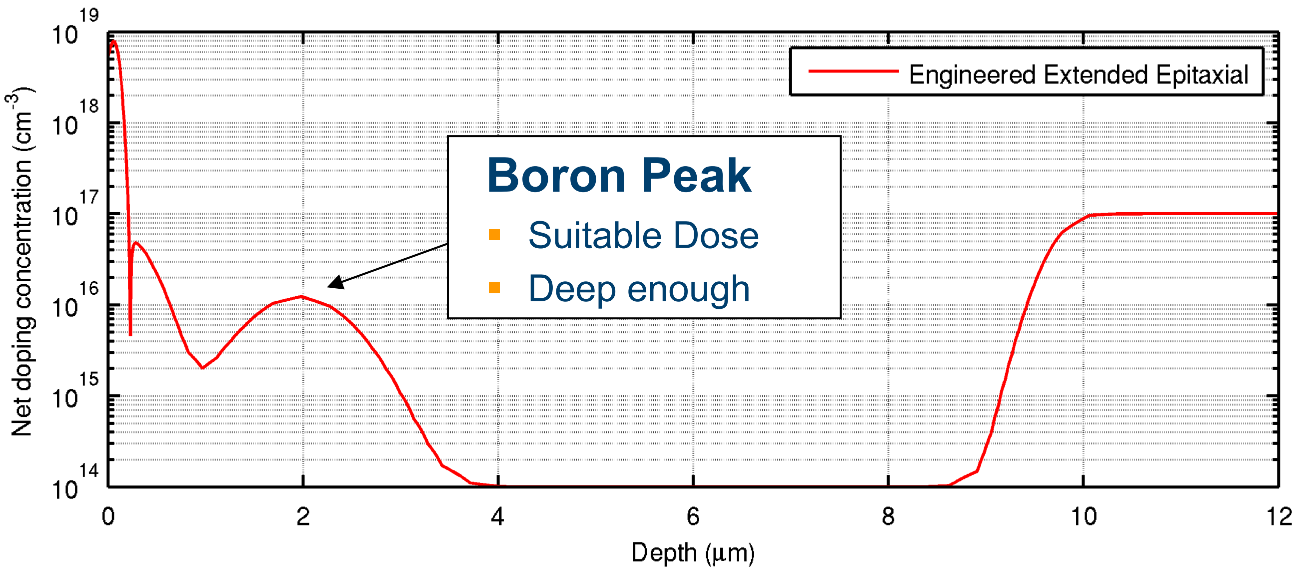

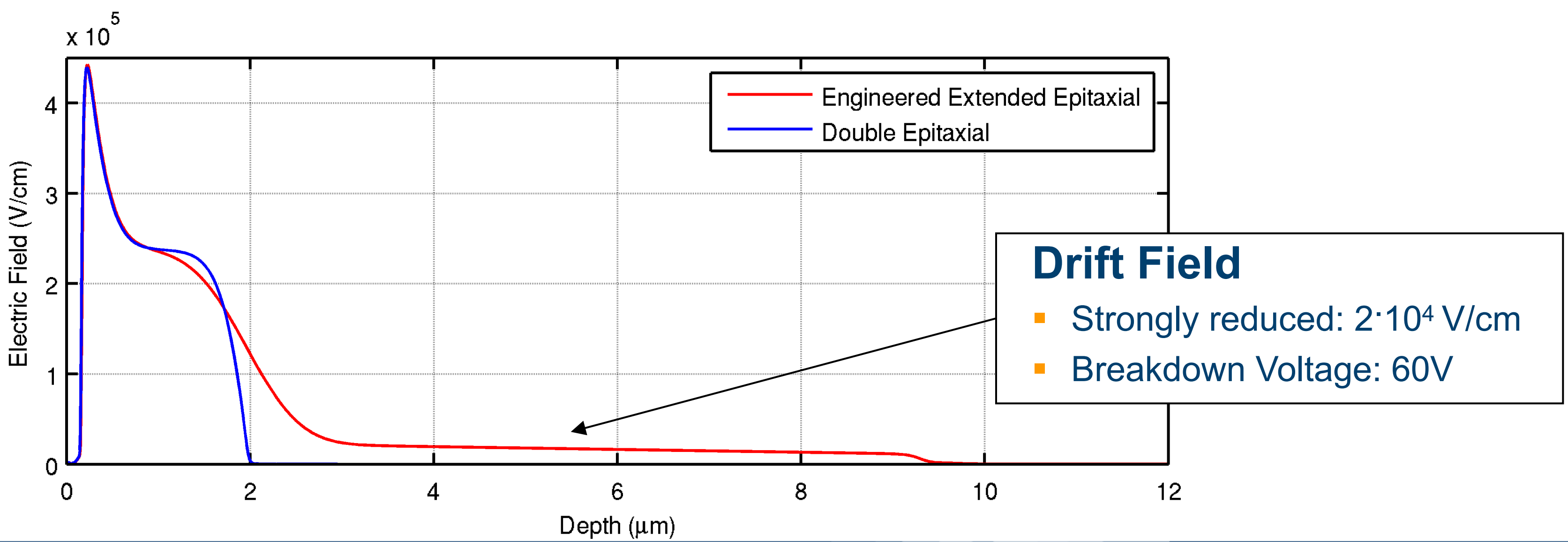

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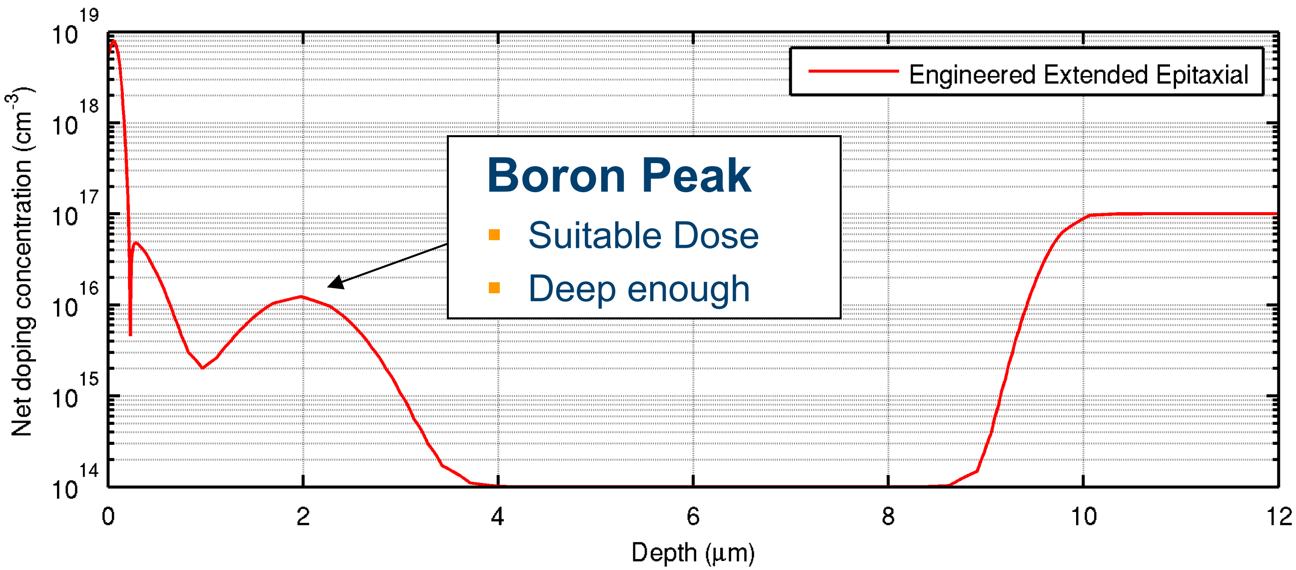
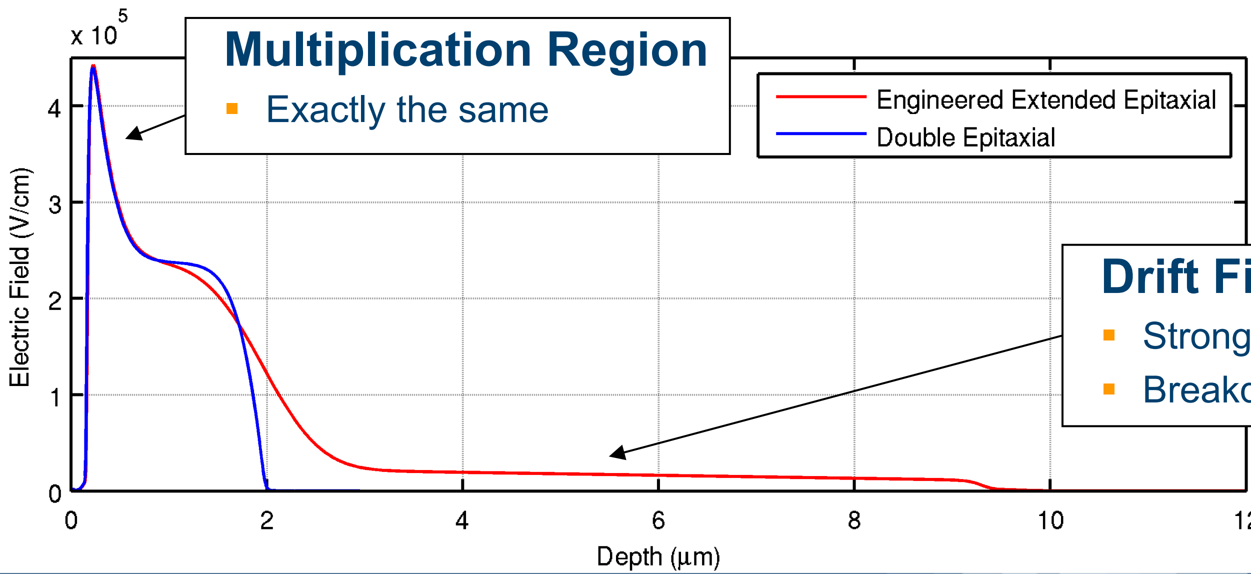


Boron Peak

- Suitable Dose
- Deep enough



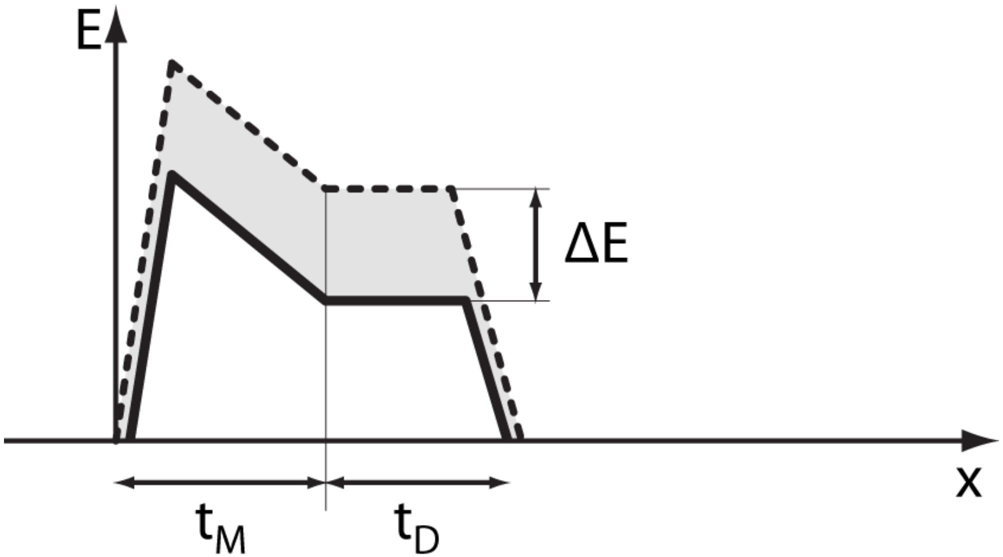
Multiplication Region

- Exactly the same

Drift Field

- Strongly reduced: $2 \cdot 10^4$ V/cm
- Breakdown Voltage: 60V

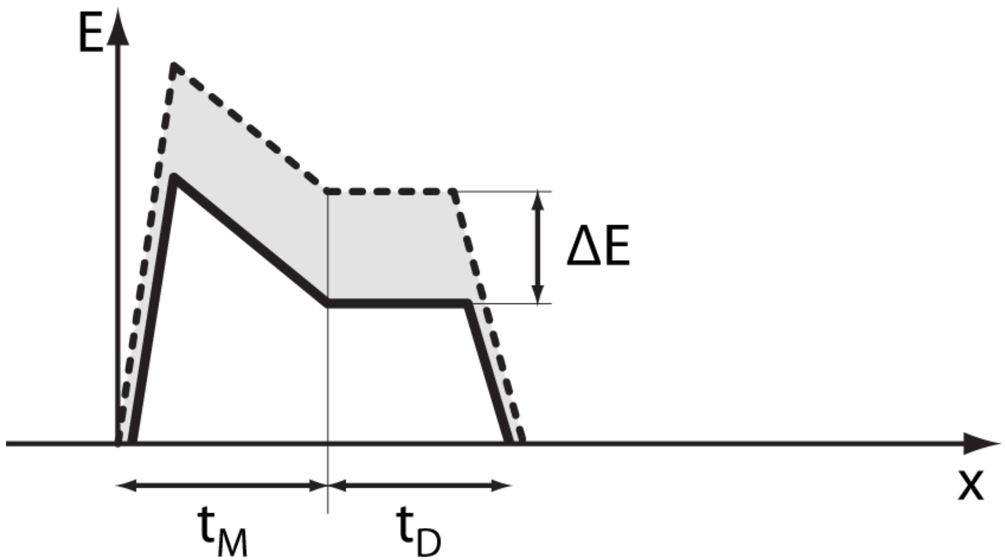
Overvoltage



Thin SPAD

- Overvoltage to optimize the performance
- Electric field increase: ΔE
- Vov= ΔE * (t_M + t_D)

Overvoltage



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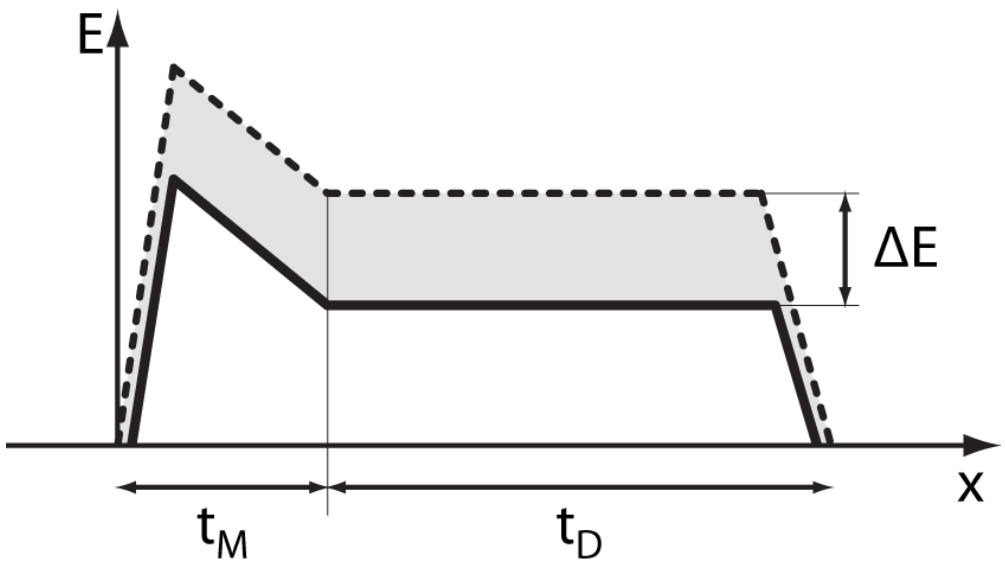
- Electric field increase: ΔE
- $V_{ov} = \Delta E * (t_M + t_D)$

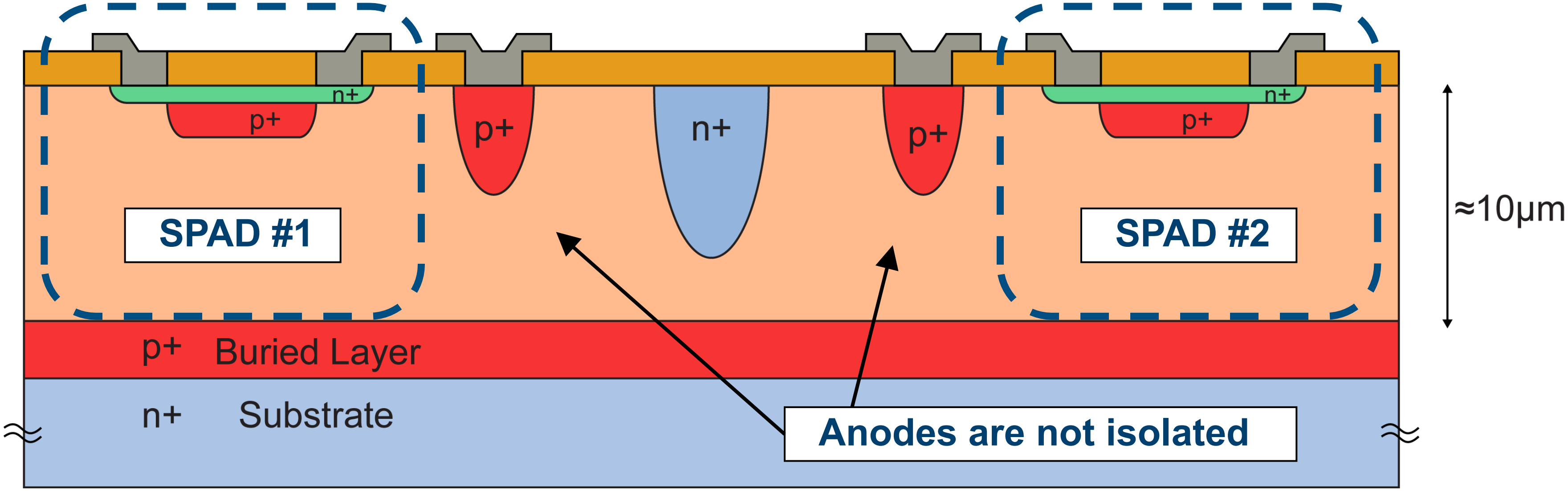


Thick SPAD

- Same multiplication field wanted
- Same ΔE
- Larger Overvoltage: **20V**

NOT READY FOR ARRAYS

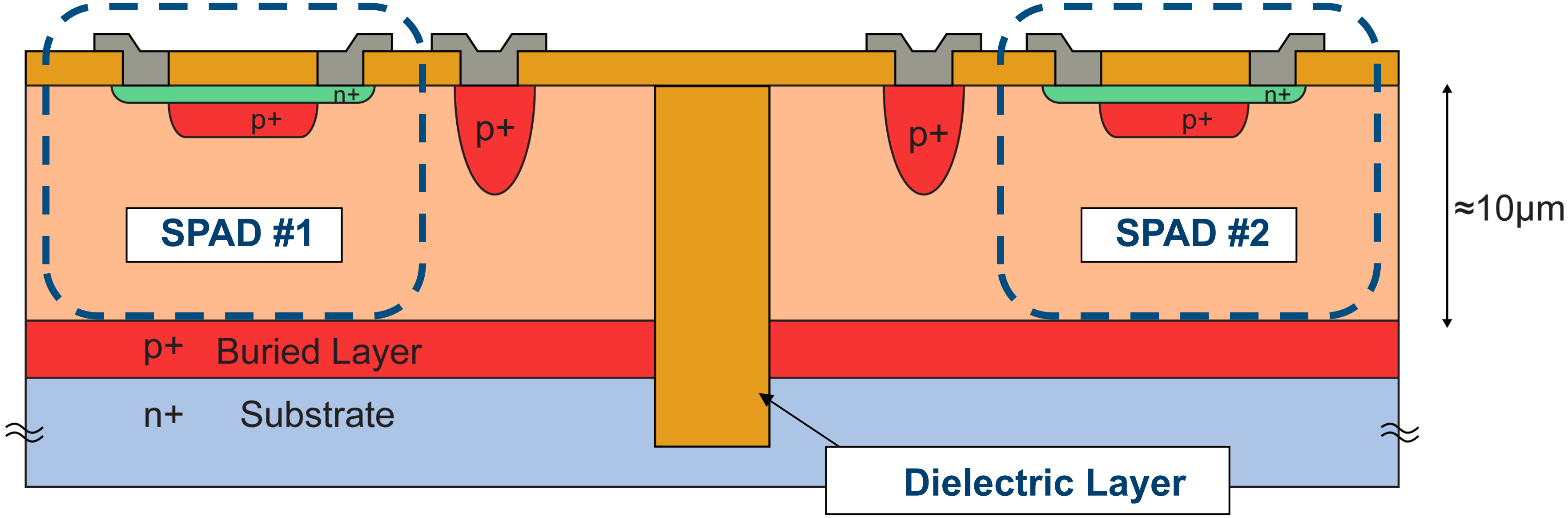
Lost Electrical Isolation



Lack of full electrical isolation

- Anodes shorted
- Lost flexibility for connecting electronic circuits

Solution: Dielectric Isolation



Dielectric Isolation

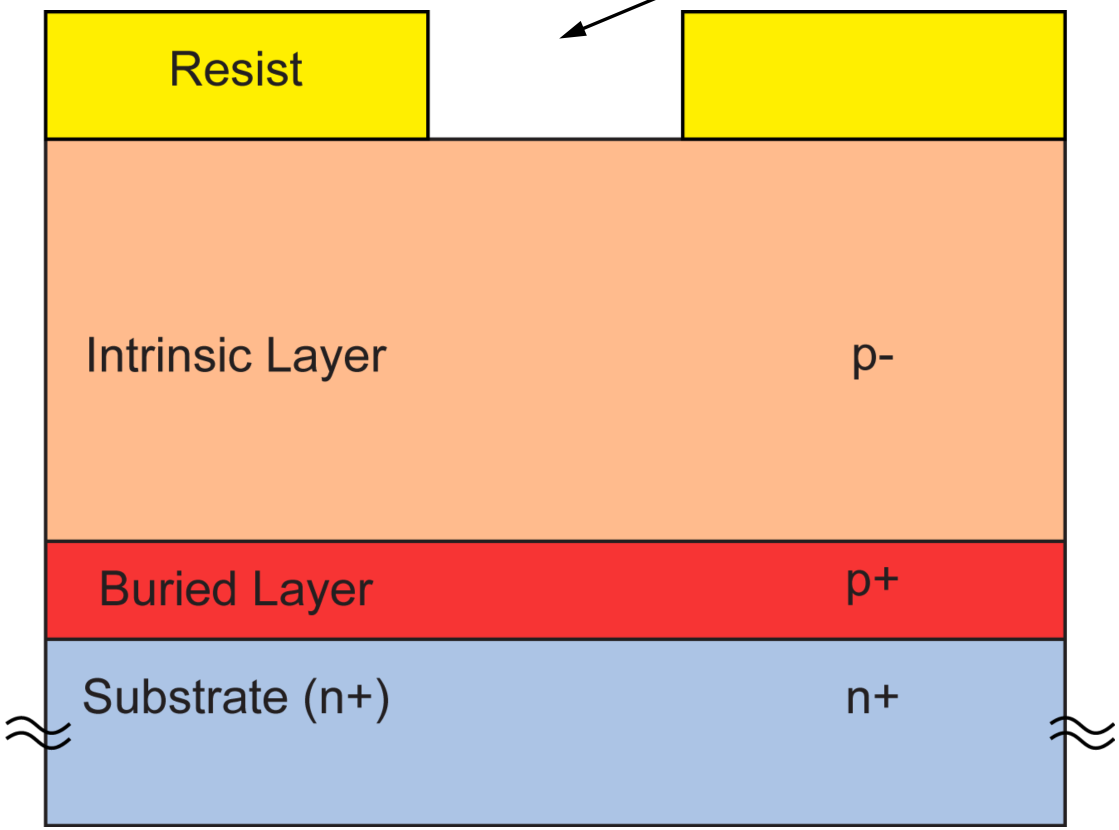
- Insulating layer between anodes
- It must reach the substrate
- Eliminates conductive paths between anodes

How can we do this?

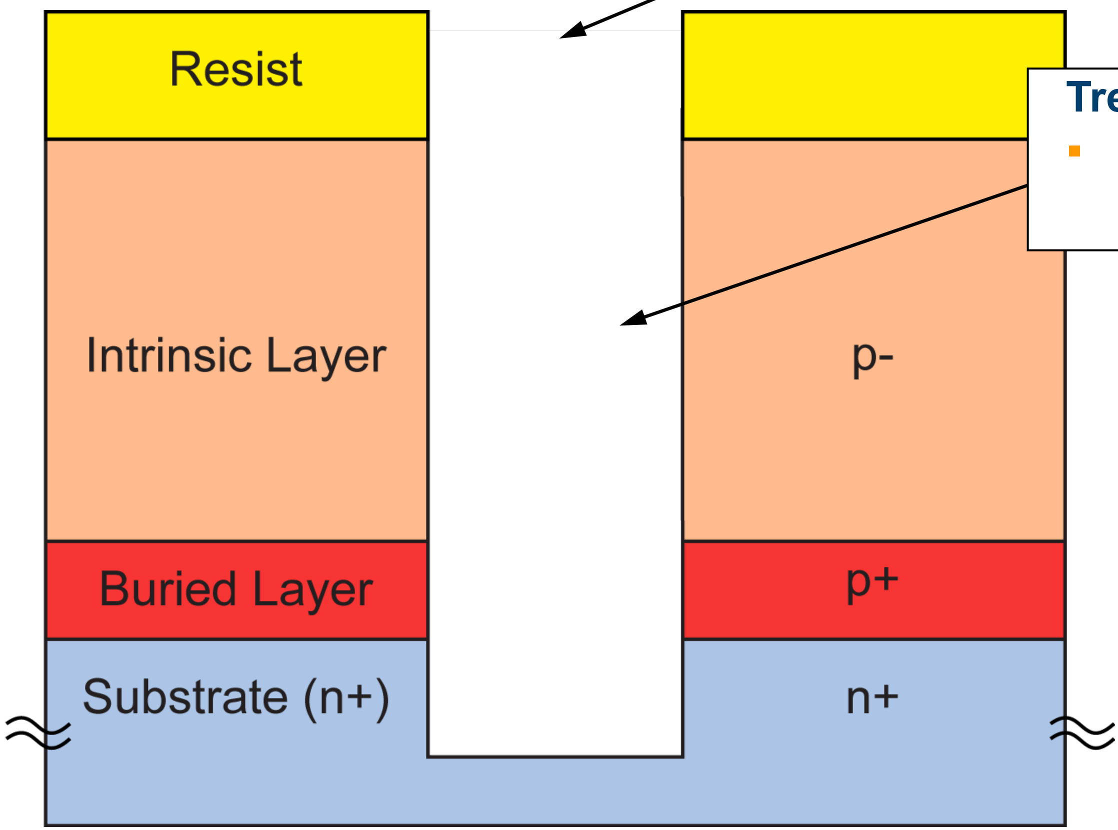
Fabrication: Lithography

Isolation Region

- Defined by lithography



Fabrication: Trench Etch



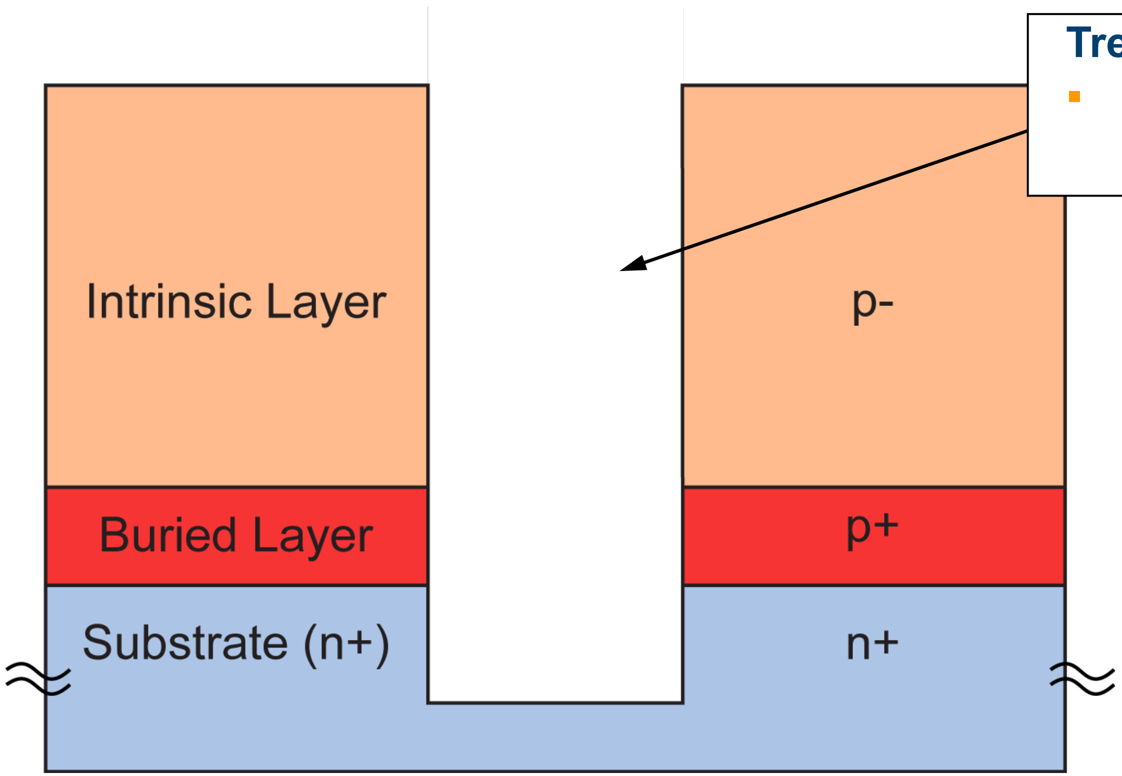
Isolation Region

- Defined by lithography

Trench Etch

- Strongly anisotropic etching process (e.g. DRIE)

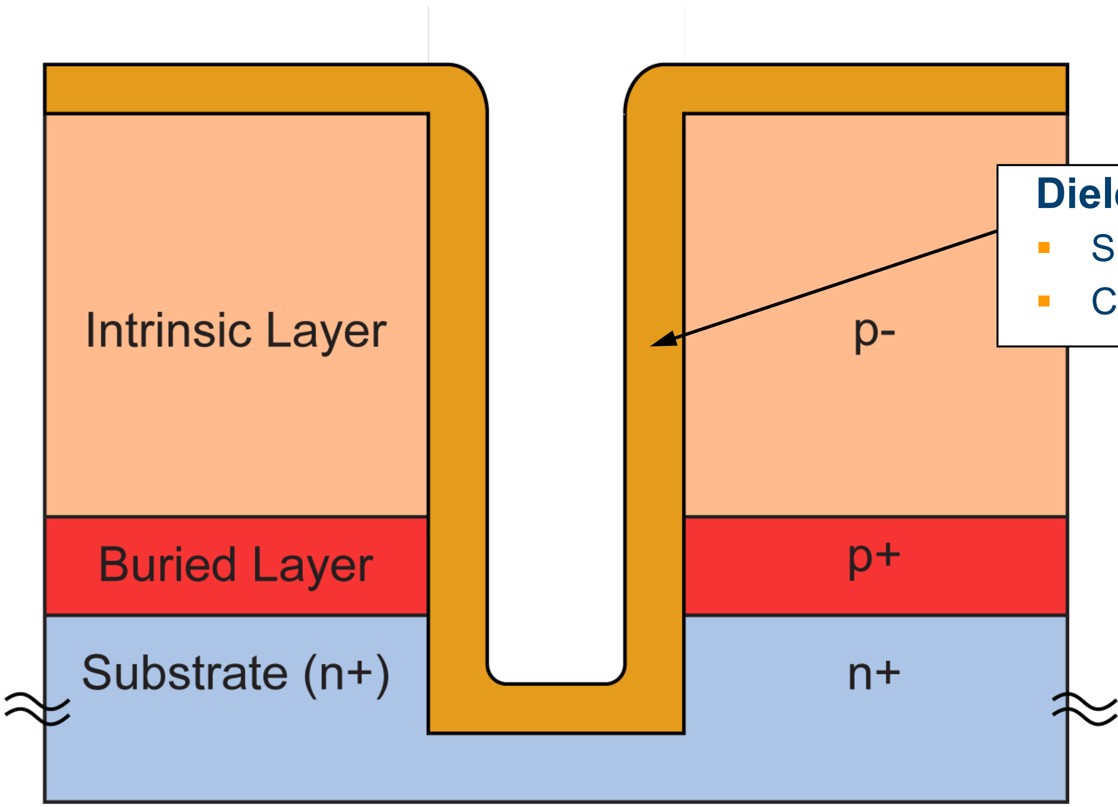
Fabrication: Resist Removal



Trench Etch

- Strongly anisotropic etching process (e.g. DRIE)

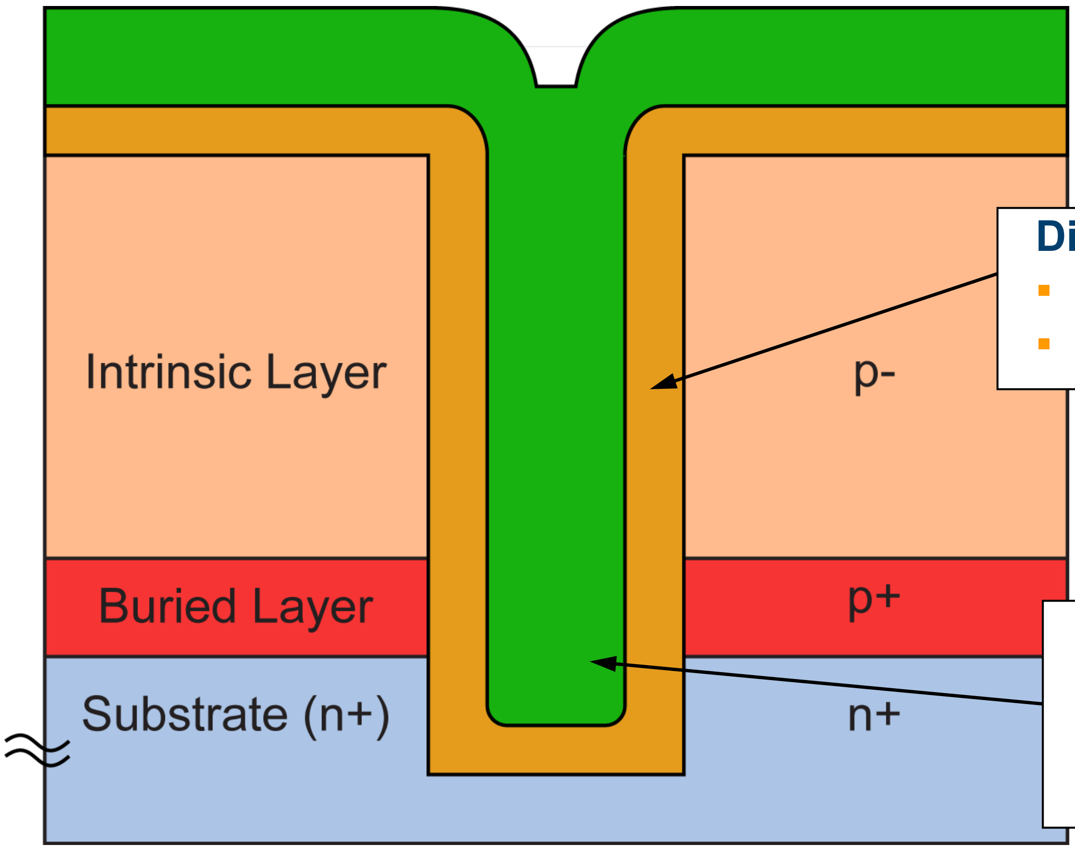
Fabrication: Oxide Deposition



Dielectric Layer

- Silicon dioxide
- Cannot completely fill the trench

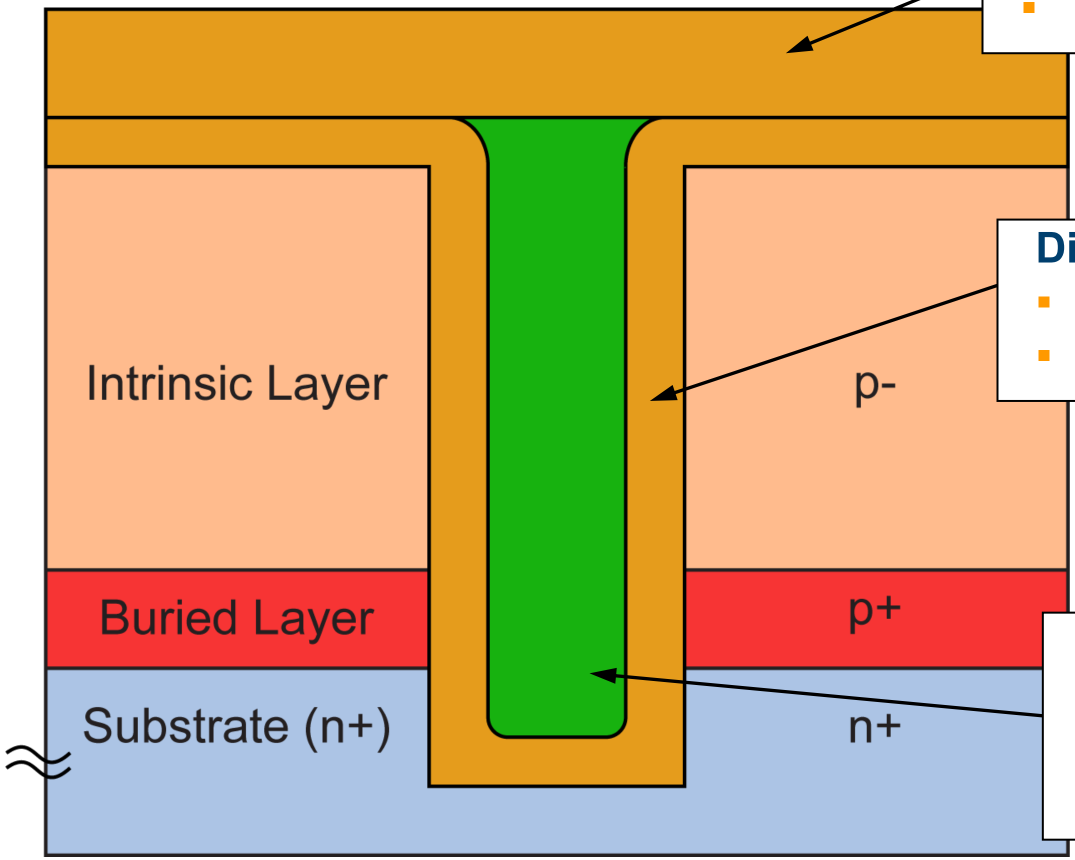
Fabrication: Polysilicon Deposition



Dielectric Layer
- Silicon dioxide
- Cannot completely fill the trench

Refill Layer
- Polysilicon
- Prevents voids
- Reduced stress

Fabrication: Planarization and Capping

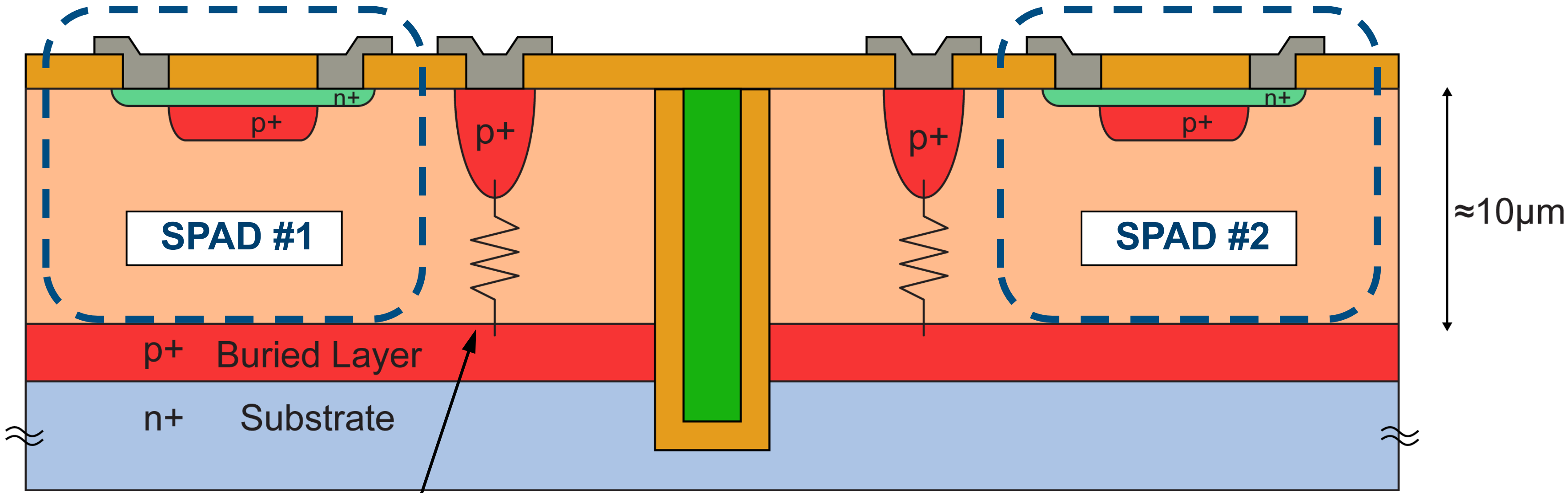


Capping Layer
- Silicon dioxide
- Trench protection from further oxidation

Dielectric Layer
- Silicon dioxide
- Cannot completely fill the trench

Refill Layer
- Polysilicon
- Prevents voids
- Reduced stress

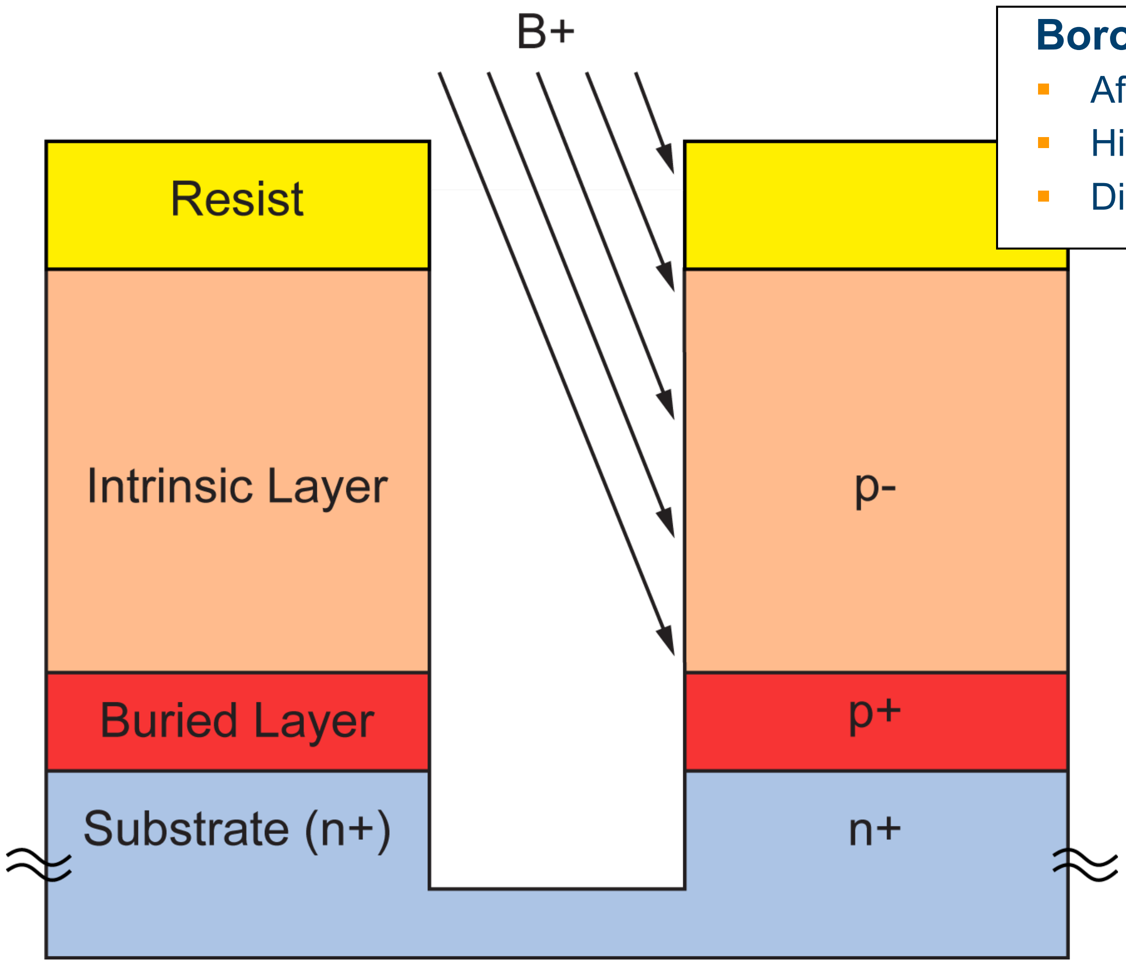
Unaddressed Problem



The Sinker does not reach the Substrate

- High series resistance
- Influences avalanche current reading
- Negative impact on timing

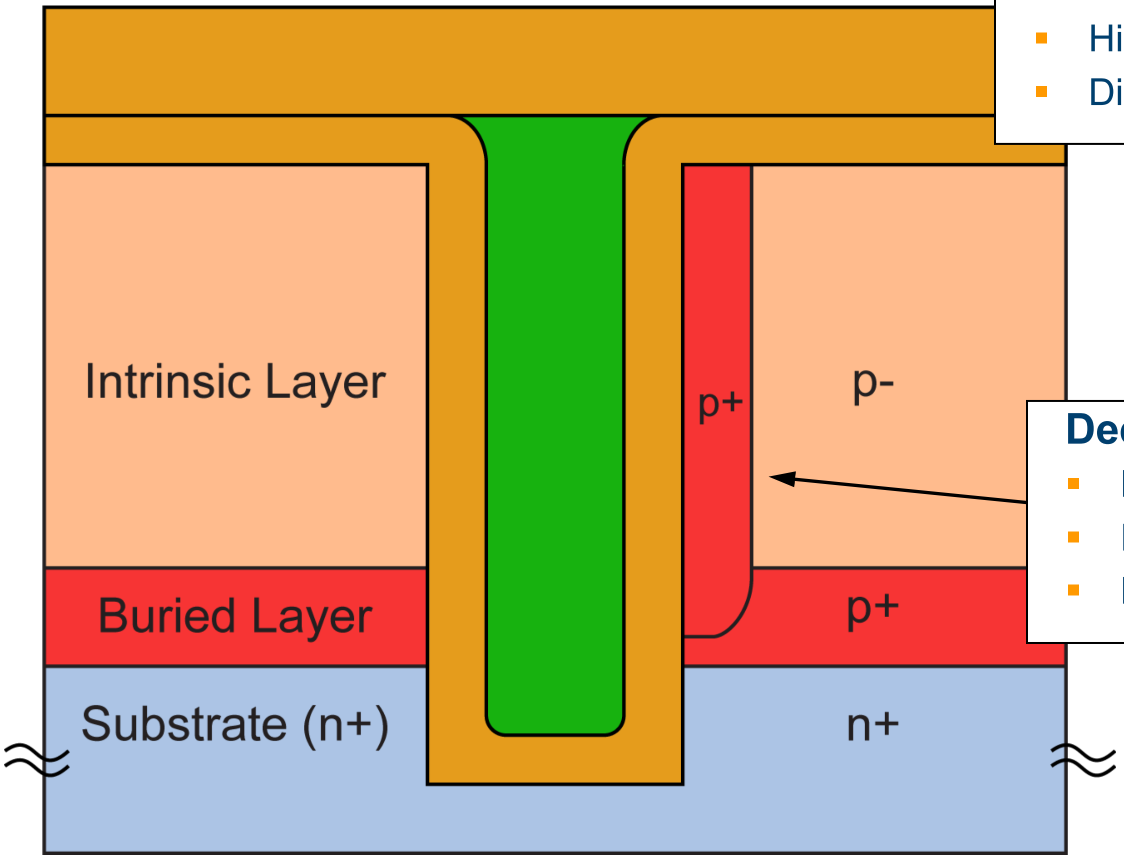
Modified Process Flow



Boron Implantation

- After trench etch
- High dose
- Diffused in following steps

Modified Process Flow



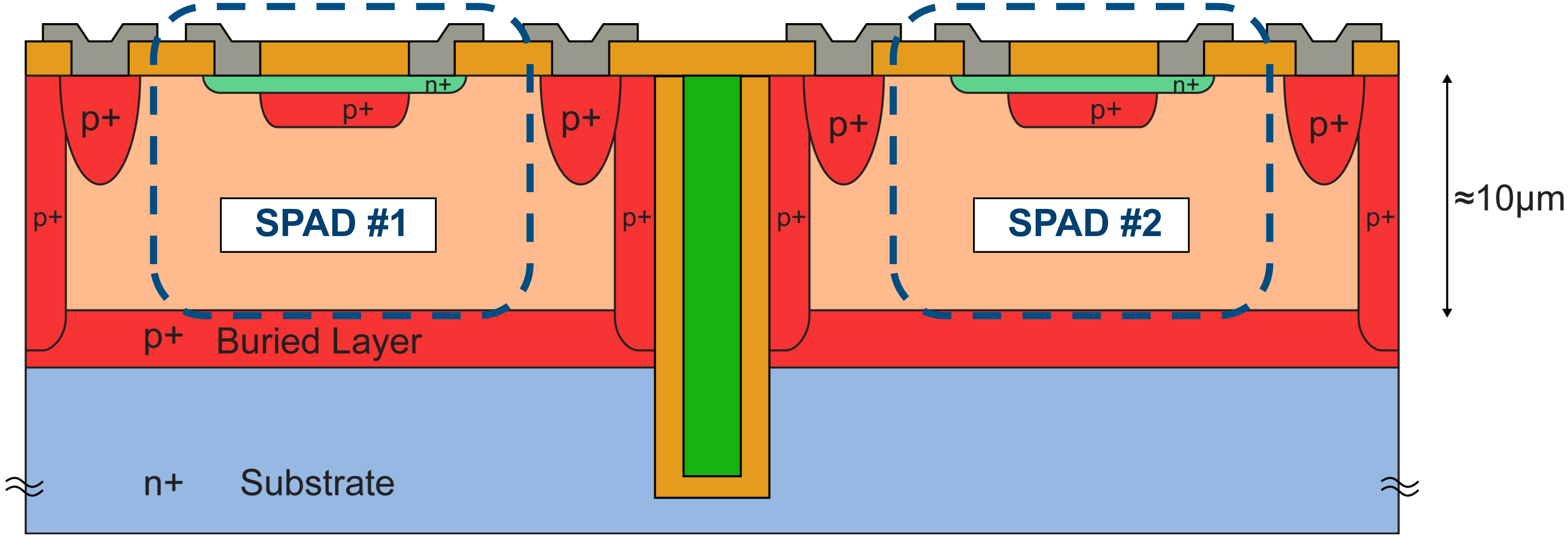
Boron Implantation

- After trench etch
- High dose
- Diffused in following steps

Deep Sinker

- Low resistivity
- Reaches the buried layer
- **No additional thermal budget**

Final Structure



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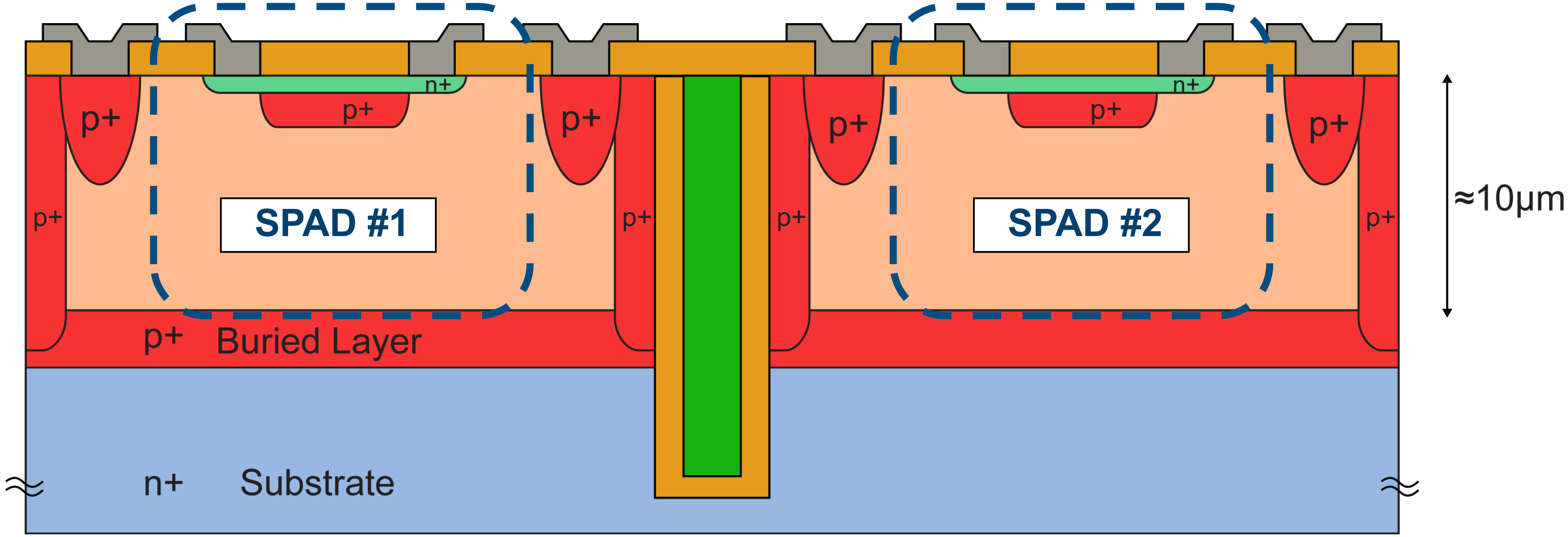
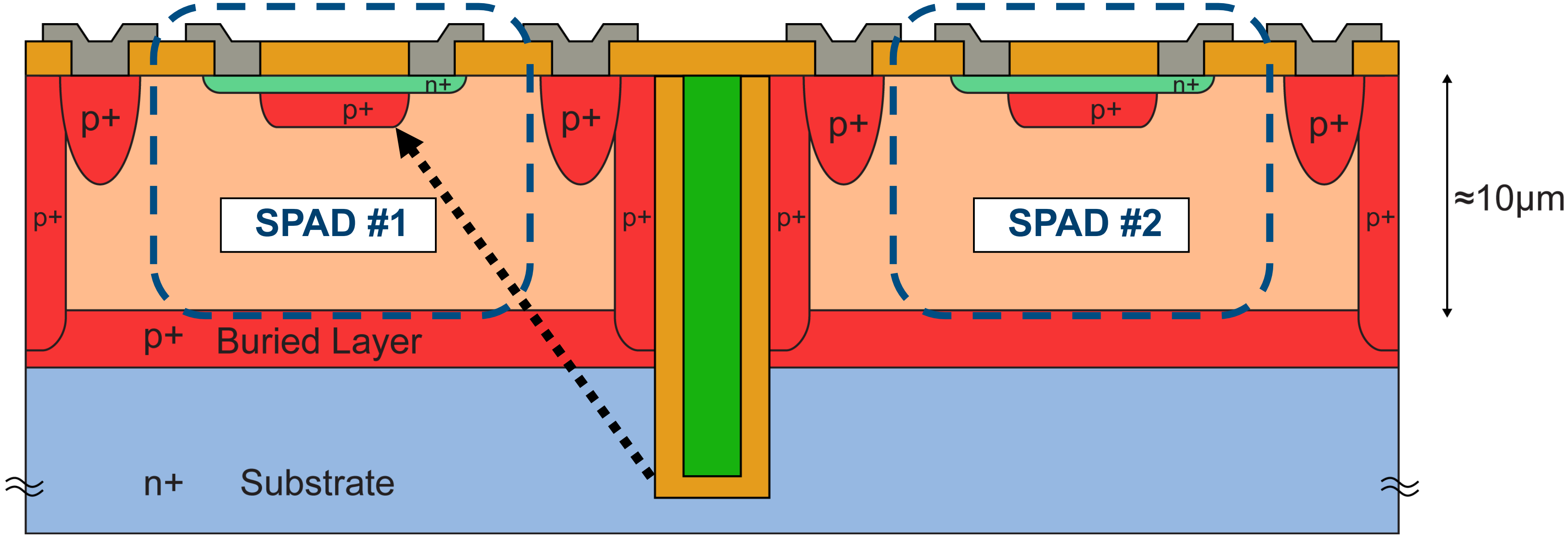


Additional advantage

- **Compactness** (3μm-wide) ➔ Denser arrays

Final Structure



Additional advantage

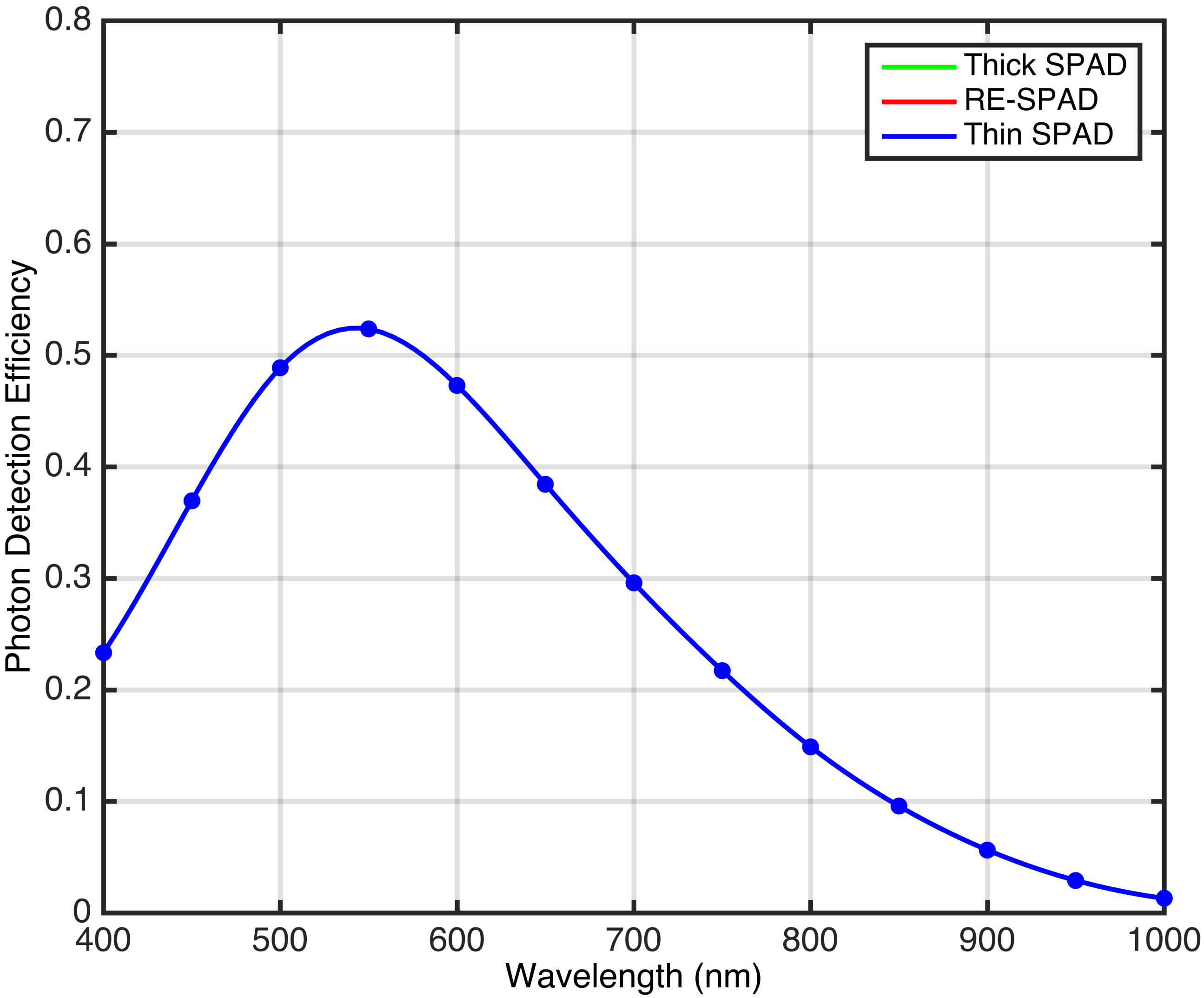
- **Compactness** (3µm-wide) ➔ Denser arrays

Potential problem

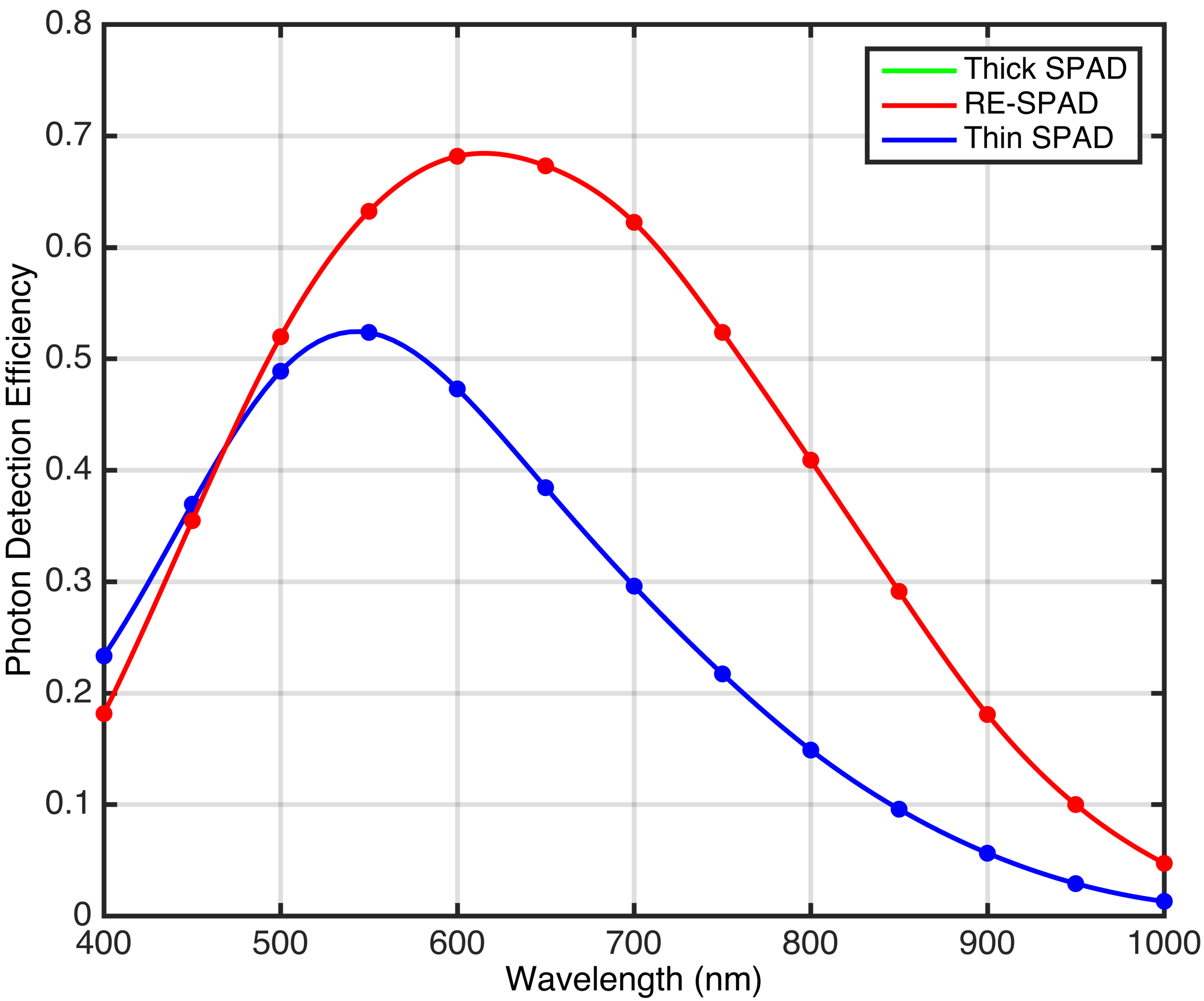
- **Stress** introduced during fabrication ➔ May increase Dark Count Rate

EXPERIMENTAL RESULTS

Photon Detection Efficiency



Photon Detection Efficiency



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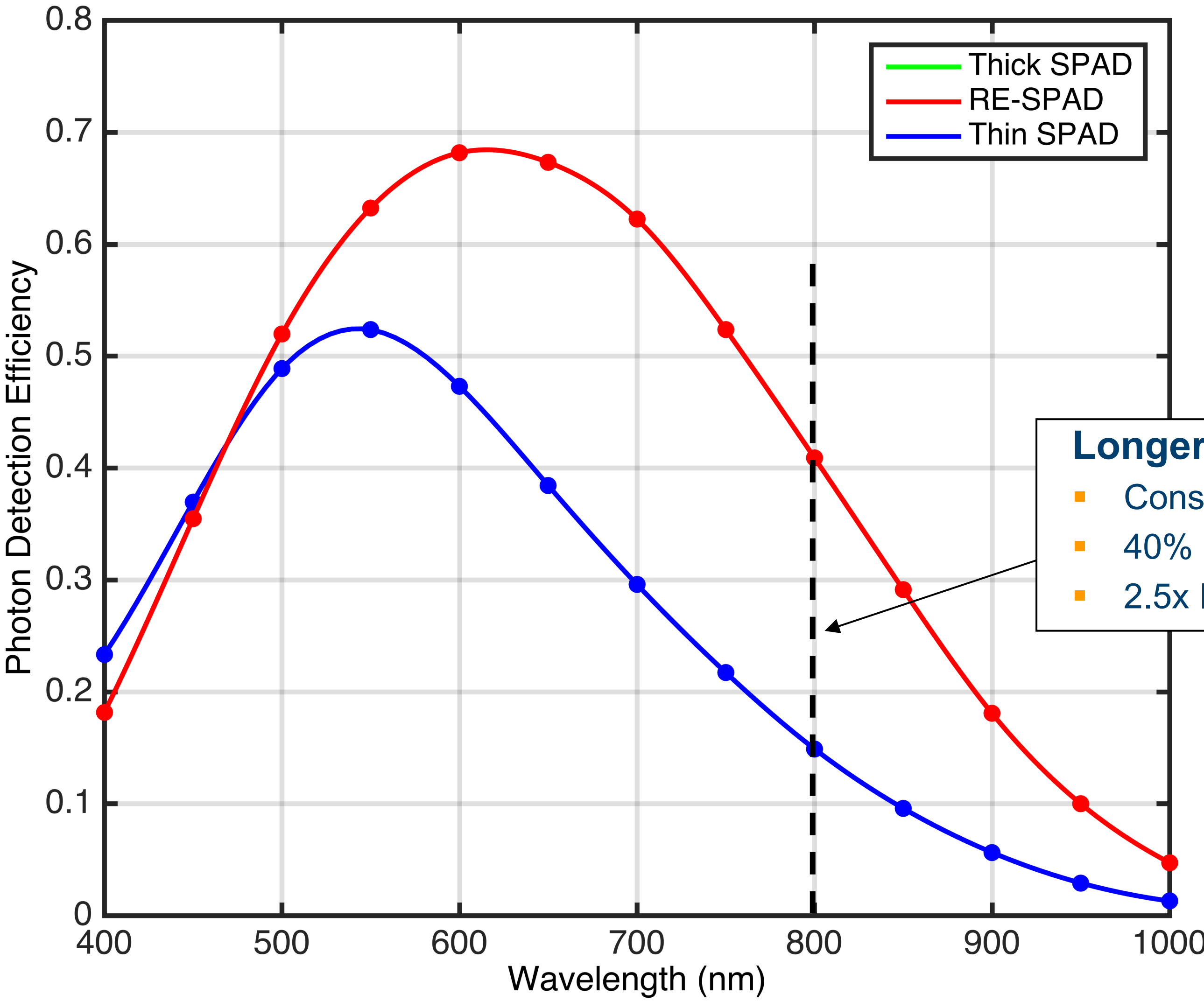
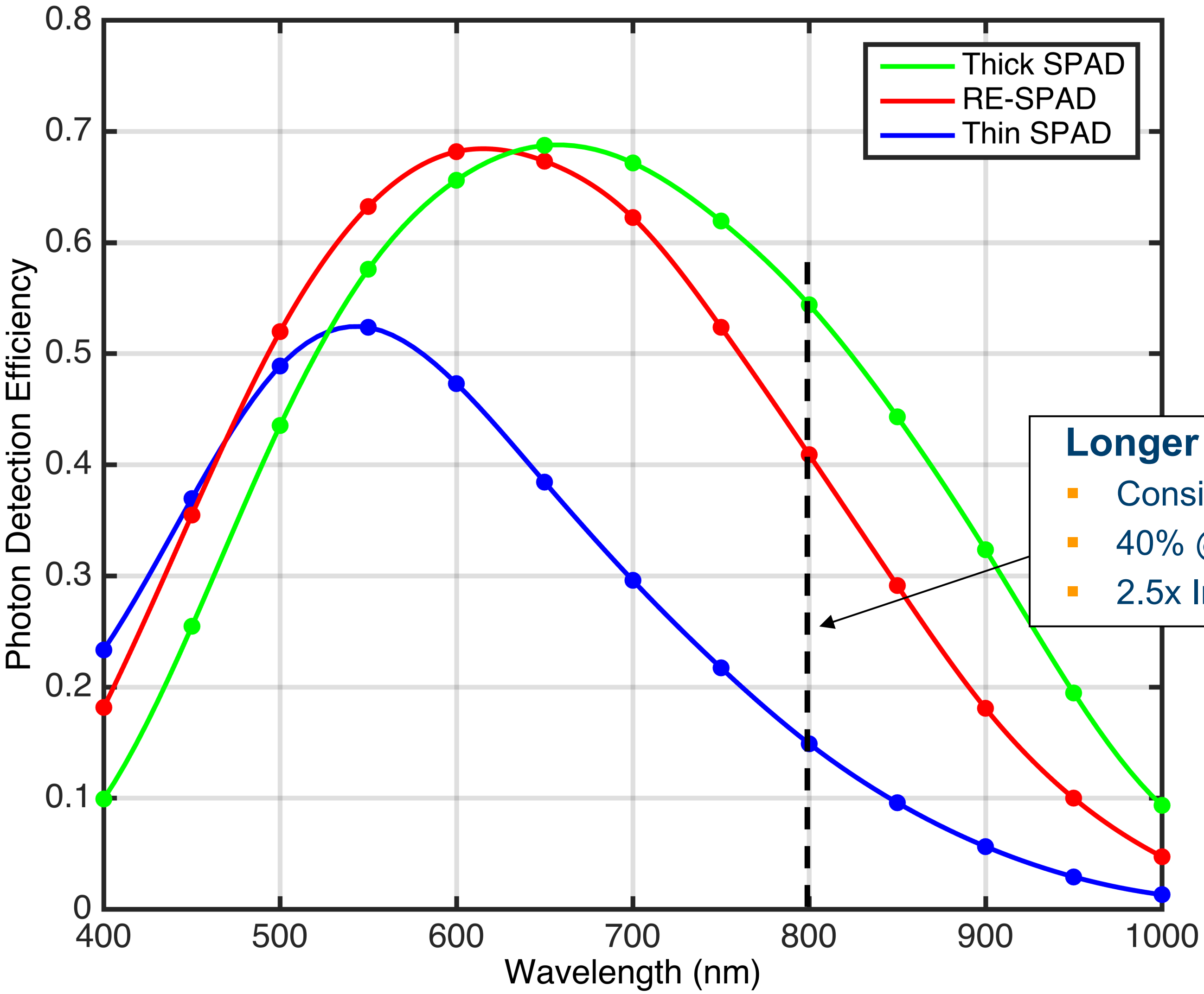


Longer Wavelengths

- Considerable improvement
- 40% @800nm
- 2.5x Improvement @800nm

Photon Detection Efficiency



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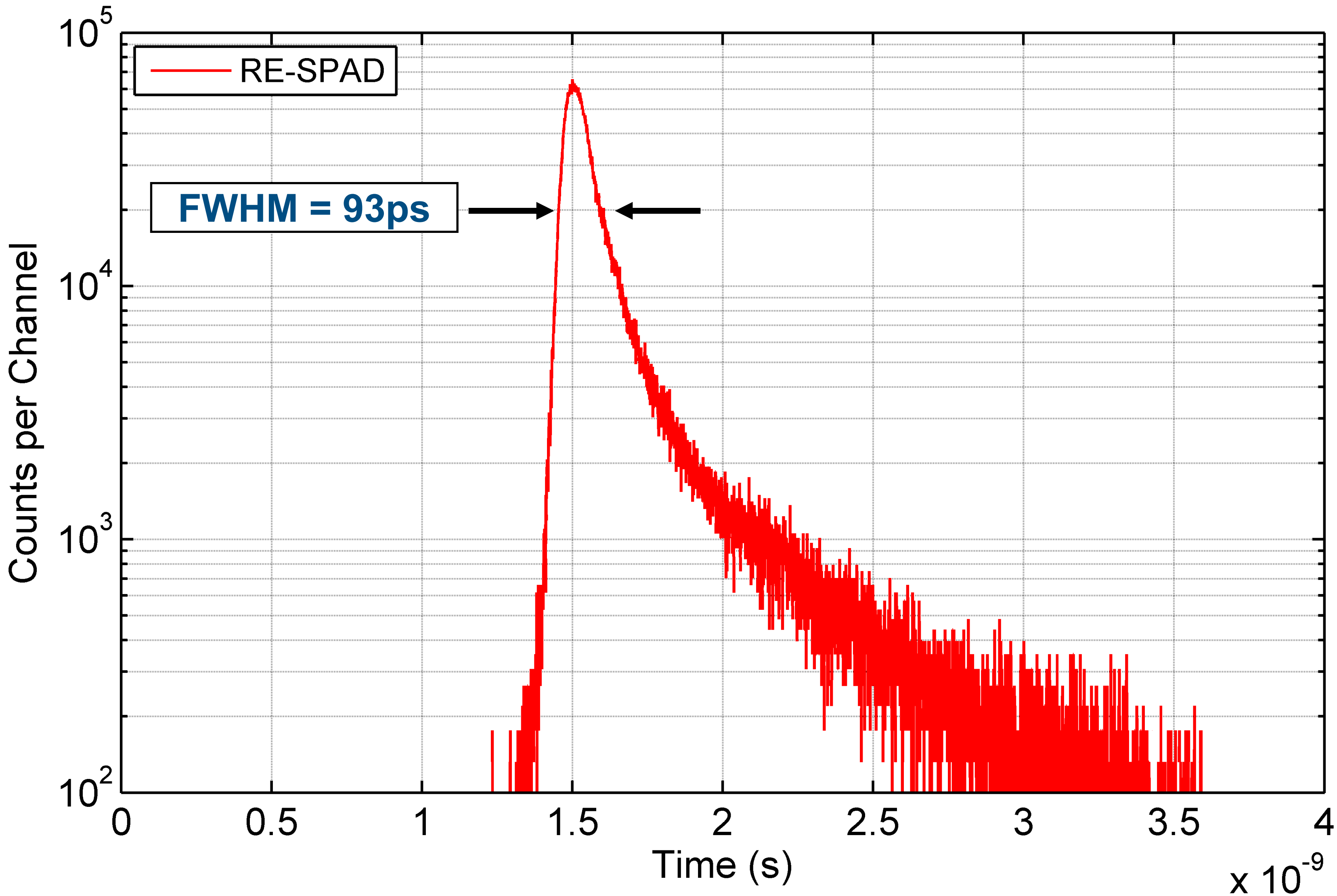
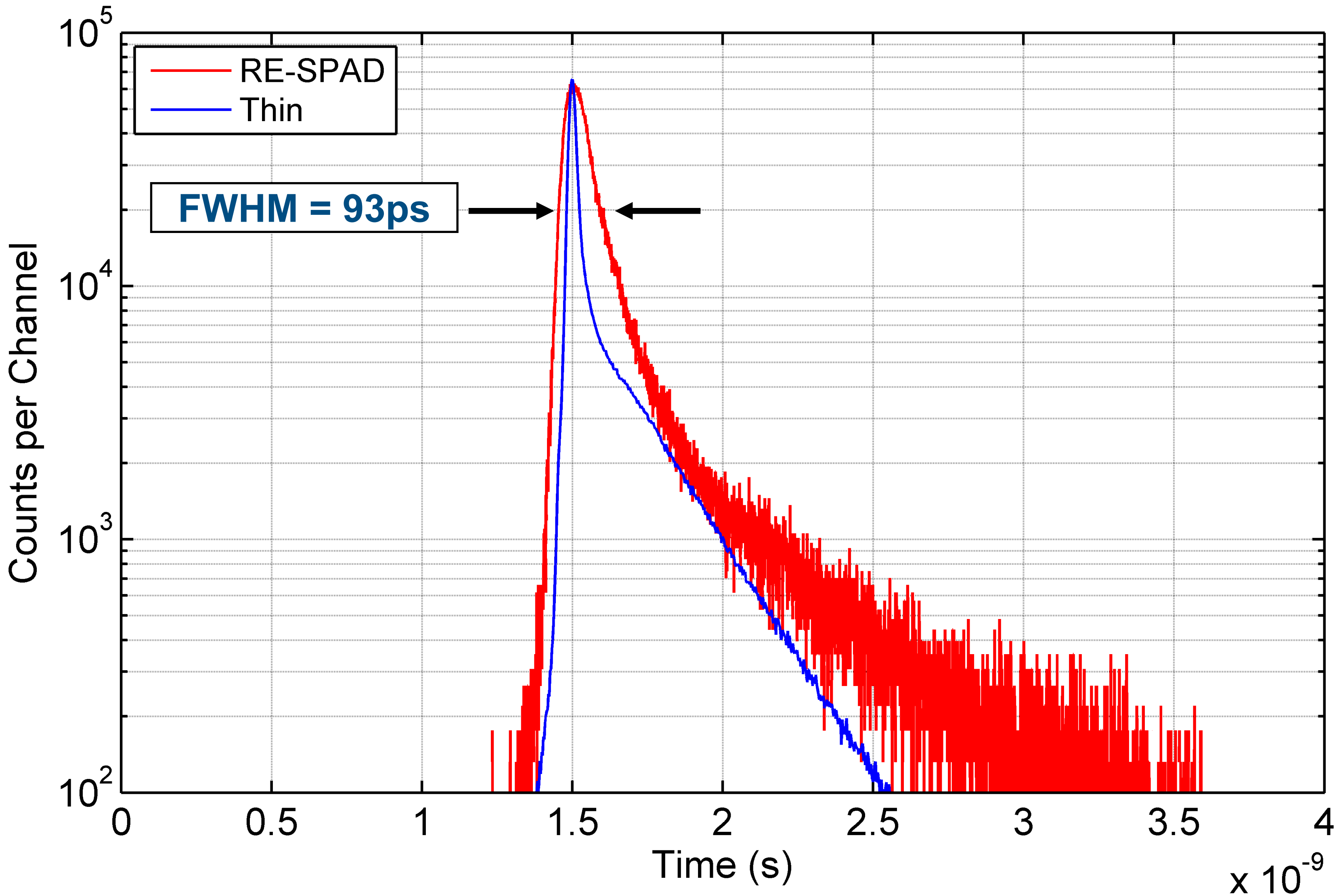
Temporal Response

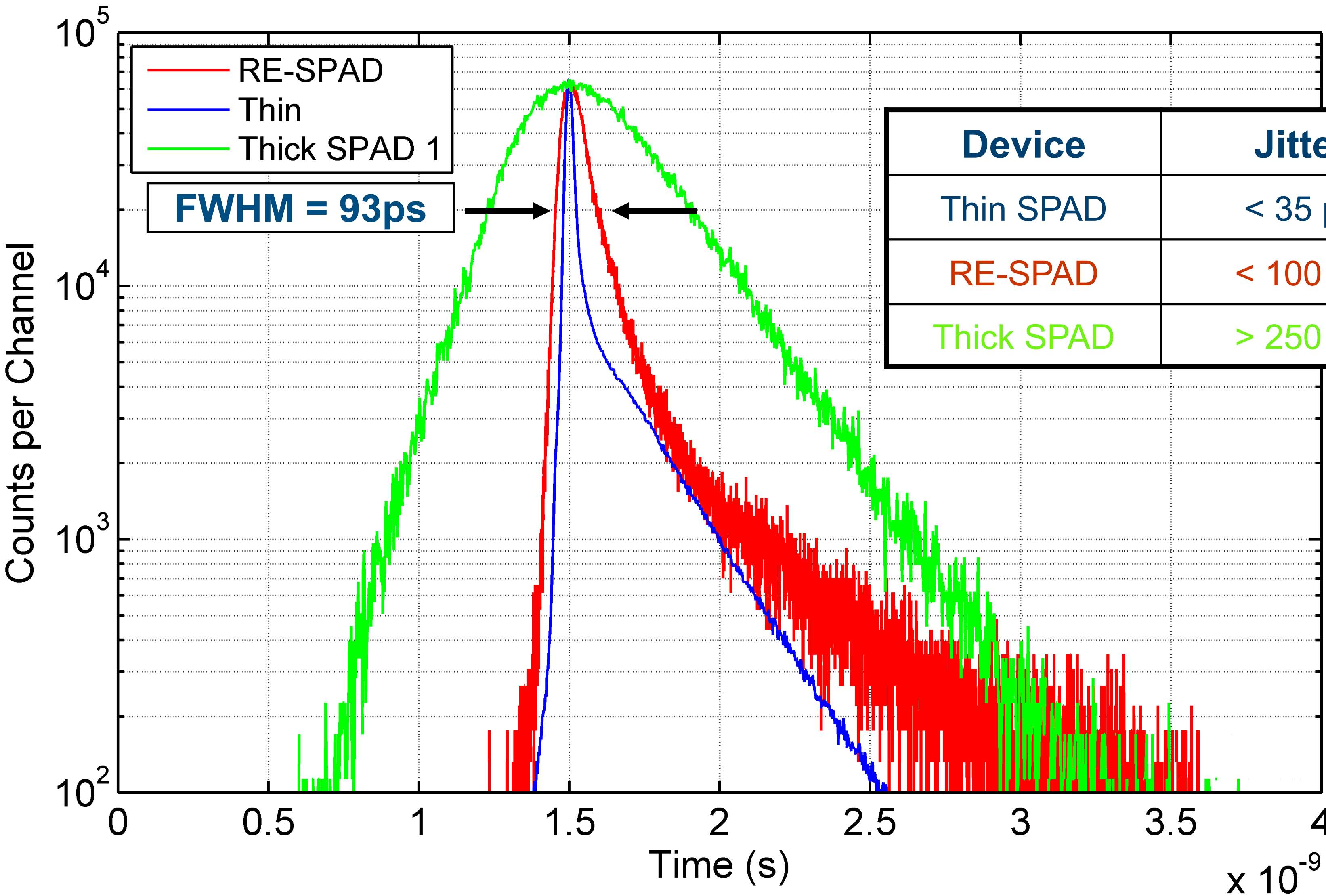


Gulinatti et al, J Mod Optic **59**(17), (2012), doi:10.1080/09500340.2012.701340



Gulinatti et al, J Mod Optic **59**(17), (2012), doi:10.1080/09500340.2012.701340

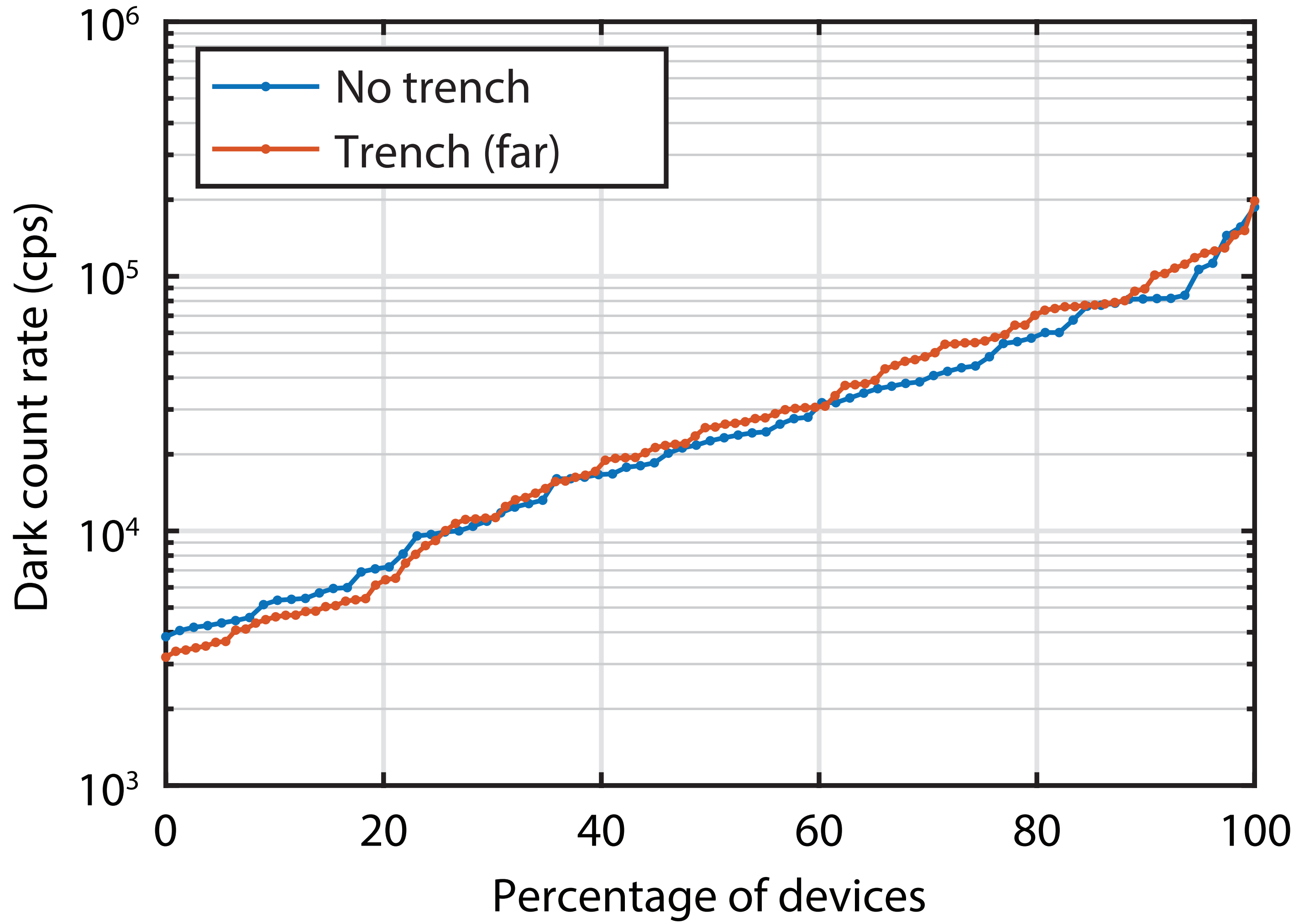
Temporal Response



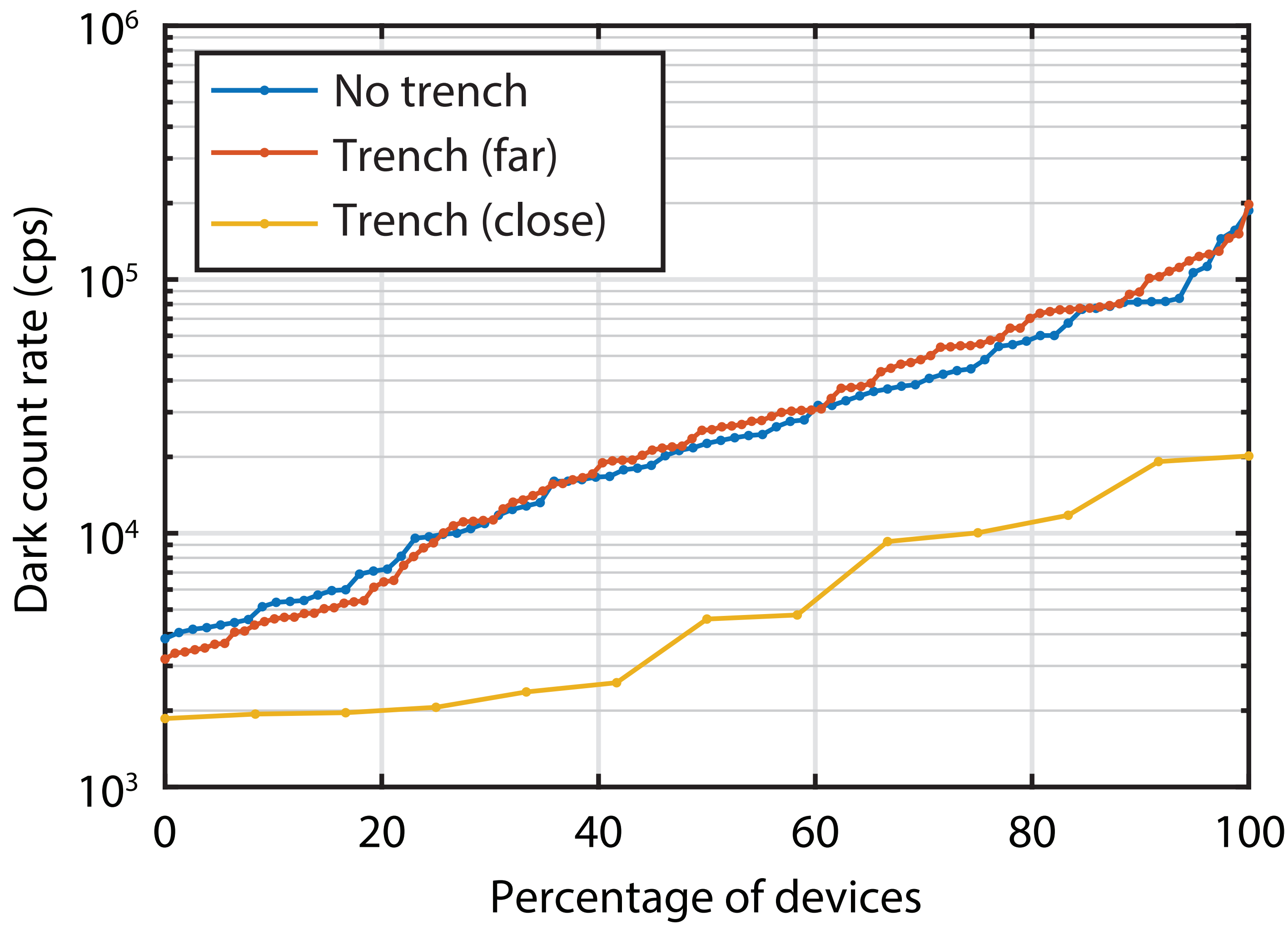
Device	Jitter
Thin SPAD	< 35 ps
RE-SPAD	< 100 ps
Thick SPAD	> 250 ps

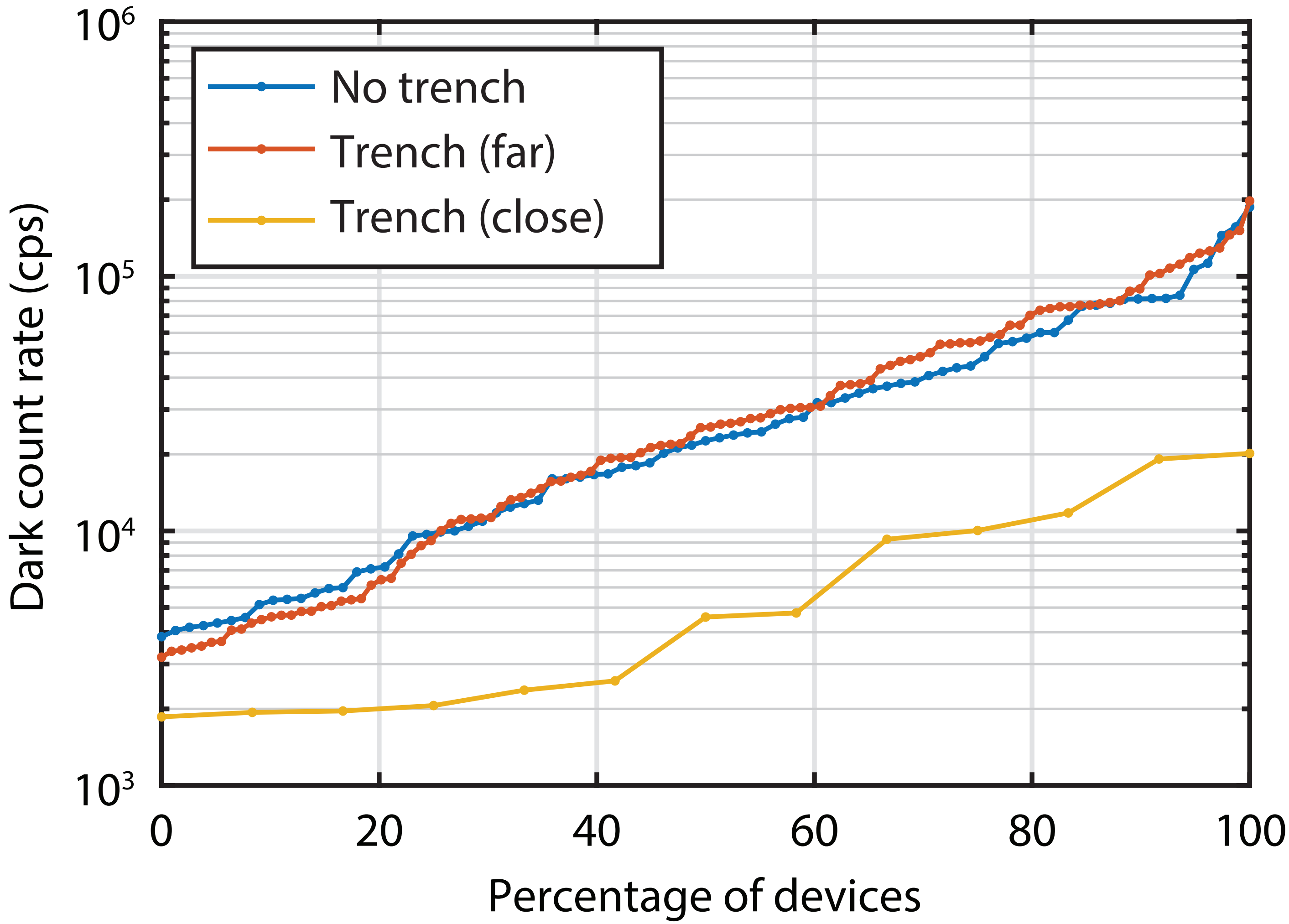
Gulinatti et al, J Mod Optic **59**(17), (2012), doi:10.1080/09500340.2012.701340

Dark Count Rate



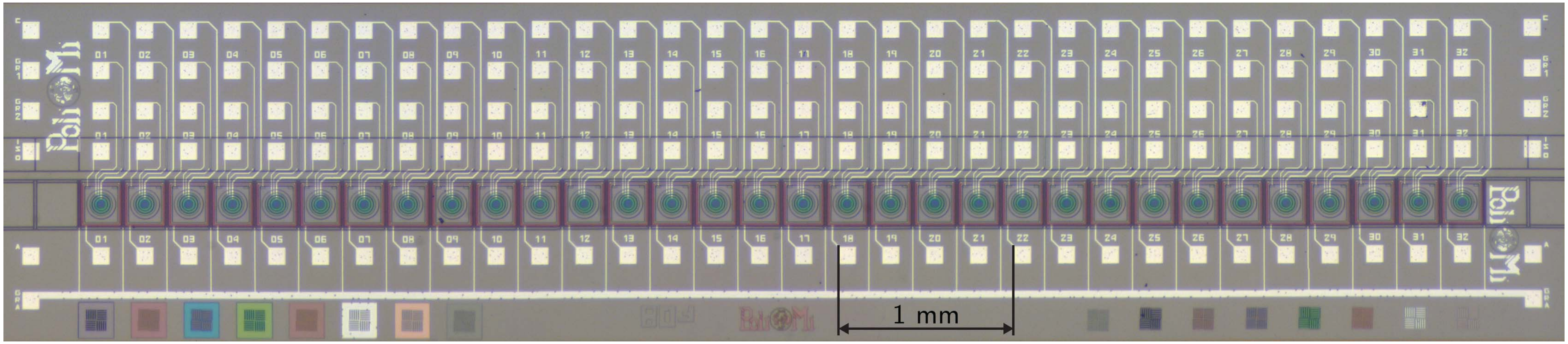
Dark Count Rate





Deep trenches have no effect on the Dark Count Rate

RE-SPAD Arrays



Designed for **NIH funded** project:

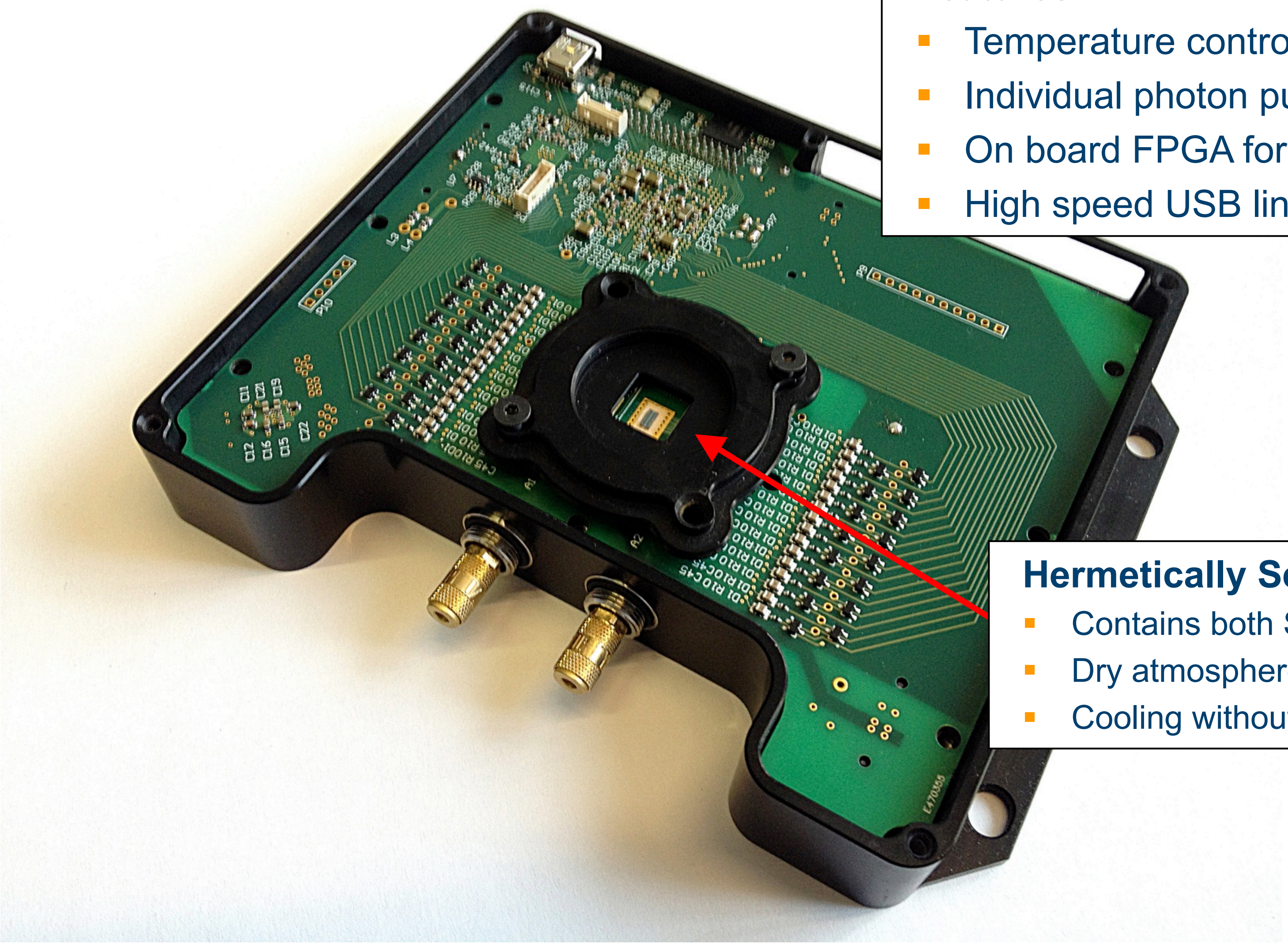
- Weiss / Michalet group at UCLA
- High-throughput Single Molecule Analysis

Array geometry:

- **32 x 1 pixels**
- Active diameter: 50 µm
- Pitch: 250 µm

Ceccarelli et al, IEEE PTL **30**(6), 557-560, (2018), doi:10.1109/LPT.2018.2804909

Compact Photon Counting Modules



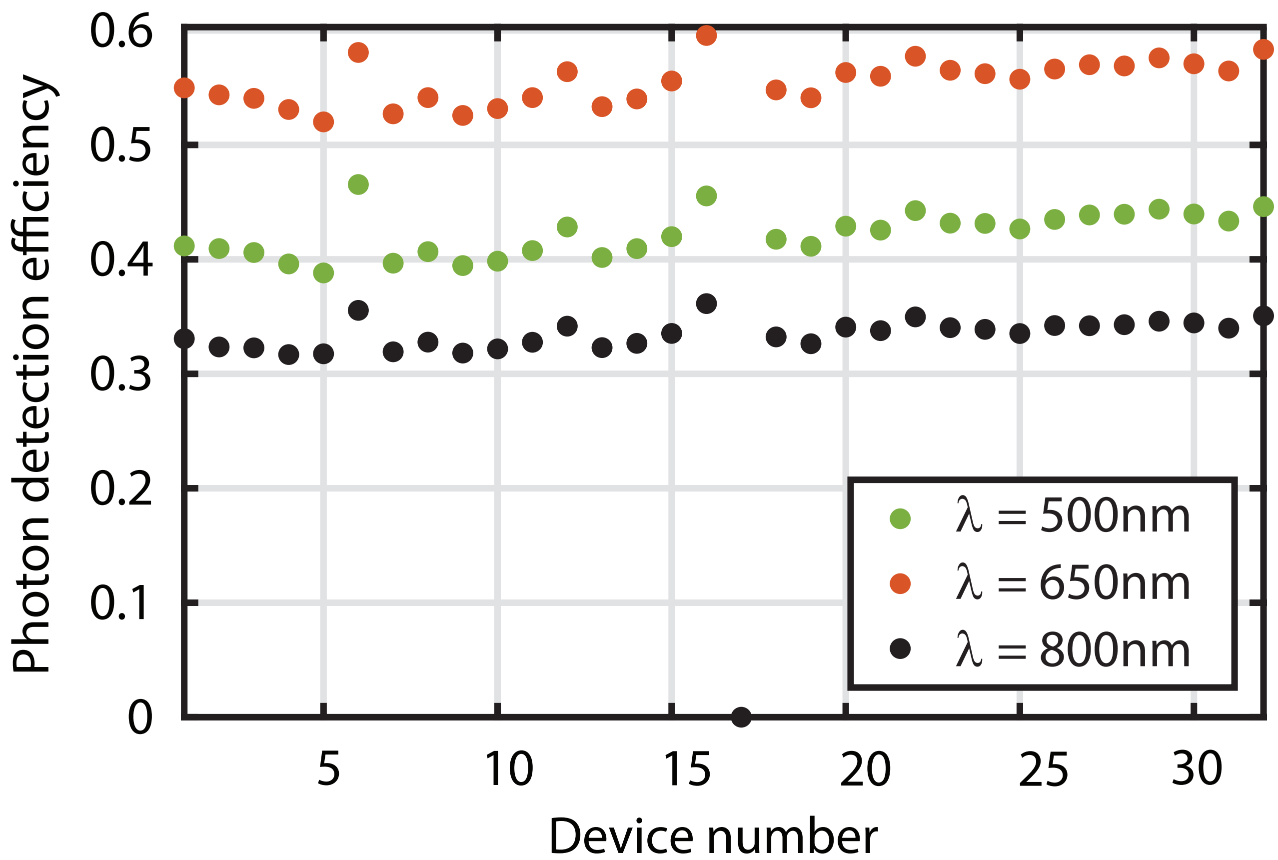
Features

- Temperature control
- Individual photon pulses available
- On board FPGA for basic processing
- High speed USB link

Hermetically Sealed Chamber

- Contains both SPADs and AQCs
- Dry atmosphere
- Cooling without moisture issues

Photon Detection Efficiency



- Confirmed high Photon Detection Efficiency
- **Good uniformity** across the arrays

NEXT DEVELOPMENTS

Scaling Down the Pixel

POLITECNICO MILANO 1863 · UCLA · University of Zurich UZH · UNIVERSITY of WASHINGTON

Aim: 3D atomic-scale movies of molecular machine in action

Funding: Human Frontier Science Program (HFSP)

Scaling Down the Pixel

POLITECNICO MILANO 1863

UCLA

University of Zurich UZH

UNIVERSITY of WASHINGTON

Aim: 3D atomic-scale movies of molecular machine in action

Funding: Human Frontier Science Program (HFSP)

Array Geometry

- **128 x 1** pixels
- Active size: 50 µm
- Pitch: **80 µm**

POLITECNICO MILANO 1863

UCLA

University of Zurich UZH

UNIVERSITY of WASHINGTON

Aim: 3D atomic-scale movies of molecular machine in action

Funding: Human Frontier Science Program (HFSP)

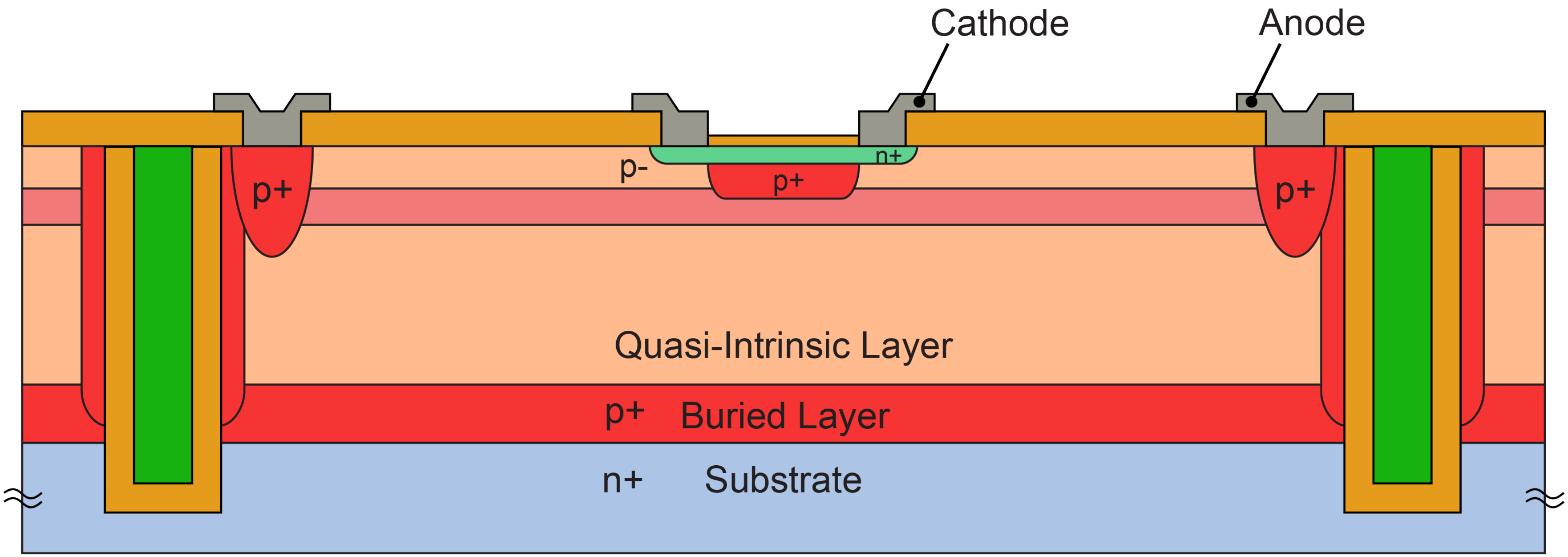
Array Geometry

- **128 x 1** pixels
- Active size: 50 µm
- Pitch: **80 µm**

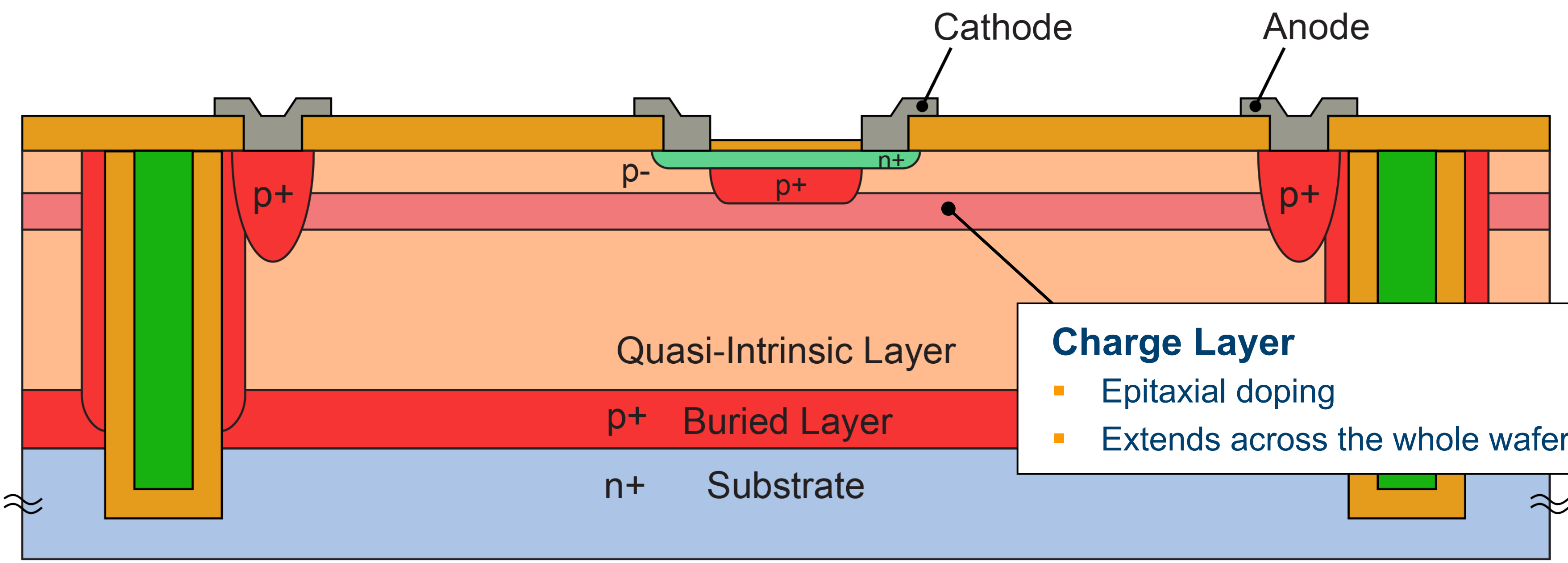
Questions

- How close we can get?
- What does limit the compactness?

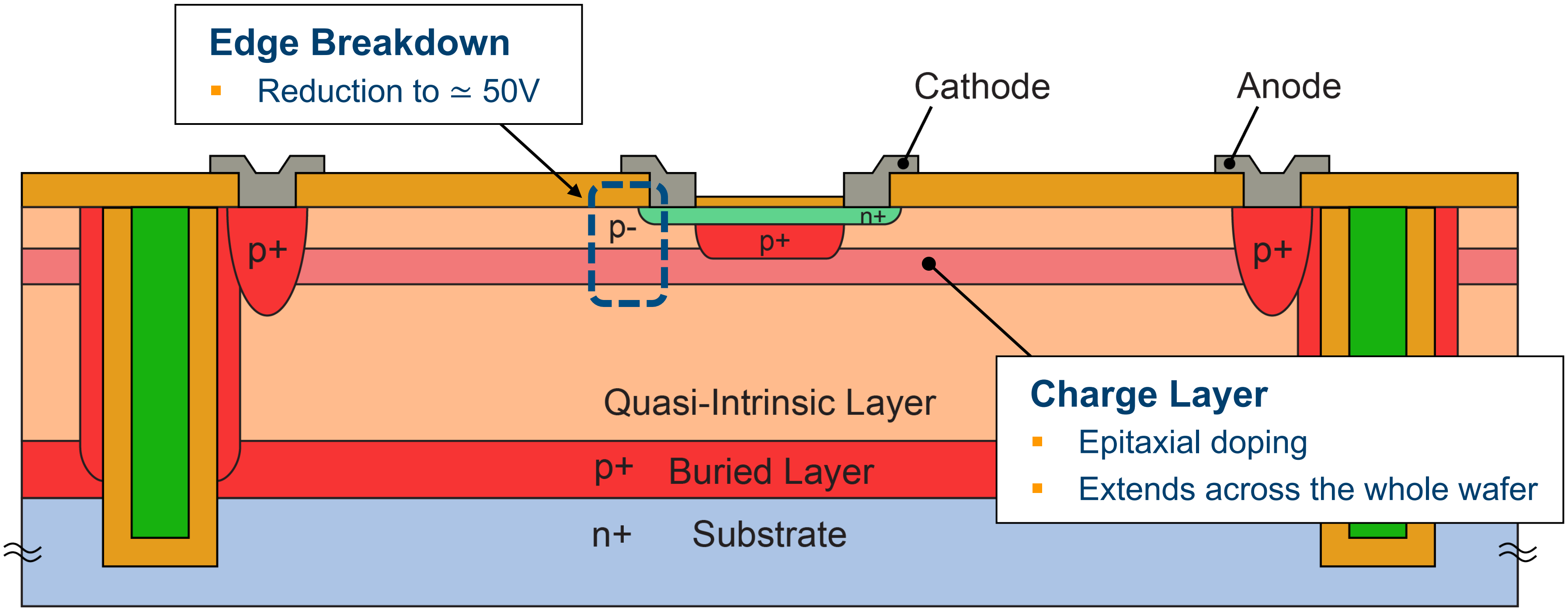
Epitaxial Charge Layer



Epitaxial Charge Layer

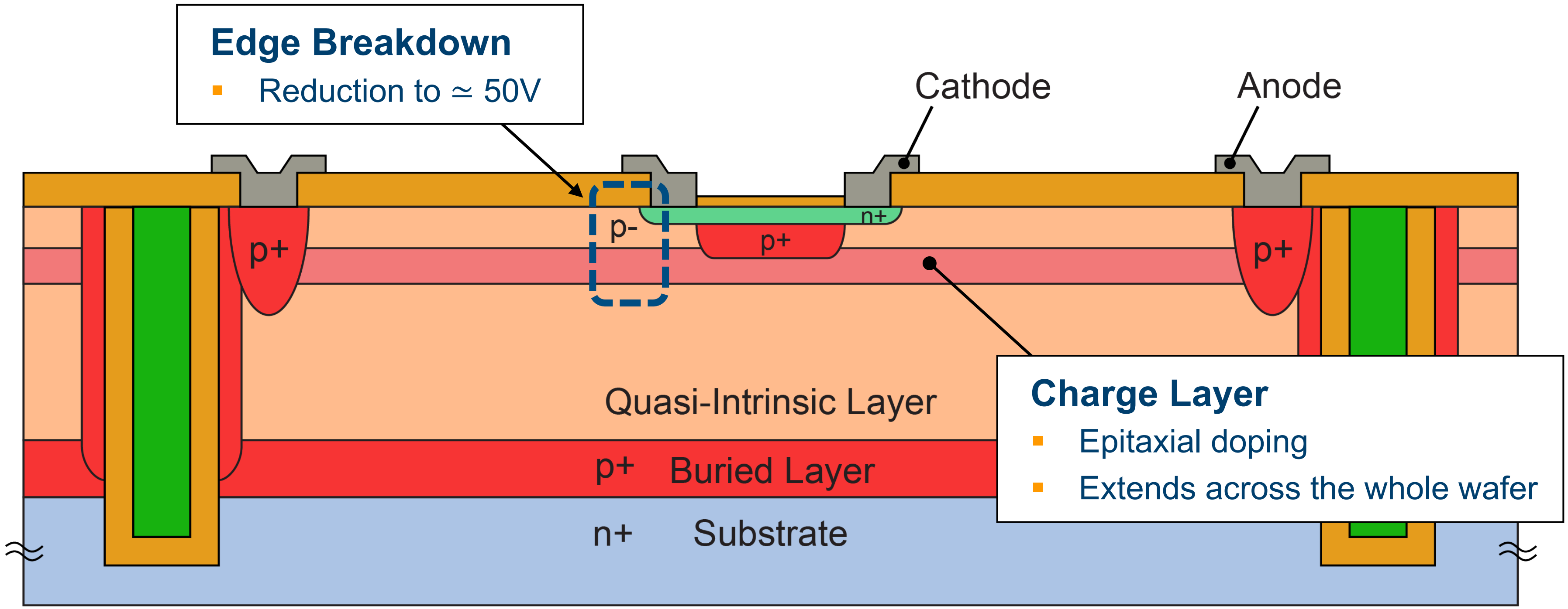


Charge Layer
- Epitaxial doping
- Extends across the whole wafer



Edge Breakdown
Reduction to ≃ 50V
Cathode
Anode
p-
n+
p+
p+
p+
Quasi-Intrinsic Layer
p+ Buried Layer
n+ Substrate
Charge Layer
Epitaxial doping
Extends across the whole wafer

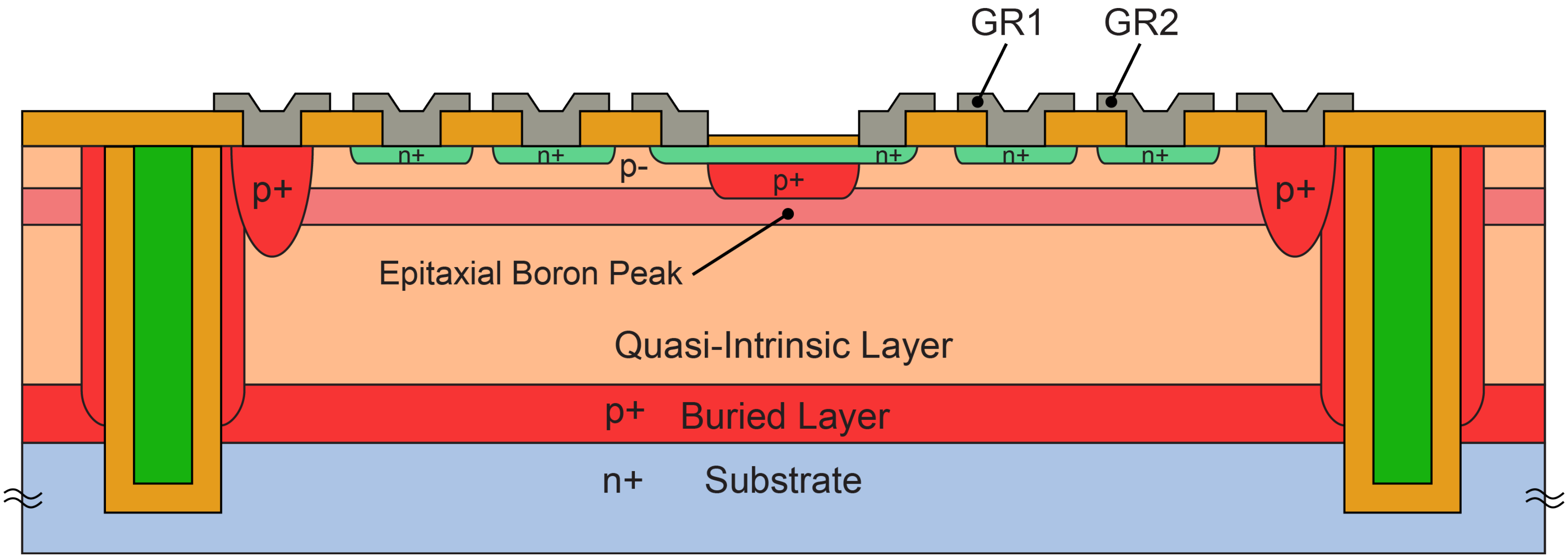
Epitaxial Charge Layer



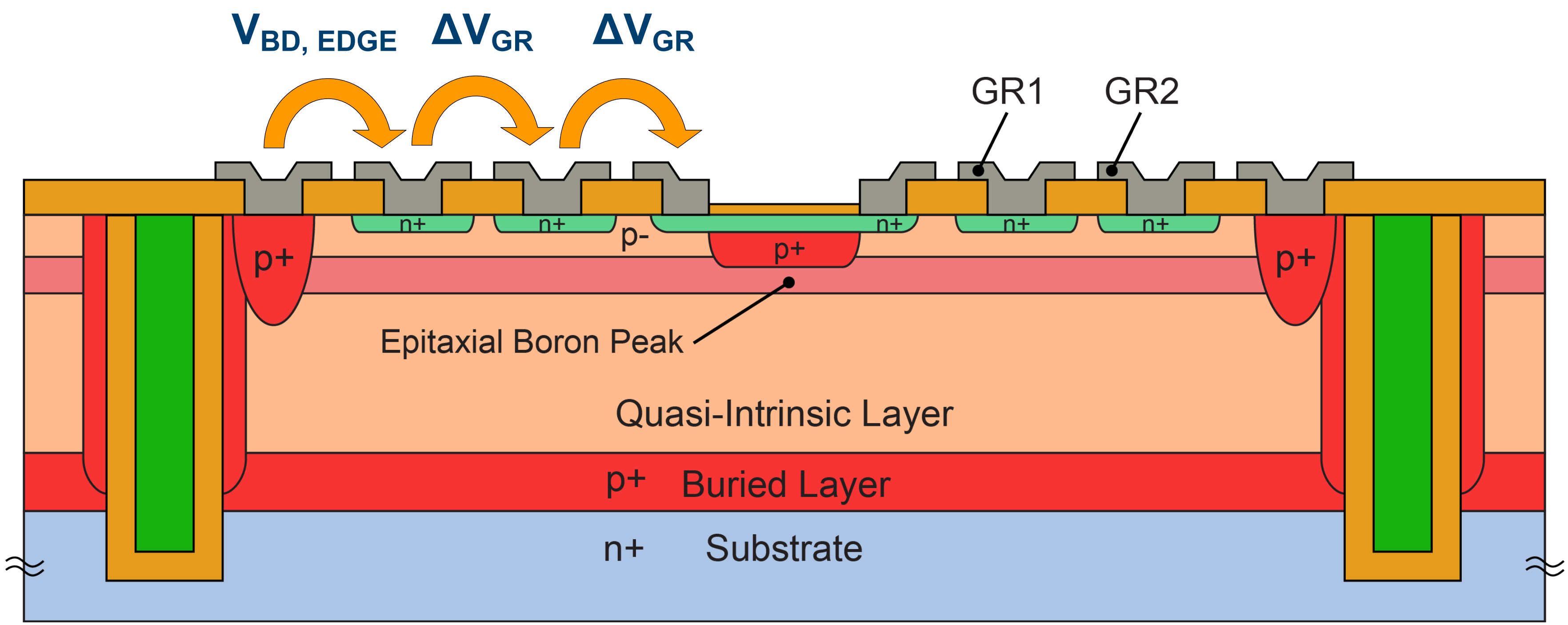
Problems

- Maximum bias voltage < 50V
- Strong limitation for biasing with Vov ≈ 20V

Guard Rings

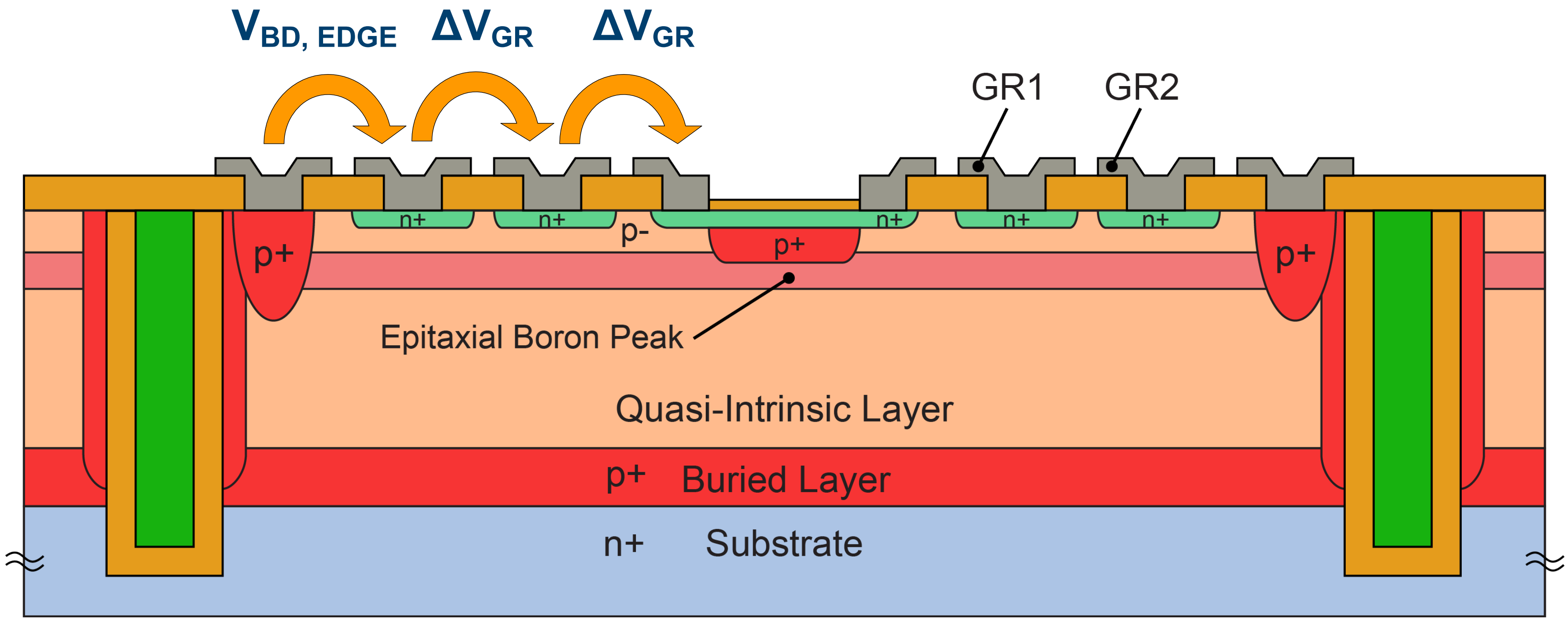

GR1
GR2
n+
n+
p-
n+
n+
n+
p+
p+
p+
Epitaxial Boron Peak
Quasi-Intrinsic Layer
p+ Buried Layer
n+ Substrate

Guard Rings



Guard Rings allow Bias Voltage > Edge Breakdown

Guard Rings

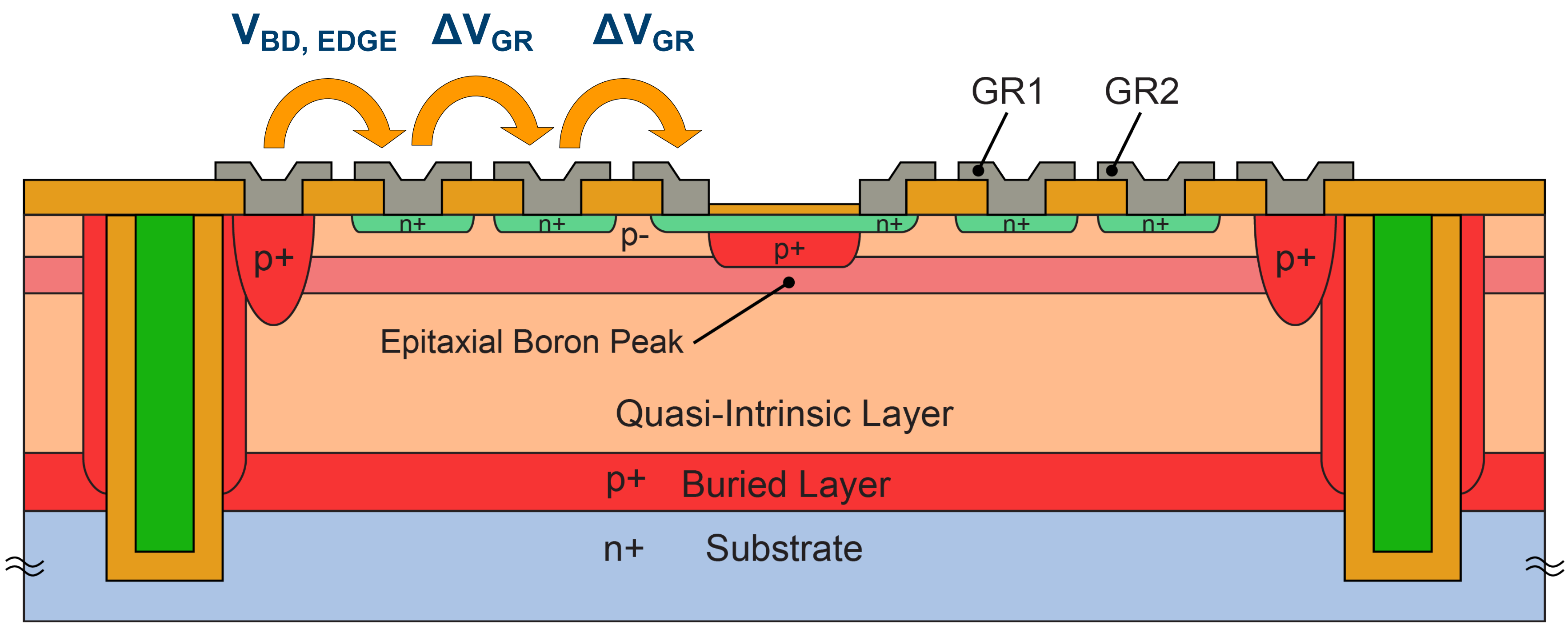


Guard Rings allow Bias Voltage > Edge Breakdown

Problems

- Lack of **Compactness**
- Complexity

Guard Rings



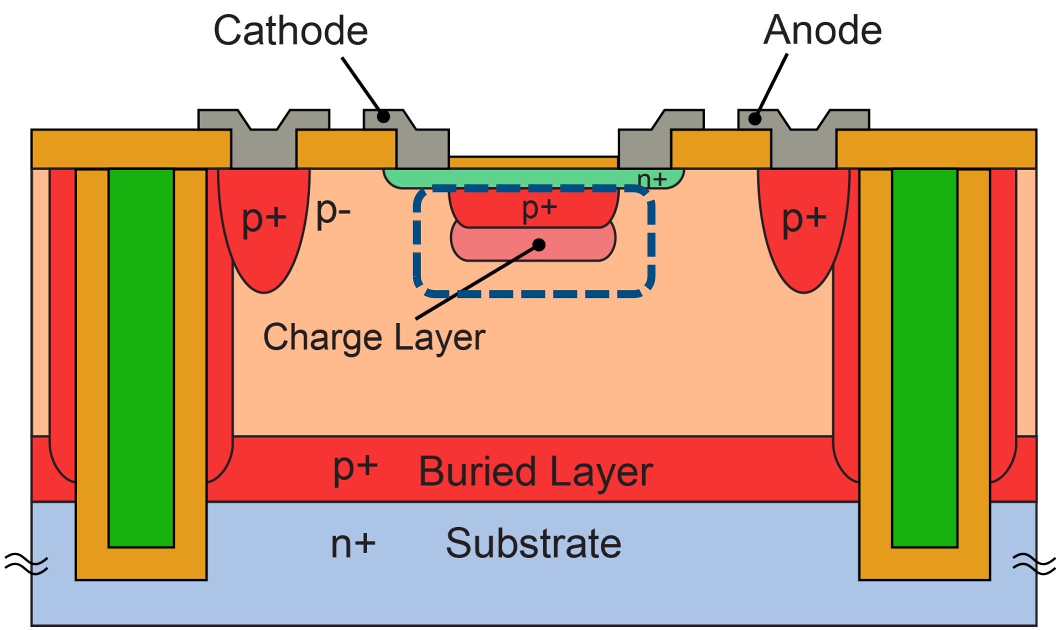
Guard Rings allow Bias Voltage > Edge Breakdown

Problems

- Lack of **Compactness**
- Complexity

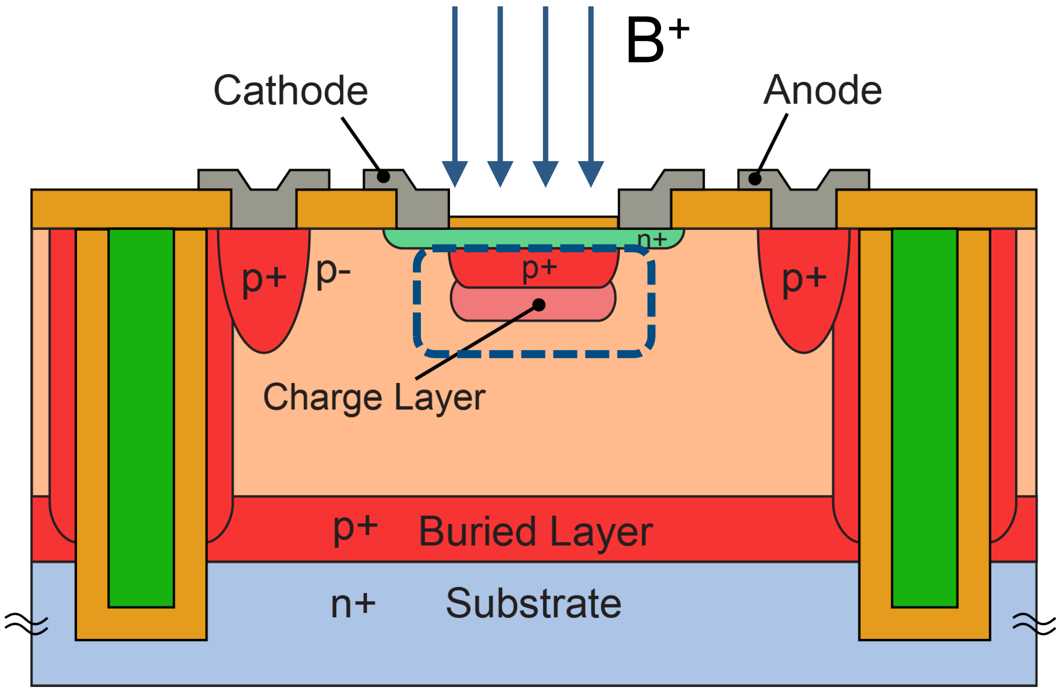
→ **Must be removed**

Implanted Charge Layer



Solution

- Confine the charge layer to the active area
- Fabrication by **high energy** ion **implantation**

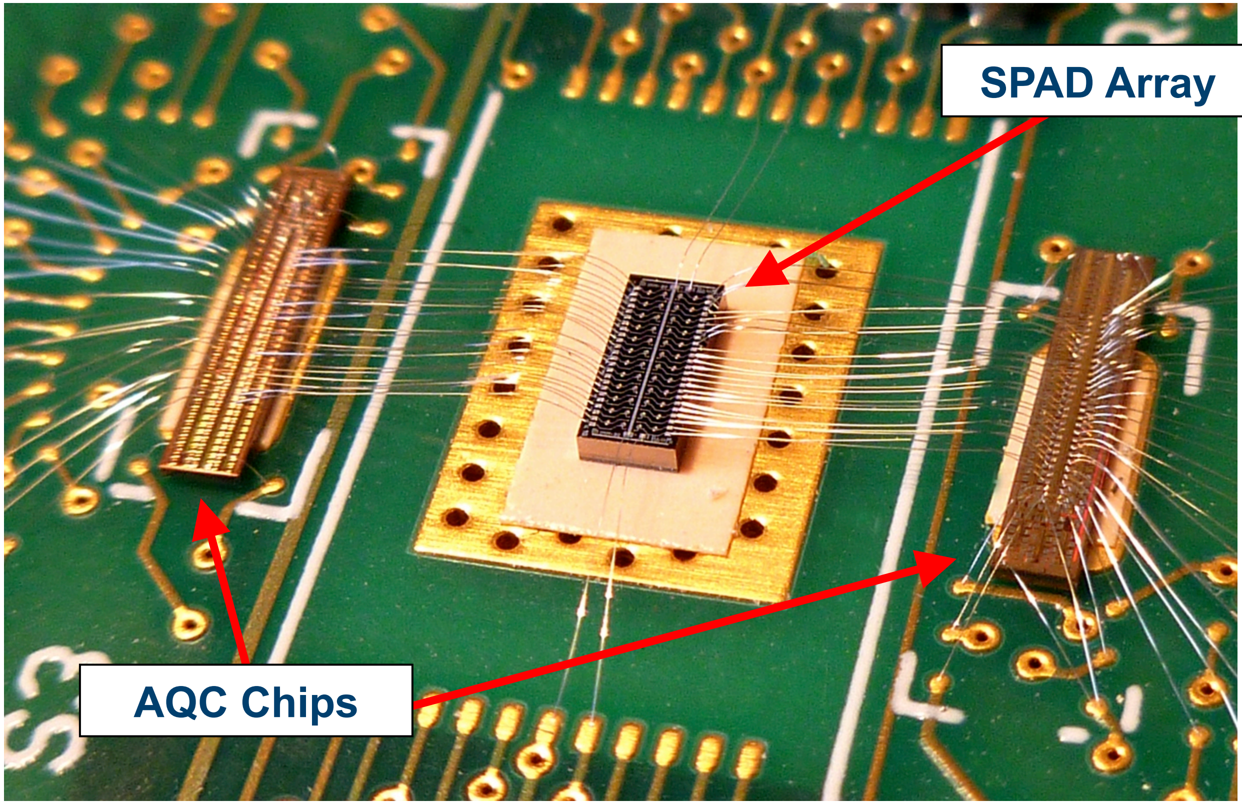


Solution

- Confine the charge layer to the active area
- Fabrication by **high energy** ion **implantation**

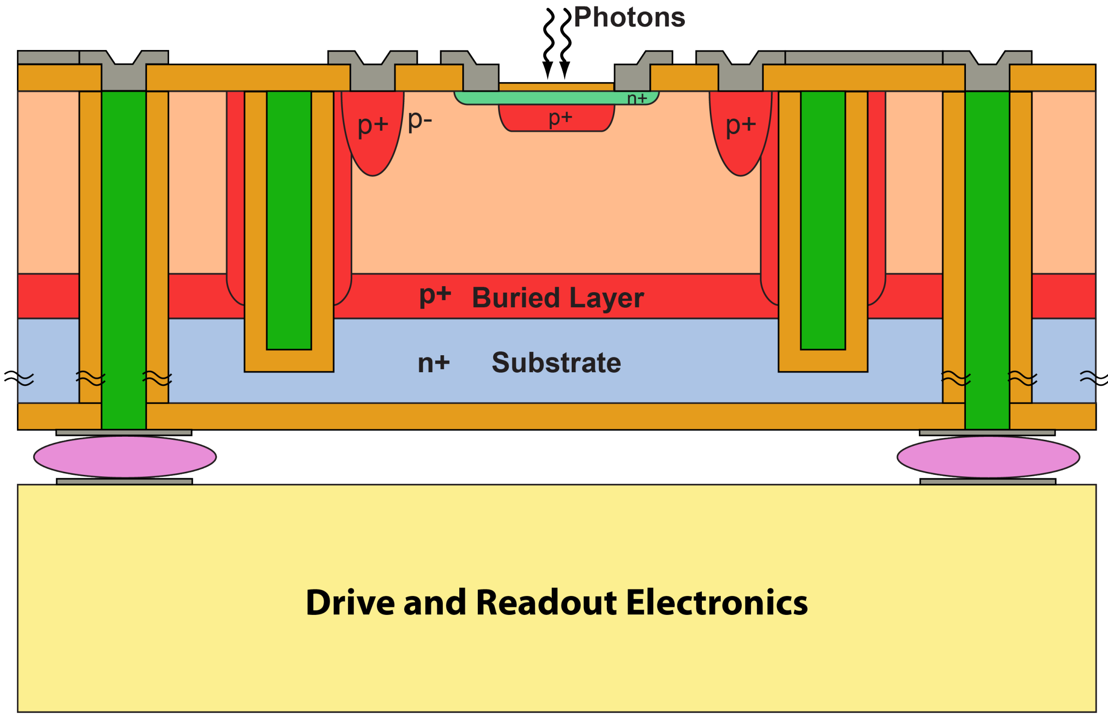
3D INTEGRATION

Connection with Quench & Reset Electronics



- Array size limited by **wire bonding**
- Max ≈ **100 pixels**

Future Developments: 3D Stacking



Best technology for SPAD **(custom)**

Bump-bonding

Best technology for read-out electronics **(CMOS)**

- Solves wire-bonding limitations
- Arrays size > **1000 pixels**

Red-Enhanced SPAD technology:

- High detection efficiency (70% @ 600 nm) / Low timing jitter (90 ps FWHM)
- **32 x 1 array** demonstrated
- Arrays with more pixels and more compact layout on the way

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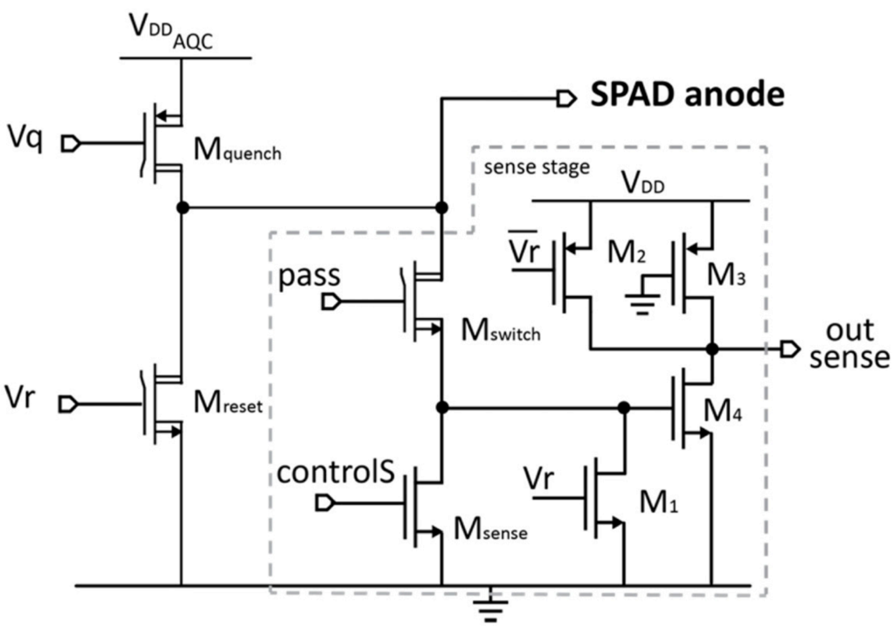
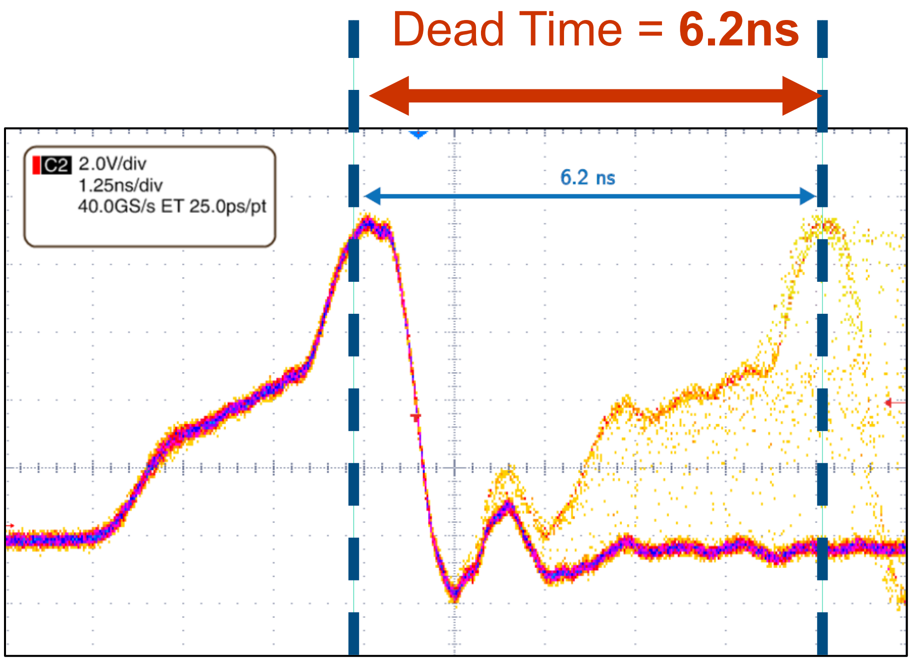
- **National Institutes of Health (**R01-GM095904)
- **Provincia Autonoma di Bolzano – Alto Adige**, (INN_R&D/2011/17)
- **European Commission,** *Q-Essence* **(**FP7-ICT-2009-4)
- **Cornell NanoScale Science & Technology Facility**
- **Human Frontier Science Program**

HIGH REPETITION RATE

Active Quenching Circuit - AQC

- Needed to quench the avalanche and to reset the bias
- *Thin SPAD:* dead time 6.2 ns ➔ **160 Mcount/s**
- *Red Enhanced SPAD:* dead time 12.5 ns ➔ **85 Mcount/s**





Acconcia et al, Optics Express **24**(16), 17819, (2016), doi:10.1364/OE.24.017819

Acconcia et al, Rev. Sci. Instr. **88**, 026103, (2017), doi:10.1063/1.4975598

Ceccarelli et al, IEEE PTL **30**(4), 391-394 (2018), doi:10.1109/LPT.2018.2792781