POLITECNICO
MILANO 1863

Low-noise InGaAs/InP SPAD with photon detection efficiency exceeding 50% at 1550 nm

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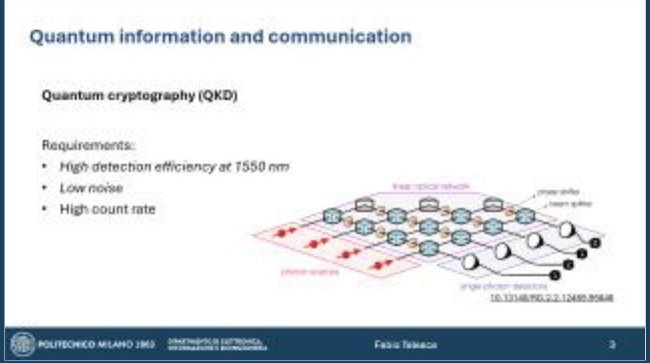
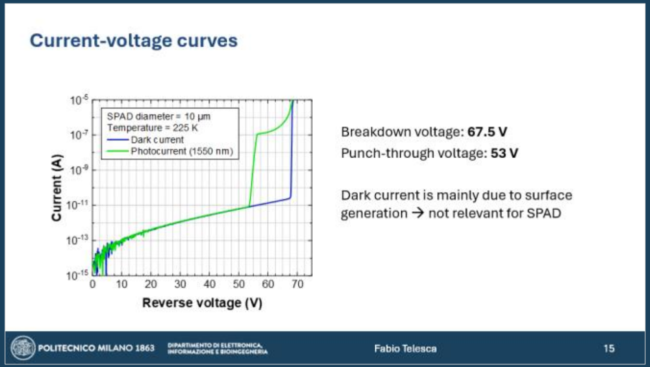
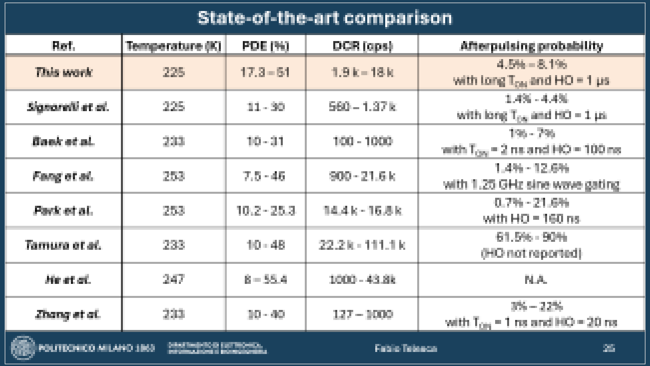
OUTLINE







State-of-the-art comparison

Ref.	Temperature (K)	PDE (%)	DCR (cps)	Afterpulsing probability
This work	225	17.3 – 61	1.9 k – 18 k	4.5% – 8.1% with long T_{ON} and HO = 1 µs
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- Design of front-illuminated planar InGaAs/InP SPAD
- Experimental characterization
- Conclusions

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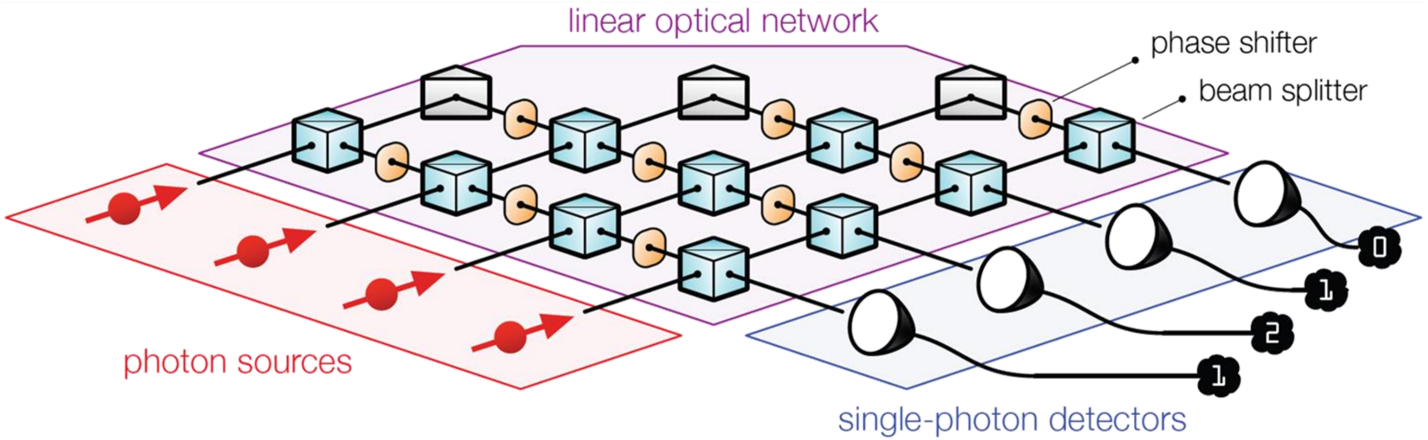
Quantum information and communication

Quantum cryptography (QKD)

Requirements:

- *High detection efficiency at 1550 nm*
- *Low noise*
- High count rate



10.13140/RG.2.2.12489.95846

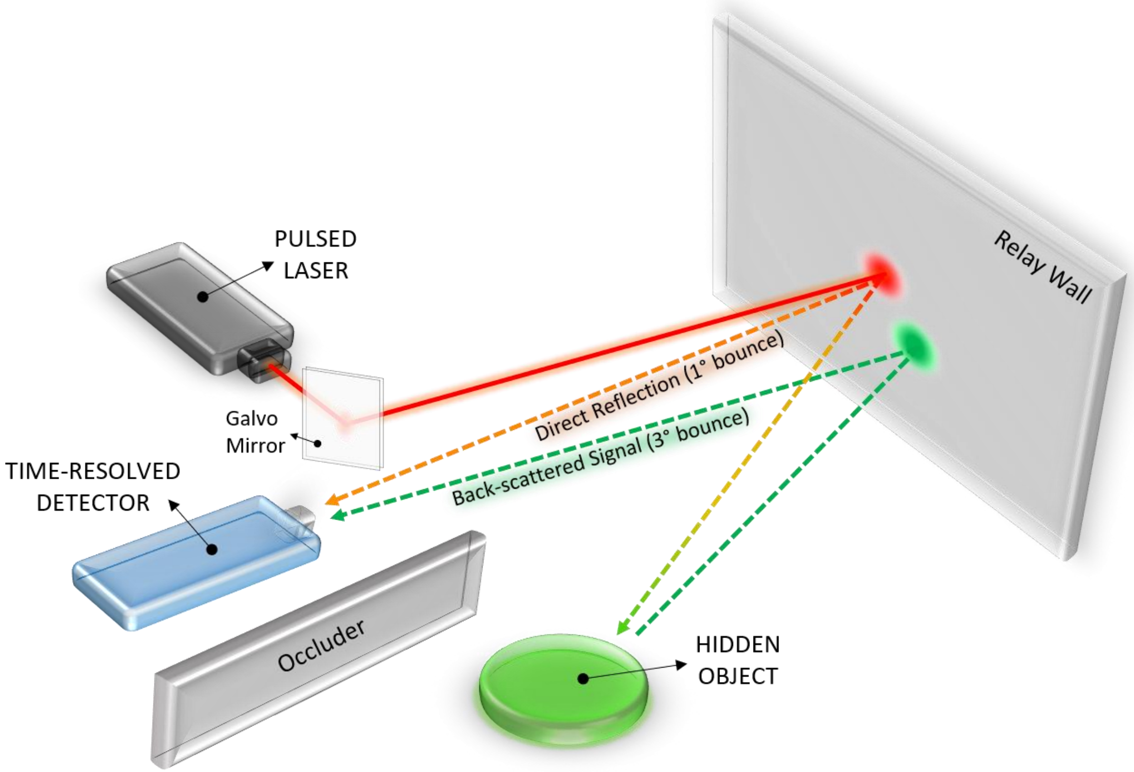
Imaging applications

Light detection and ranging (LiDAR)

Non-line-of-sight (NLOS) imaging

Requirements:

- High efficiency in SWIR range for eye-safety
- Sharp timing response



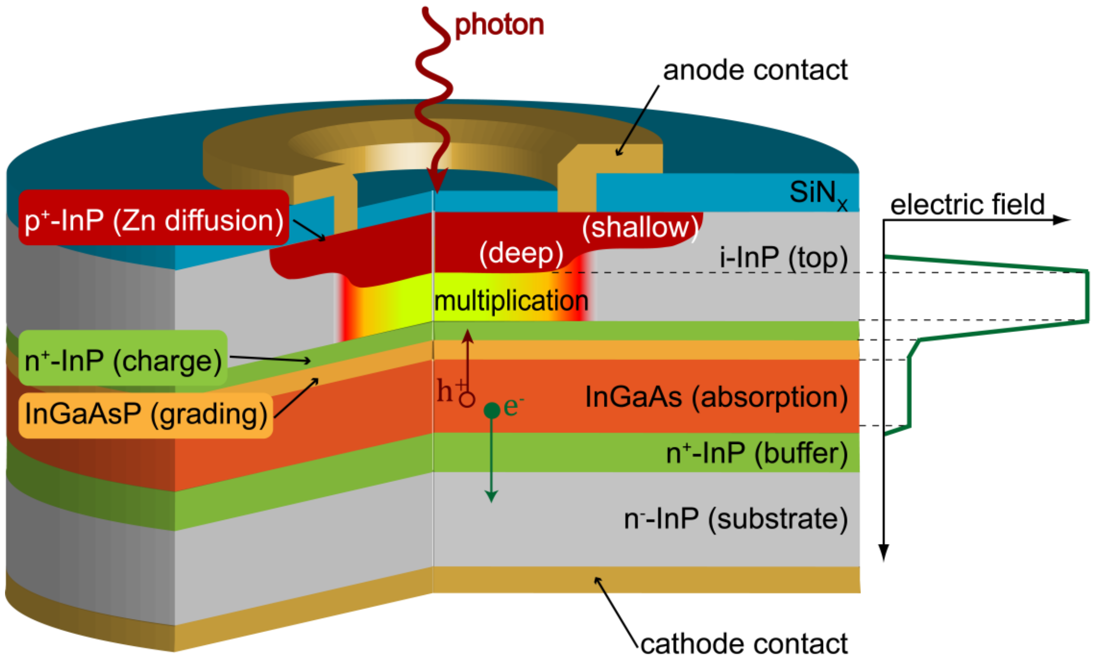
Front-illuminated planar InGaAs/InP SPAD

$In_{0.53}Ga_{0.47}As$ (E_G = 0.75 eV):

- Absorption up to λ = 1700 nm
- Unsuitable for avalanche multiplication (tunneling)

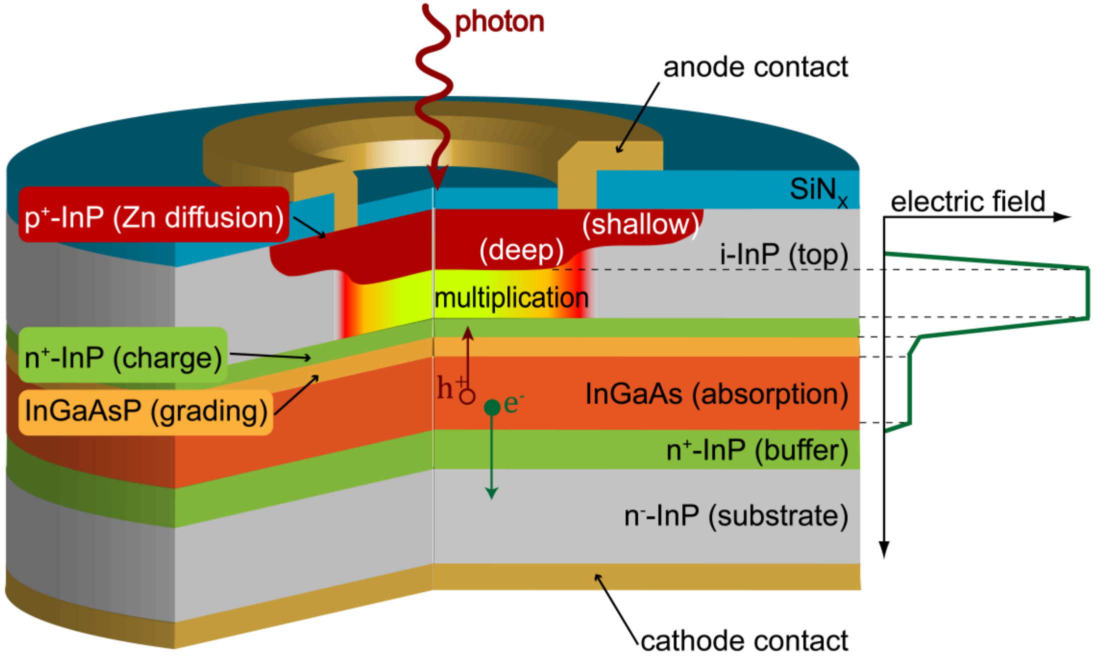
InP (E_G = 1.35 eV) – *lattice matched*

→ **Separate Absorption Charge and Multiplication** (SACM)



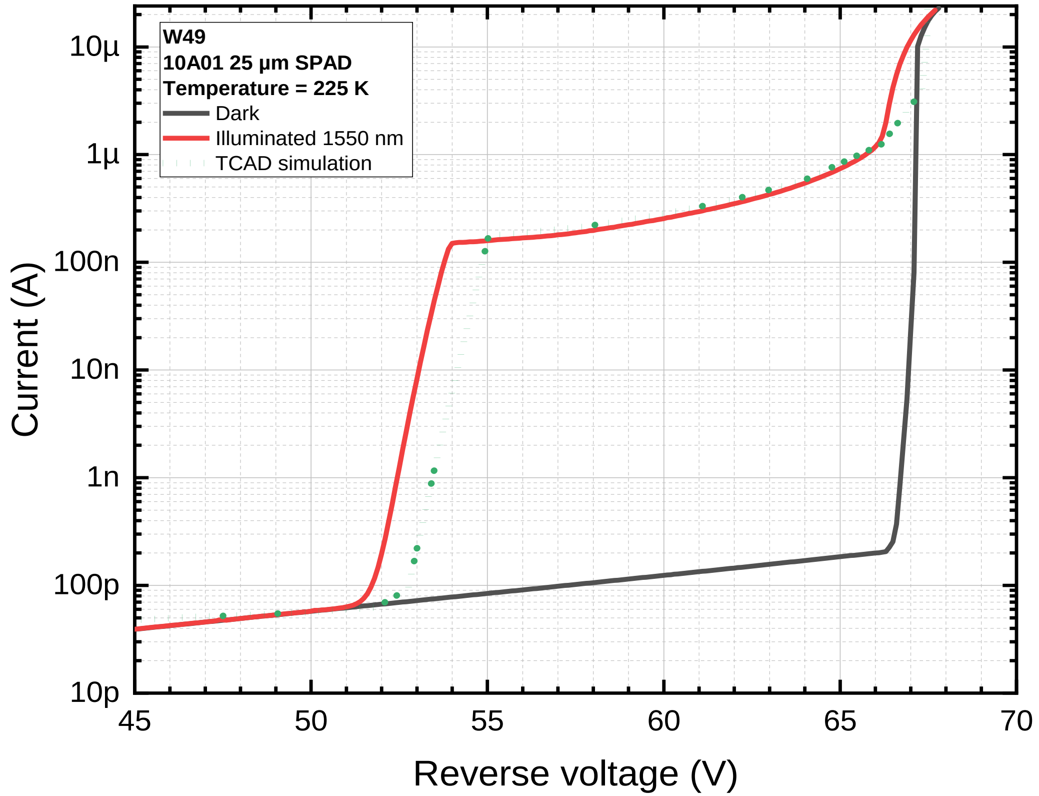
Front-illuminated planar InGaAs/InP SPAD

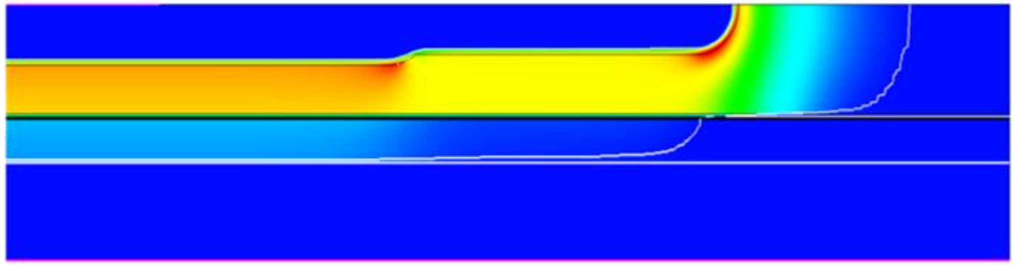
- **Charge layer** (n-doped)
  → Shapes the electric field
- **Double zinc diffusion** (p-dopant)
  → Defines active area
- **5 grading layers** (InGaAsP)
  → Reduces barrier for facilitating photo-generated holes transit



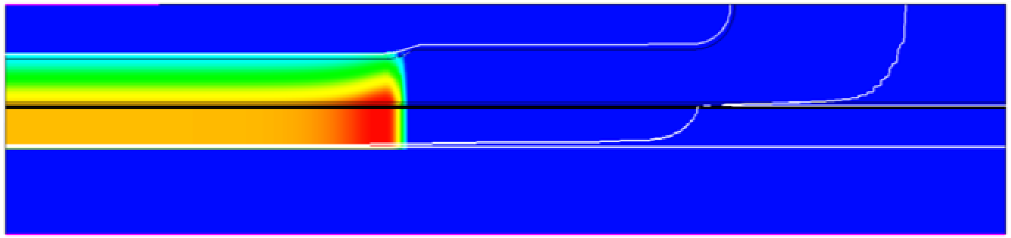
TCAD modeling and simulation

TCAD simulations (*Sentaurus, Matlab*) → optimize the internal structure for different objectives





Electric field (V/cm)



Avalanche triggering probability (%)

Avalanche triggering probability: diffusion of carriers

Avalanche triggering probability
(Oldham *et al.*):

$$\frac{dP_e}{dx} = (1 - P_e) \cdot \boldsymbol{\alpha} \cdot (P_e + P_h - P_e \cdot P_h)$$

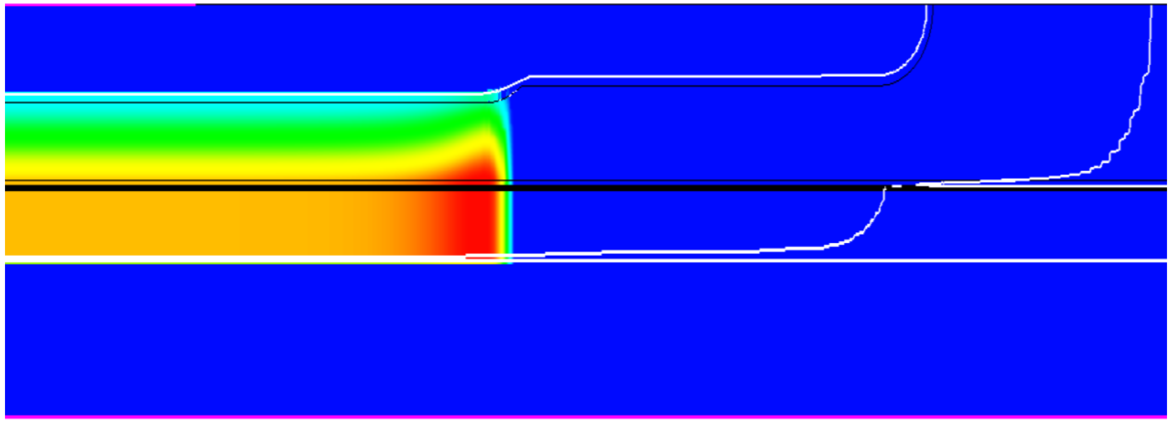
$$\frac{dP_h}{dx} = -(1 - P_h) \cdot \boldsymbol{\beta} \cdot (P_e + P_h - P_e \cdot P_h)$$

Carrier **diffusion** from quasi-neutral regions:

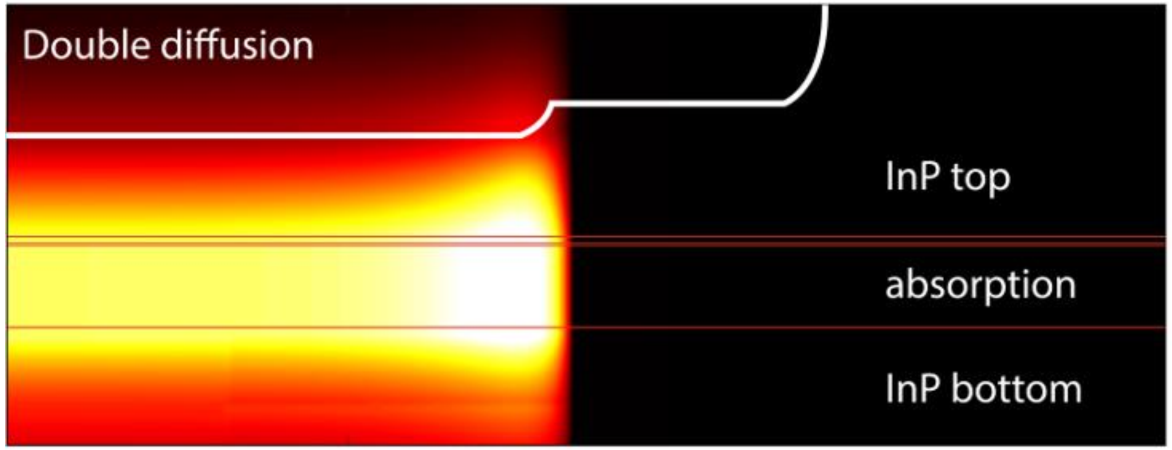
$$P_e(y) = P_e(w_p) e^{\frac{y - w_p}{L_e}}, for\ y < w_p$$

$$P_h(y) = P_h(w_n) e^{\frac{w_n - y}{L_h}}, for\ y > w_n$$

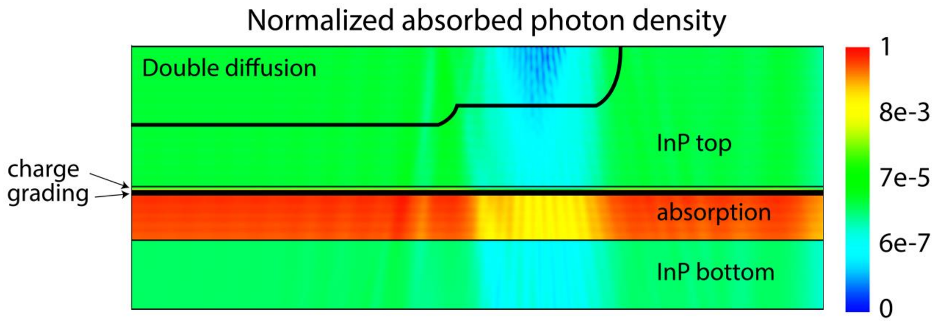
Avalanche triggering probability



Extended **avalanche triggering probability**



Optical simulations: InP and InGaAs complex refractive index



$$n^* = \boldsymbol{n} + i\boldsymbol{k}$$

$\boldsymbol{n}$ = accounts for refraction

$\boldsymbol{k}$ = accounts for absorption

→ Absorption coefficient:

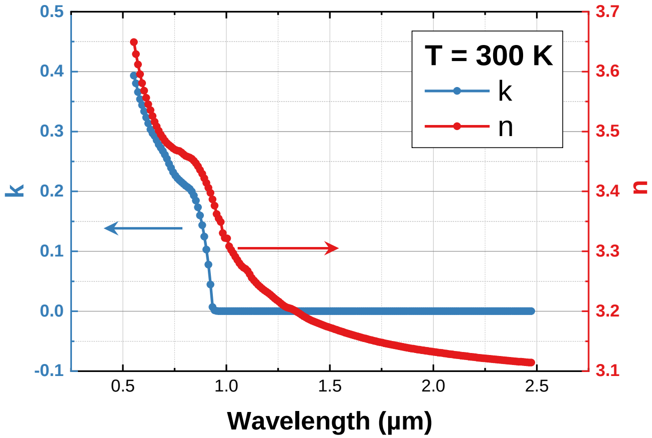
$$\boldsymbol{\alpha} = 4\pi \frac{\boldsymbol{k}}{\lambda}$$

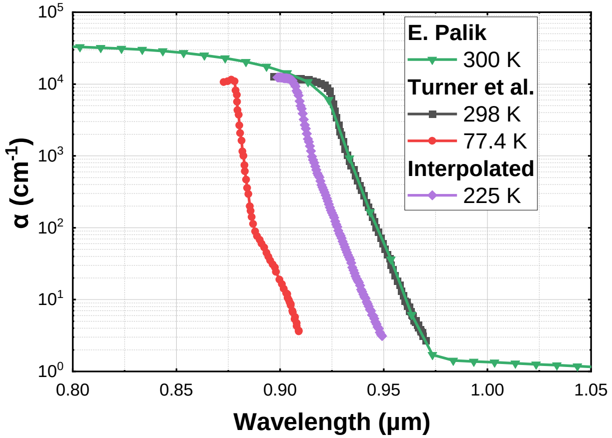
Temperature dependence extrapolated from range around the cut-off wavelength

Absorption coefficient ($\boldsymbol{\alpha}$) at RT

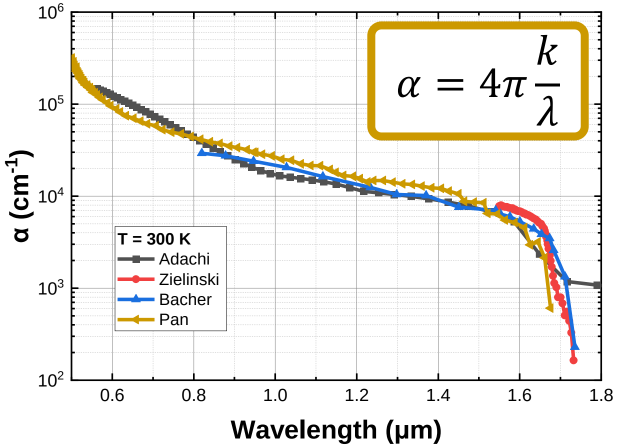
Temperature dependence of α

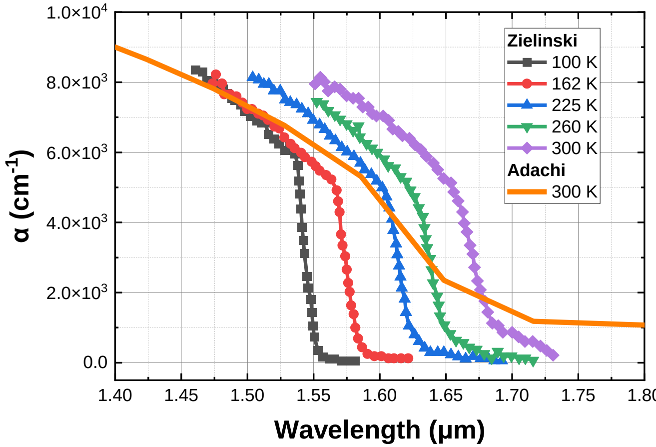
InP



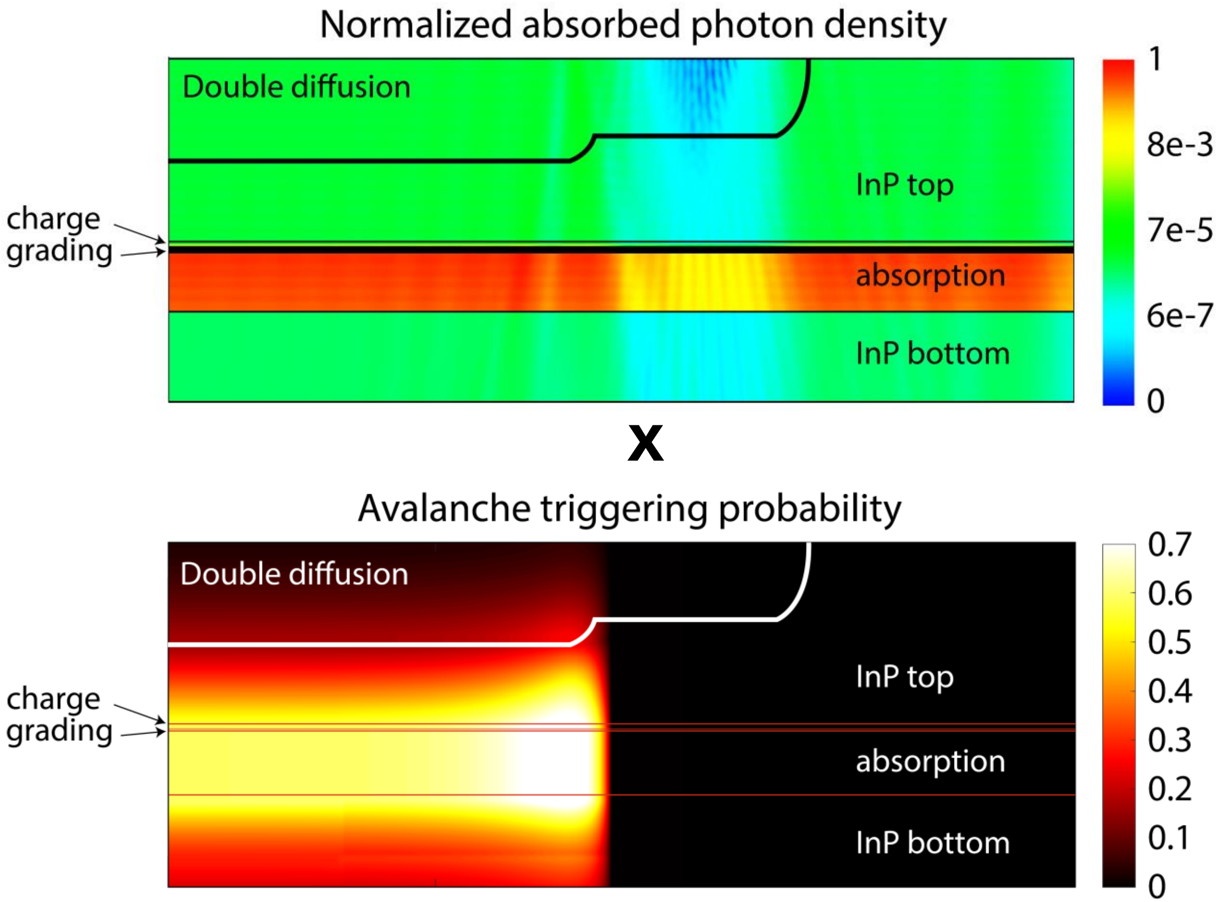


InGaAs



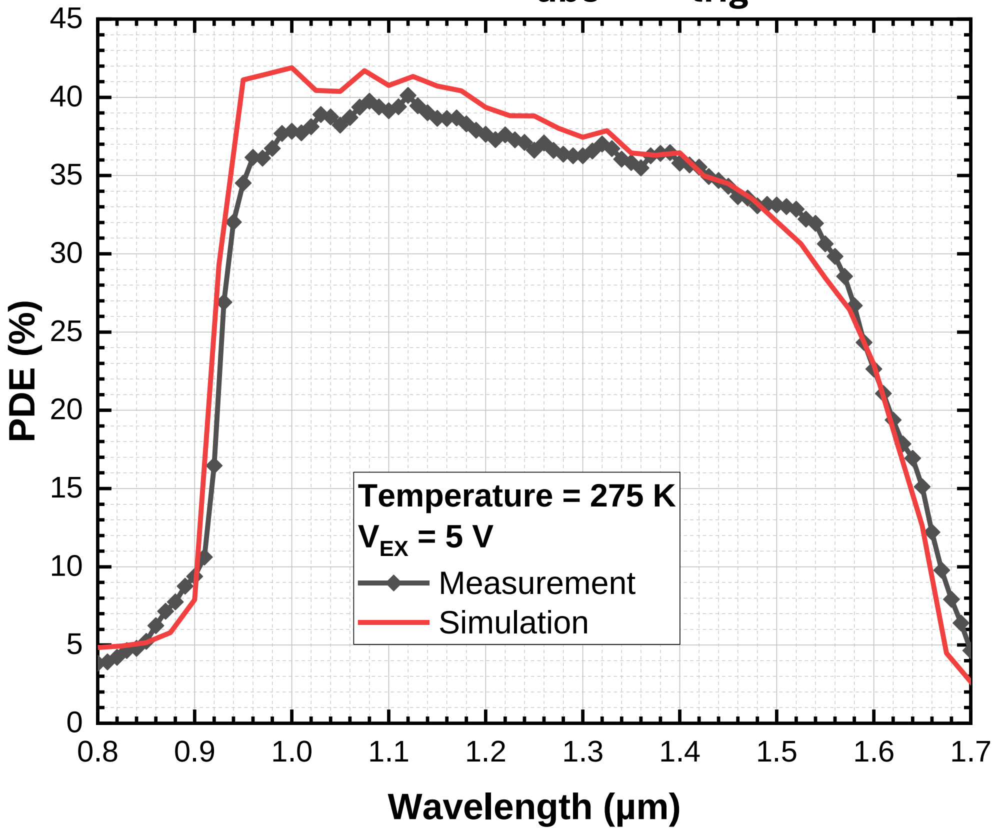


Photon detection efficiency simulation

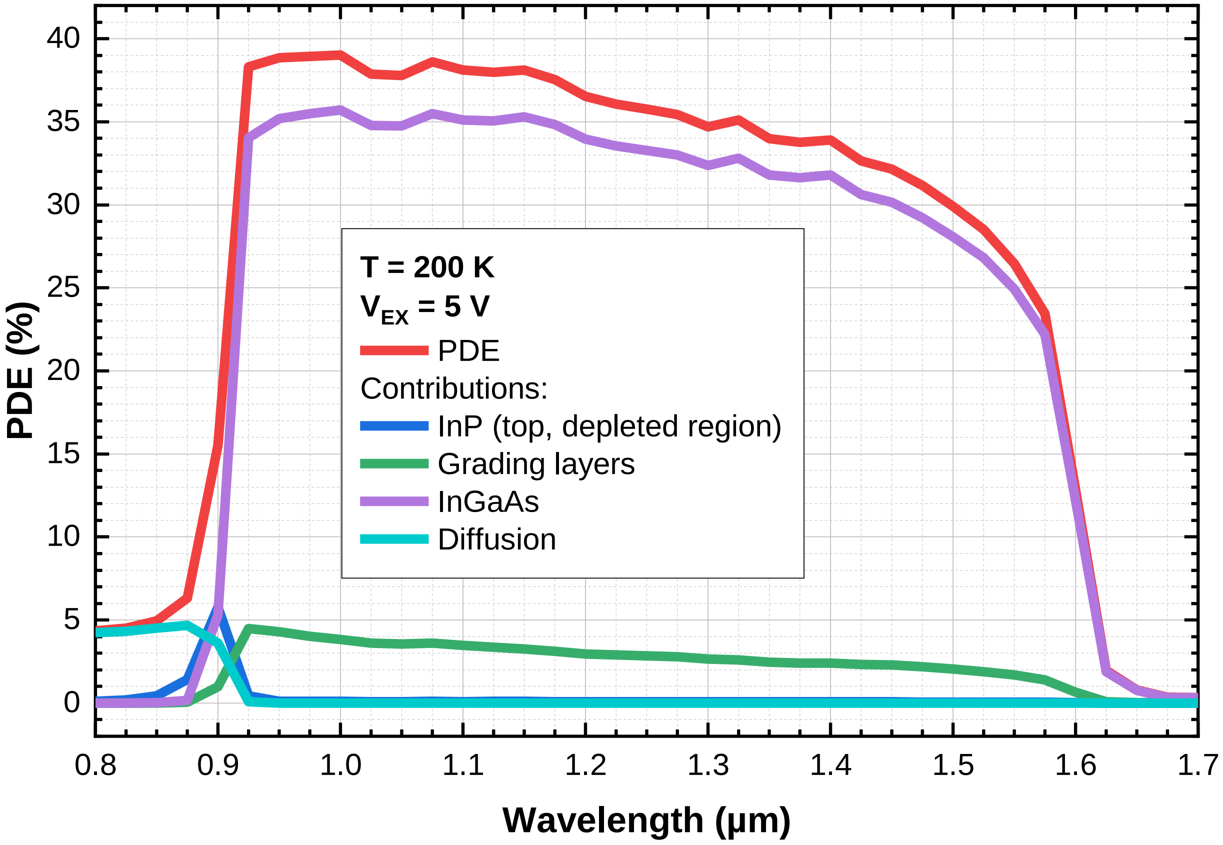


→

$$PDE = P_{abs} \times P_{trig}$$



PDE simulation results

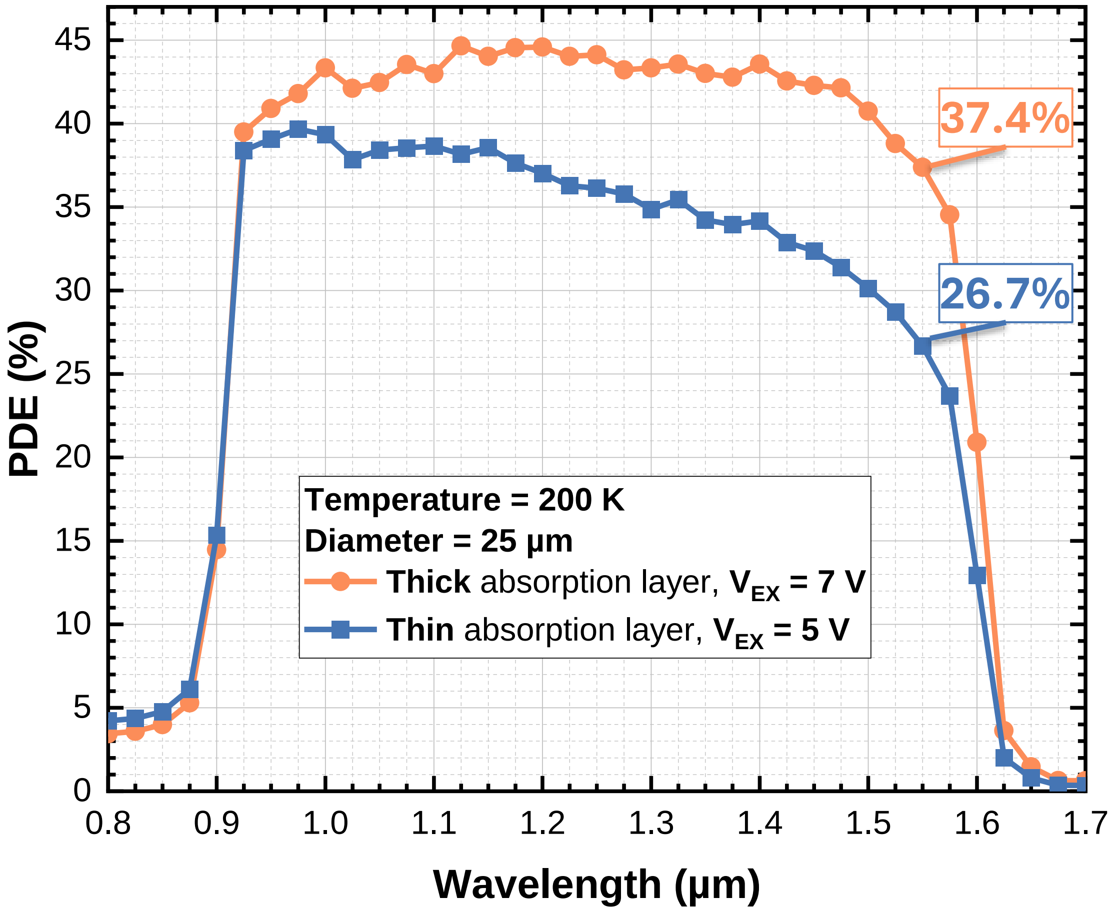


Contributions to PDE from various regions:

- **InGaAs** is the **main contribution**
- Carrier diffusion is only relevant up to 900 nm
- InGaAsP grading layers have a non-negligible contribution (about 10% of the total PDE)
- InP bottom layers do not contribute to PDE

Enhanced PDE InGaAs/InP SPAD: TCAD modeling

PDE estimated from TCAD simulations

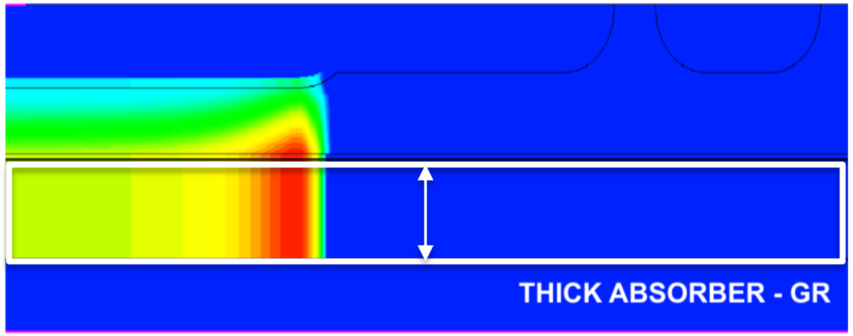


Thicker InGaAs **absorption layer**

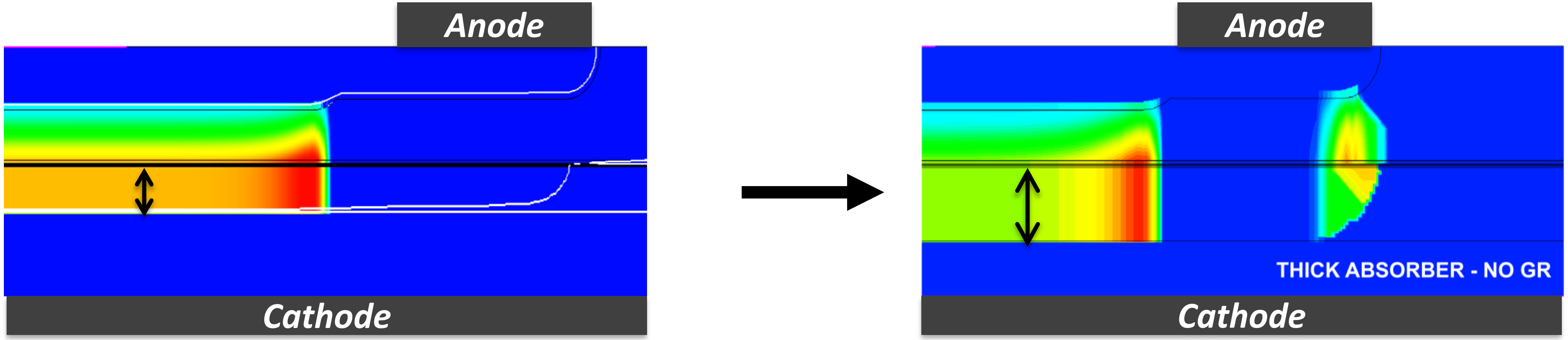
&

Optimized double zinc diffusion profile,

Charge layer thickness

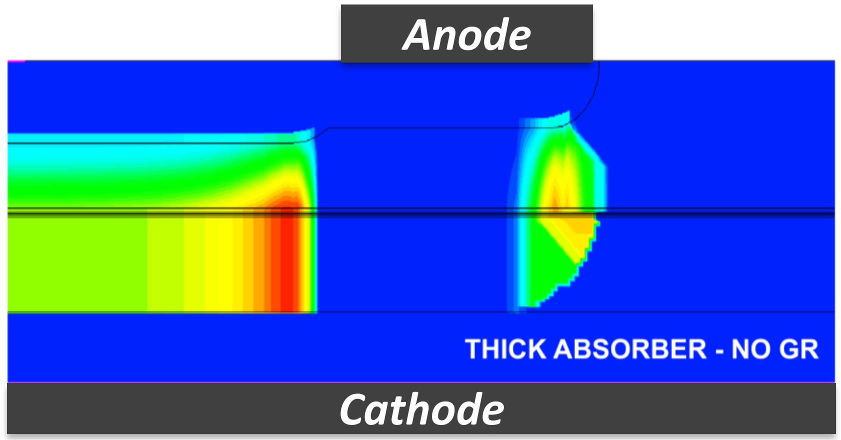


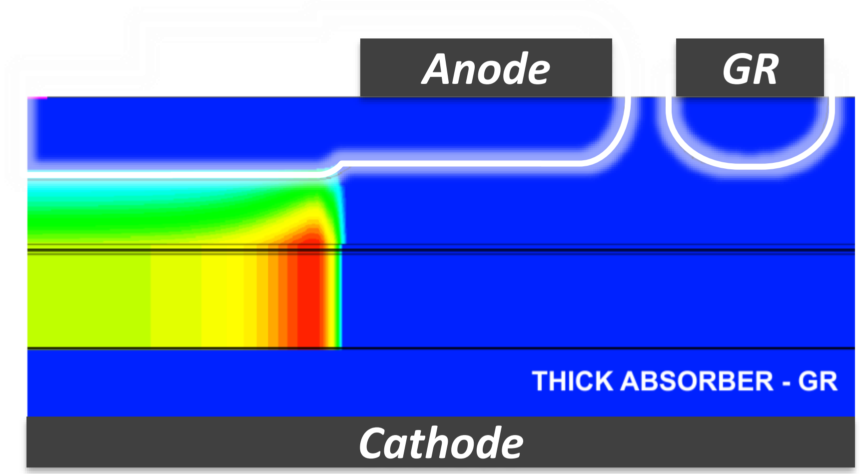
Structure for high photon detection efficiency



Thicker InGaAs **absorption layer** → Higher noise, reduced active area uniformity

Structure for high photon detection efficiency





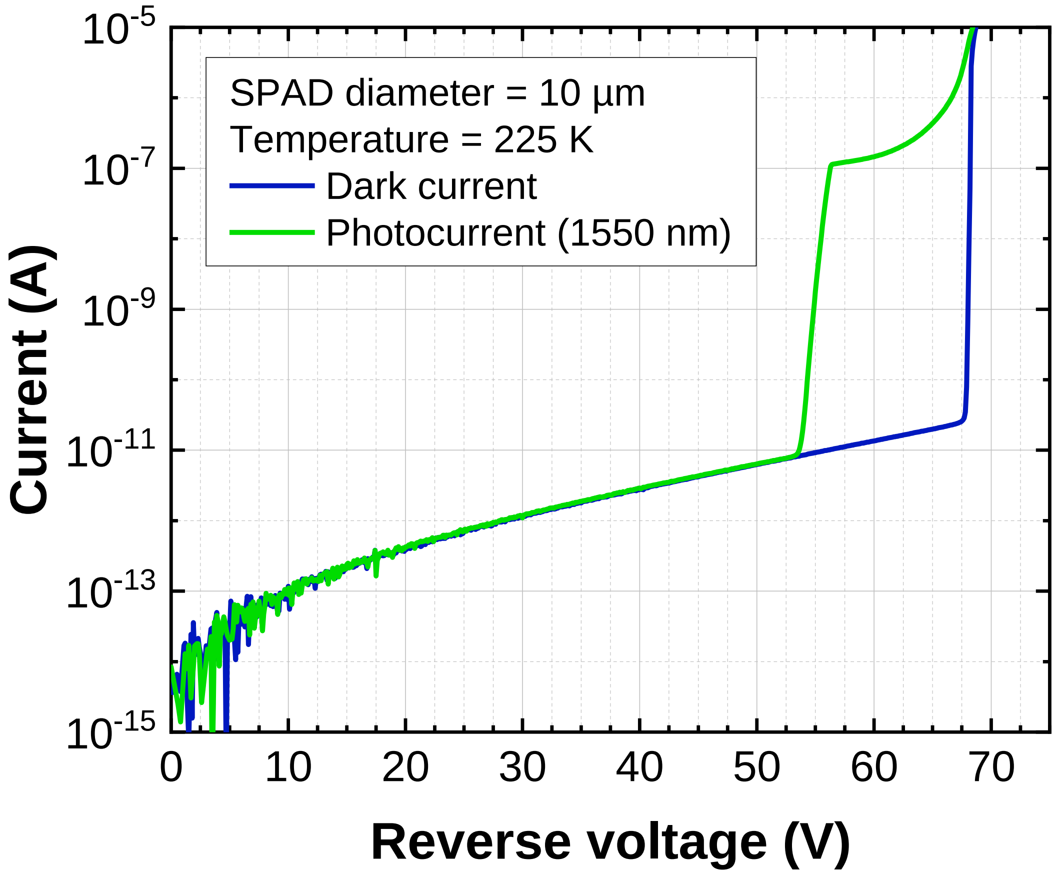
TCAD simulations with commercial software and custom models:

- Optimized double diffusion → Enhanced active-area uniformity
- Contacted **guard ring** → Prevent edge breakdown, mitigate charge persistence

Small active area (10 μm diameter):

→ Reduced noise, still good for fiber pigtailing

Current-voltage curves

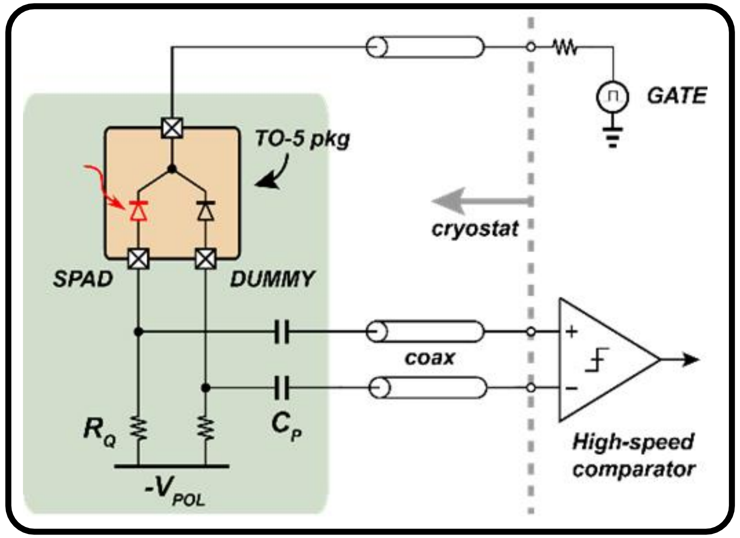


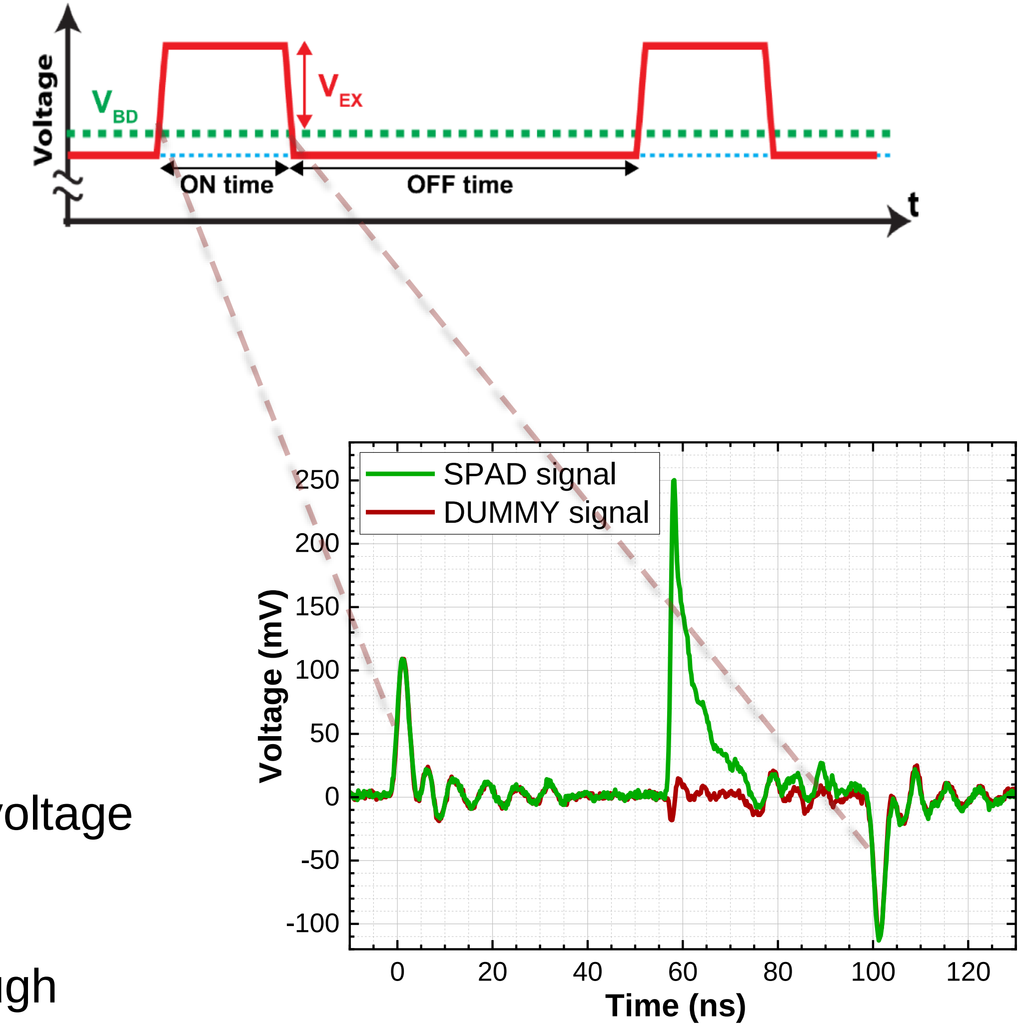
Breakdown voltage: **67.5 V**

Punch-through voltage: **53 V**

Dark current is mainly due to surface generation → not relevant for SPAD

Gated-mode SPAD operation

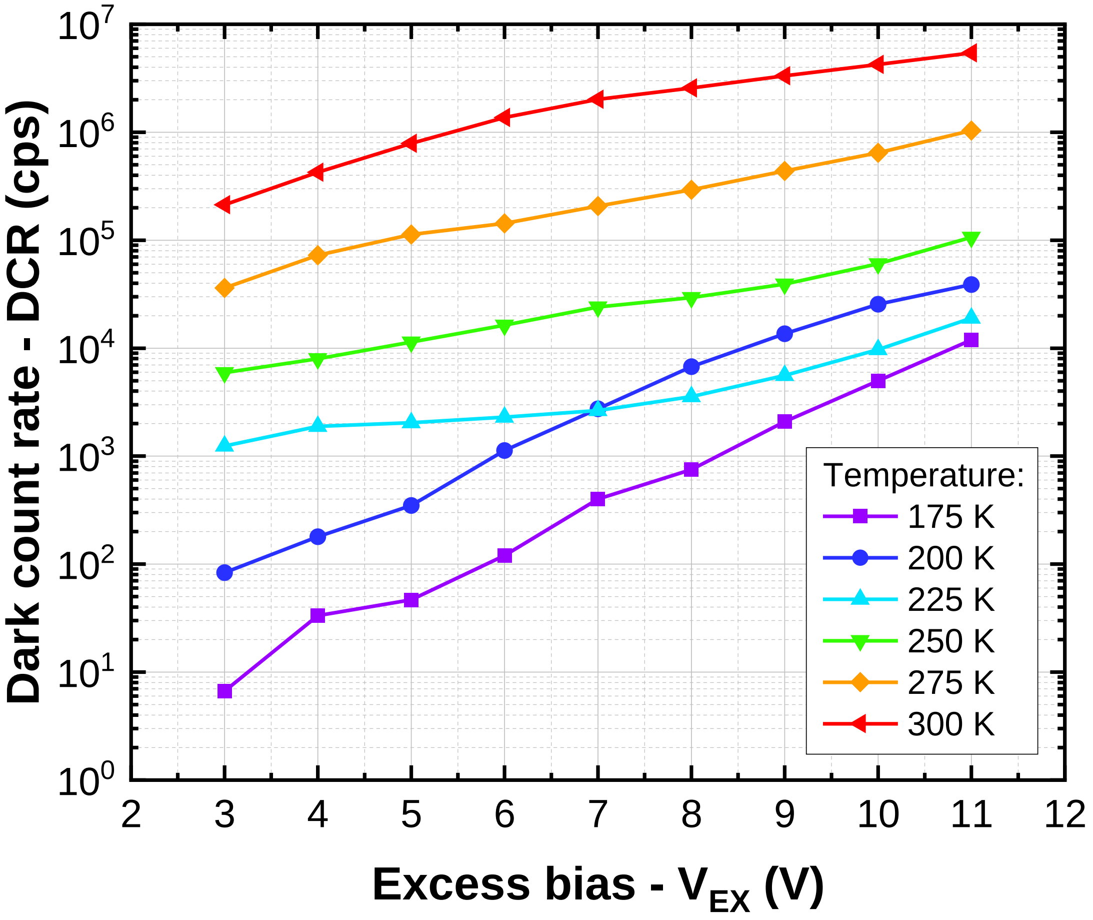




*Basic schematic for **square-wave gating***

- Passive quenching in the starting phase
- Complete quenching by pulling down the gate voltage
- Long enough OFF time to limit afterpulsing
- **SPAD-DUMMY** approach to subtract feed-through

Dark count rate

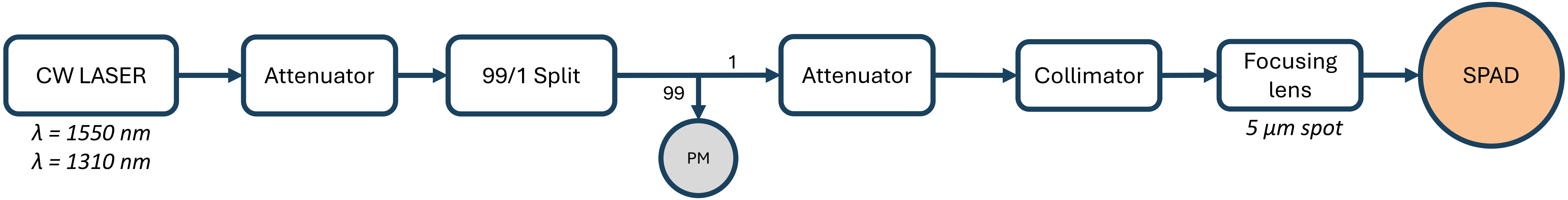


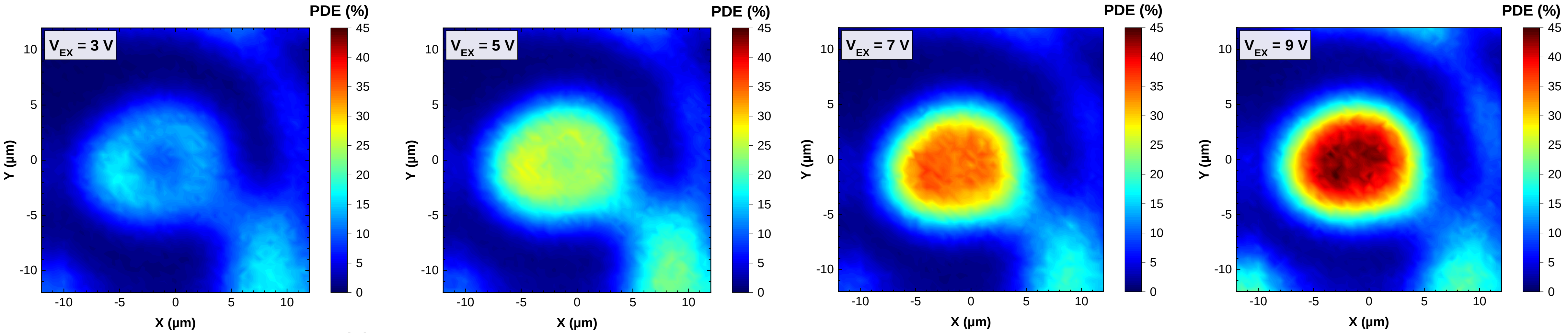
Long $\mathbf{T_{OFF}}$ (100 µs) to avoid afterpulsing

At **T = 225 K**:
DCR of few kcps

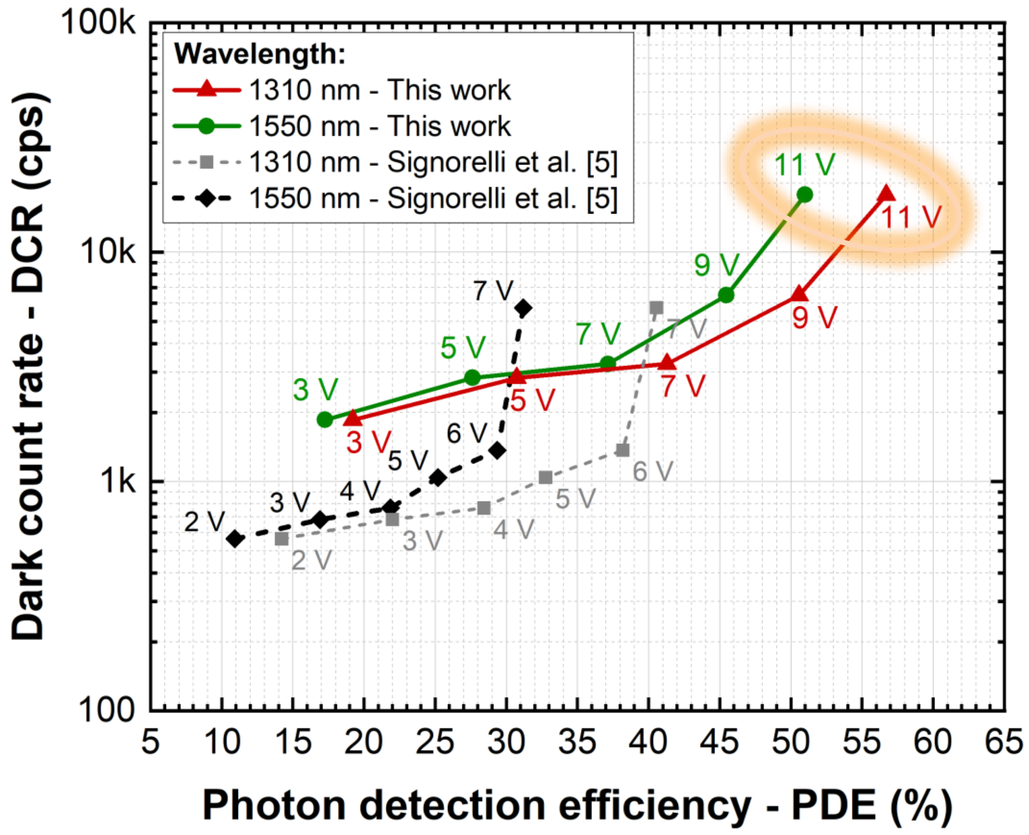
At **T ≤ 200 K**:
Charge persistence is stronger

Photon detection efficiency





Photon detection efficiency



Laser source:

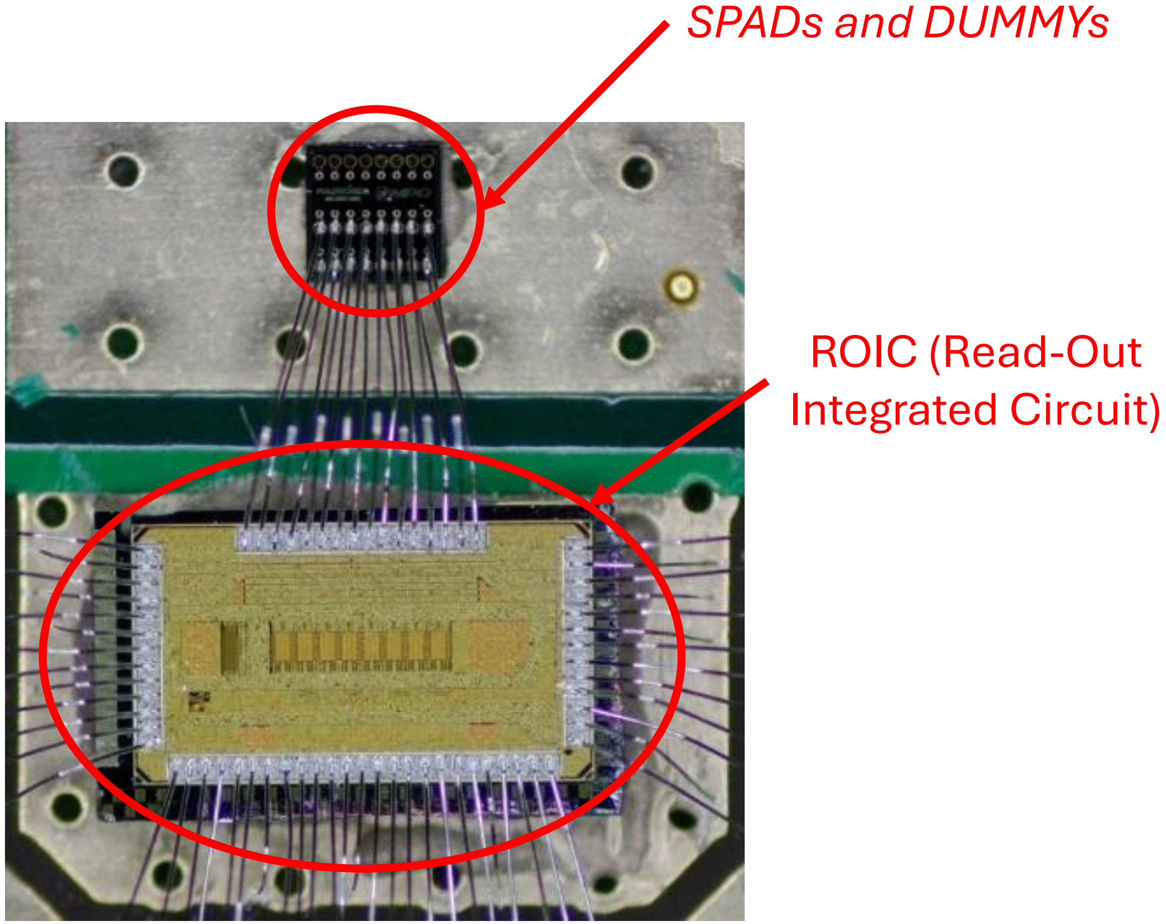
- λ = 1550 nm or λ = 1310 nm
- 5 μm laser spot size

Photon detection efficiency:

- up to **51%** for λ = 1550 nm
- up to **57%** for λ = 1310 nm

with DCR = 18 kcps

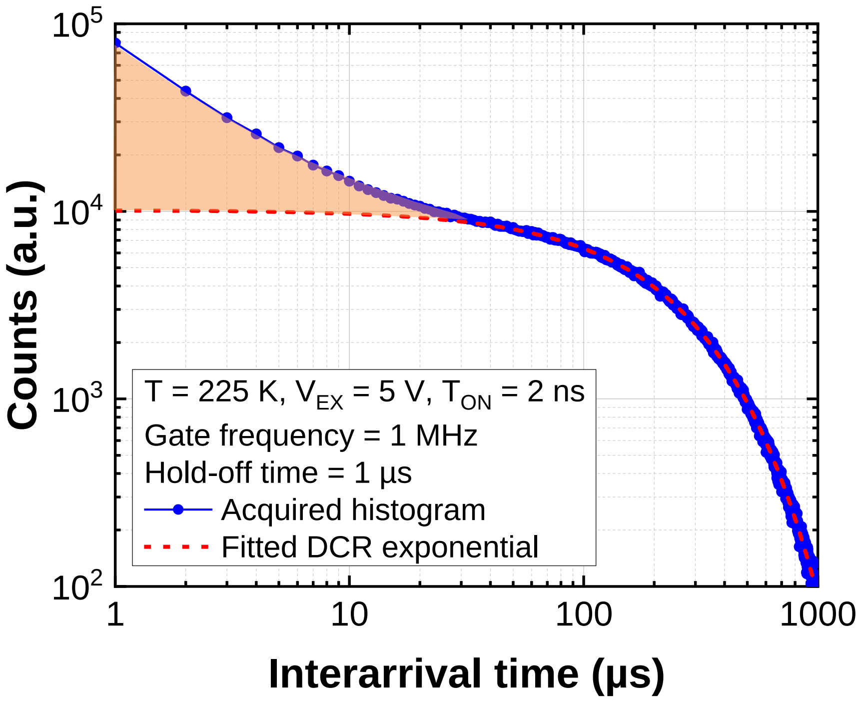
Afterpulsing probability

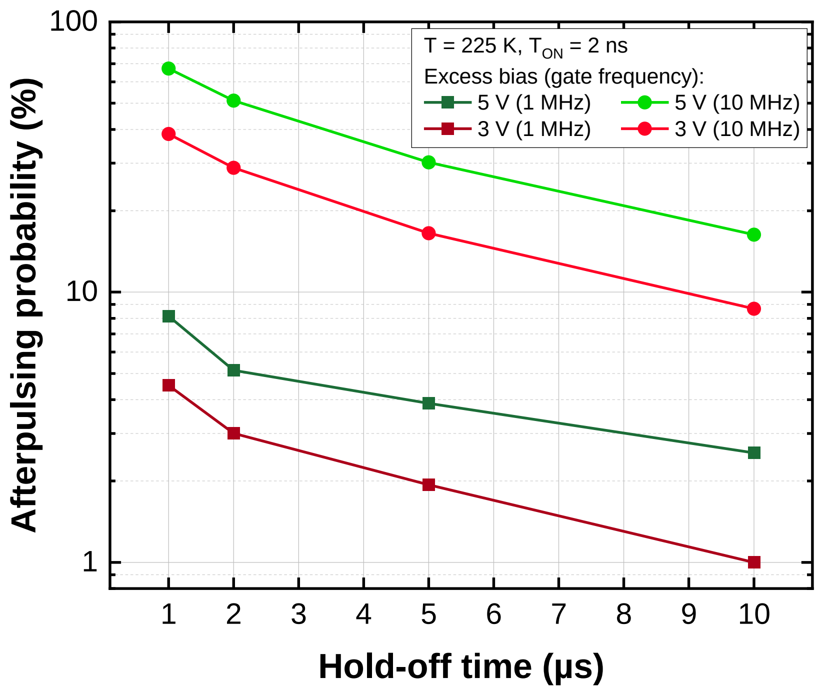


Read-out integrated circuit (**ROIC**):

- 0.16 μm BCD technology
- Up to 8 SPADs (and DUMMYs)
- Up to 5 V excess bias
- Up to 100 MHz gate
- Tunable hold-off time
- **~ 1-2 ns** quenching time

Afterpulsing probability

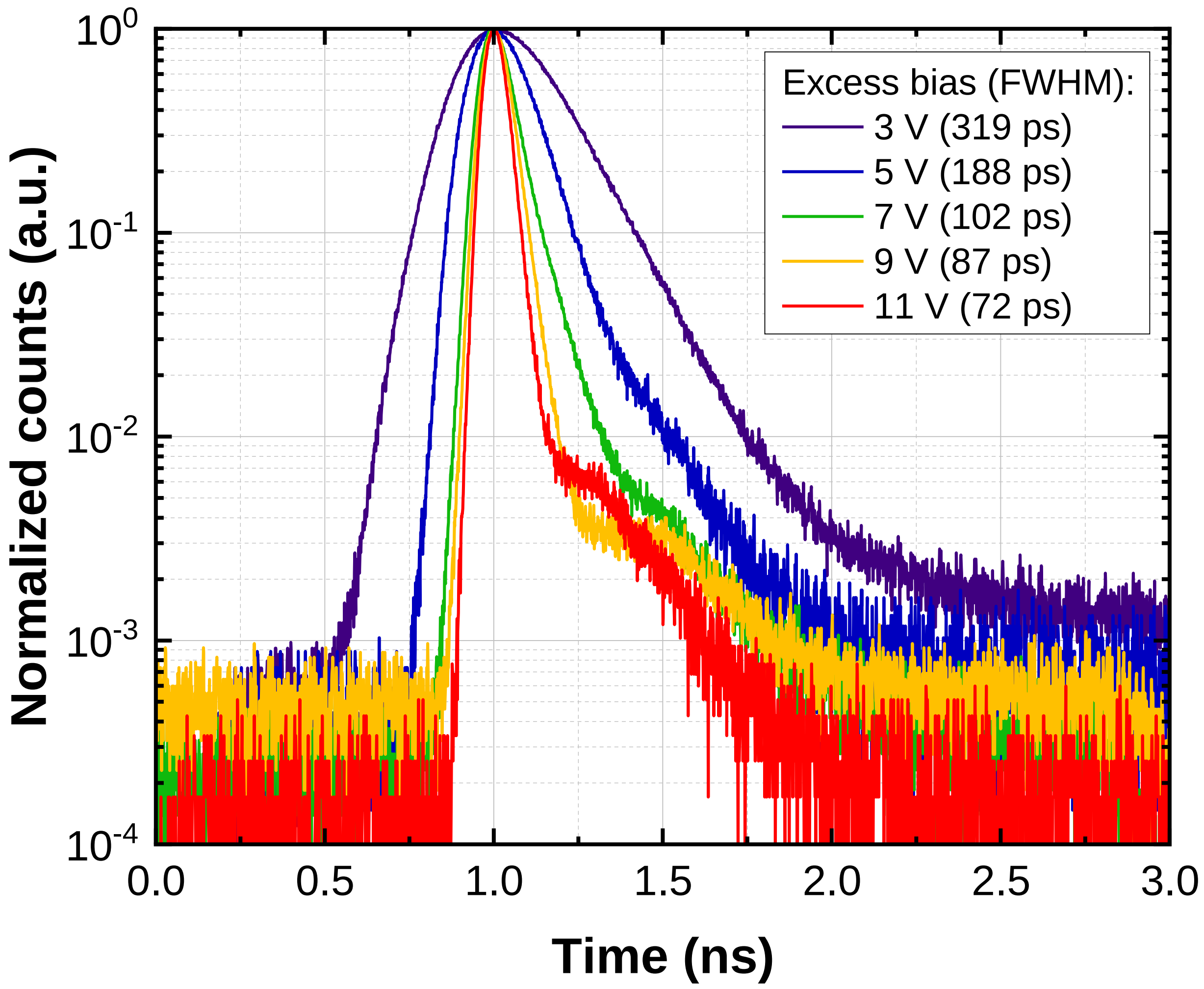




High gate frequency, hold-off time enforced after every avalanche.

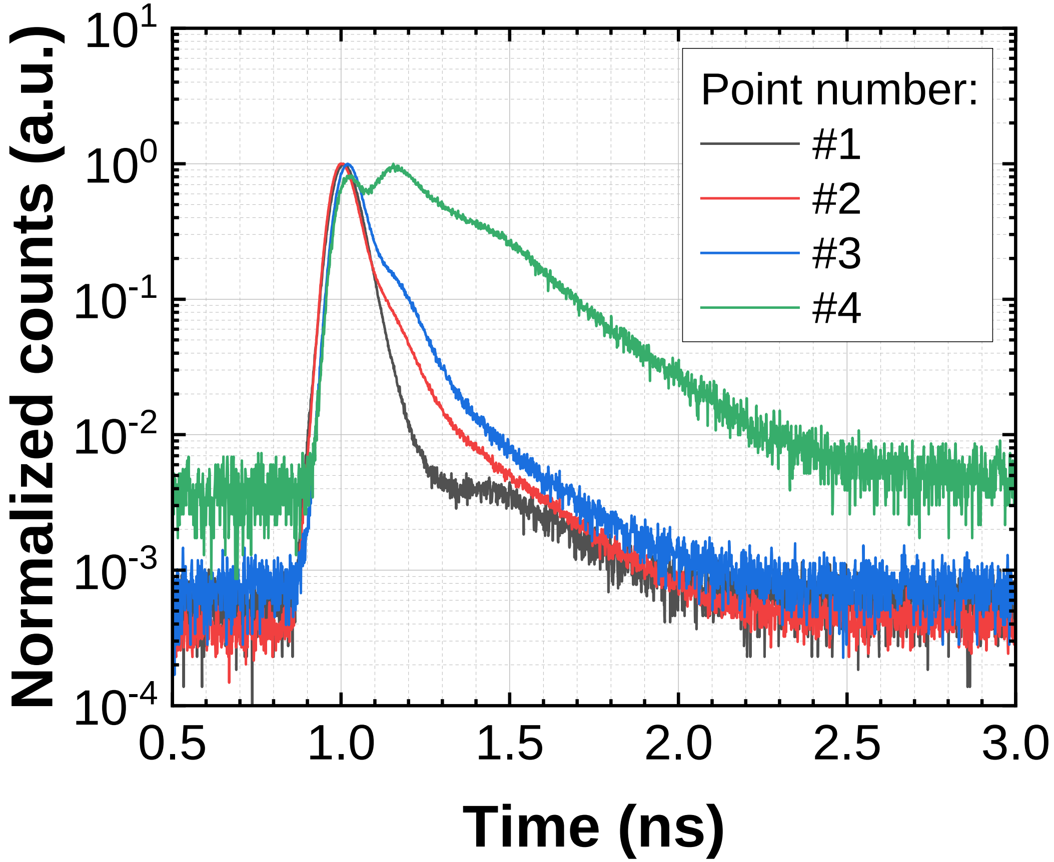
Afterpulsing is just few percent at 225 K and 1 MHz gate frequency.

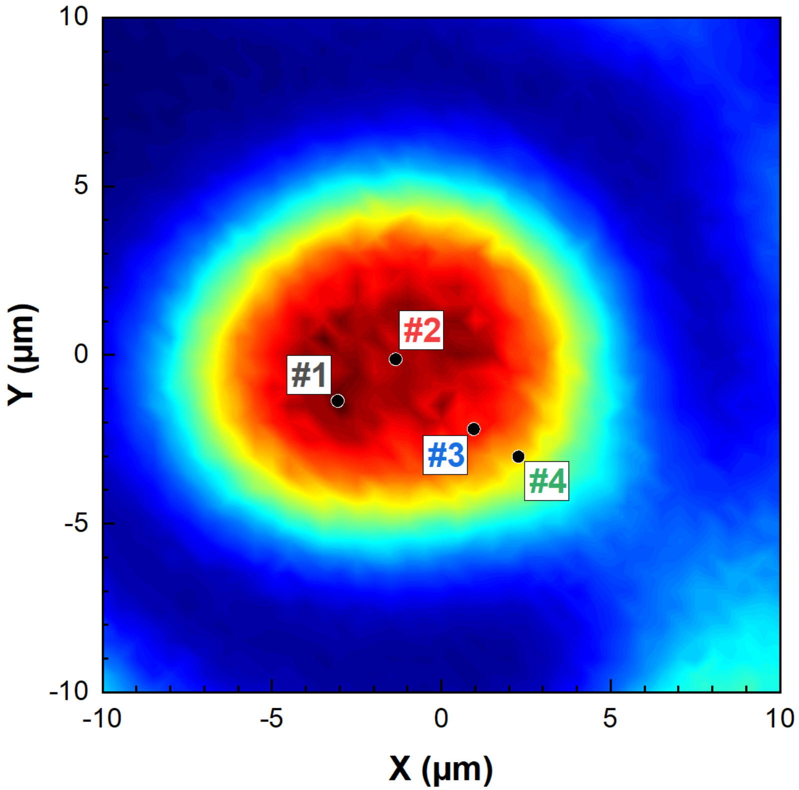
Temporal response



- **18 ps** (FWHM) pulsed laser
- **λ = 1550 nm, T = 225 K**
- Laser spot **focused** on a high-efficiency peak inside the active area

Temporal response





Position and amplitude of secondary peak depend on the laser position

→ Residual non-uniformities inside the active area

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CONCLUSIONS

- **Optimized InGaAs/InP SPAD structure** for **enhanced PDE**
  - TCAD simulations to tailor double diffusion depth, charge layer and absorption layer thicknesses
  - PDE simulations to estimate the PDE enhancement
- **Best-in-class PDE (up to 51%) at 1550 nm with:**
  - DCR < 20 kcps
  - Timing jitter ~ 70 ps (FWHM)
- **Reduced afterpulsing** (few percent) thanks to a custom-designed integrated circuit

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We acknowledge co-funding support from the Autonomous Province of Bozen/Bolzano
Südtirol/Altoadige under LP 14/06 - Bando 2016 - SPIR project

AUTONOME PROVINZ BOZEN SÜDTIROL

PROVINCIA AUTONOMA DI BOLZANO ALTO ADIGE