Scalable Backside-Illuminated Charge-Focusing Silicon SPADs with Enhanced Near-Infrared Sensitivity

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[3] now with *Gpixel, Antwerp, Belgium*

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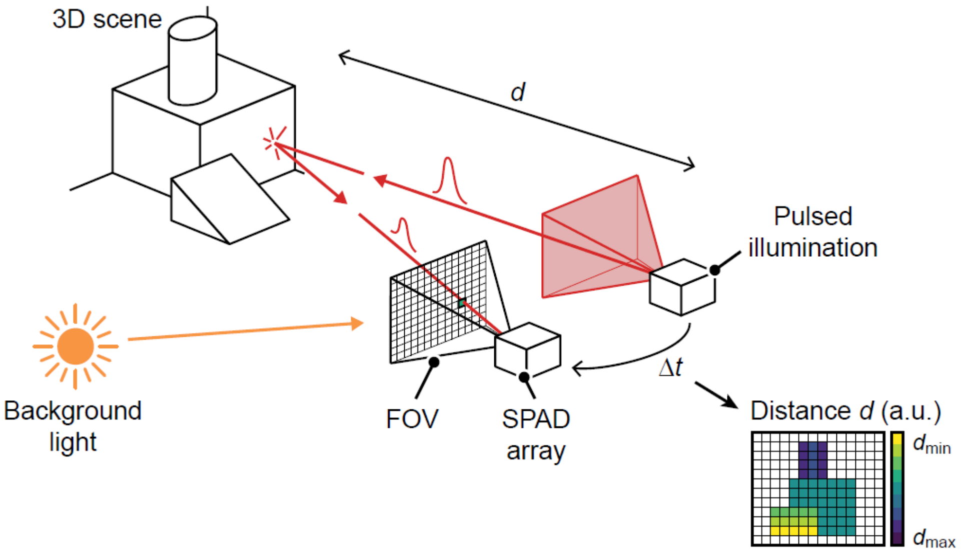
Research Foundation Flanders
Opening new horizons

Contents

Direct time-of-flight (d-ToF)

- **Temporally resolve faint scattered signals from a 3D scene**

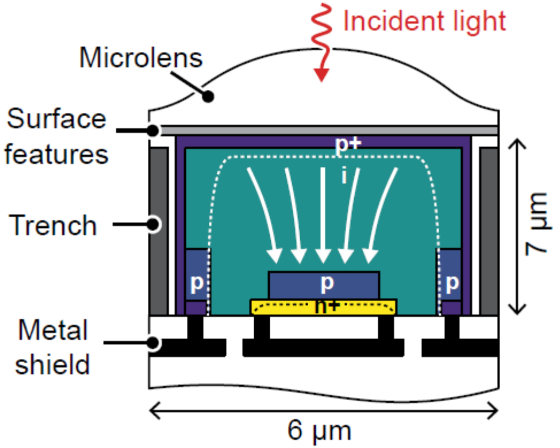
- **Benefits from:**
  - SPADs in large arrays
  - NIR sensitivity
    - Reduced ambient light
    - Improved eye safety
    - Fog & rain penetration
  - High dynamic range
    - Faint signal
    - Strong background
  - Good timing resolution
  - Silicon



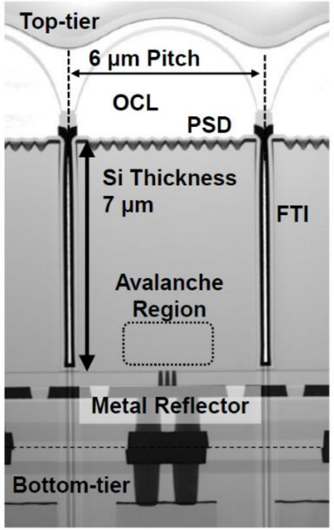
Scalable NIR-sensitive silicon SPADs

- **The detector requirements are determined by the application:**
  - Deep epi layer
    - NIR ↯ silicon
  - Full depleted / Drift field
    - No compromise on jitter
  - Scalable / High fill factor
    - Array integration
    - Macro cells
  - Optics enhancing features

‘prototype’



Could resemble…



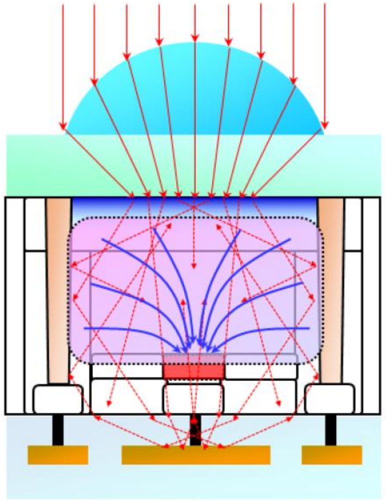
S. Shimada, et al., in *IEEE International Electron Devices Meeting (IEDM)*, 2021, pp. 446–449.

Field engineering

- **How to go from (d-ToF) performance requirements to actual devices?**
  Doping & field engineering

- **Notably: Charge focusing**
  - Electrons funneled into multiplication field
    - ⇒ High fill factor & PDE
    - ⇒ Scalable
  - Small multiplication region
    - ⇒ Low DCR
    - ⇒ Low afterpulsing
    - ⇒ Low junction cap.

K. Morimoto, et al. (Canon)



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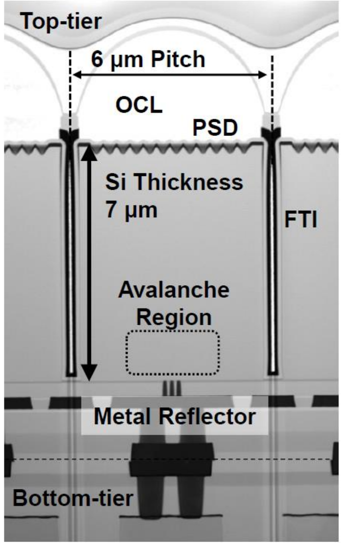
K. Morimoto, et al., in *IEEE International Electron Devices Meeting (IEDM)*, 2021, pp. 450–453.

Field engineering

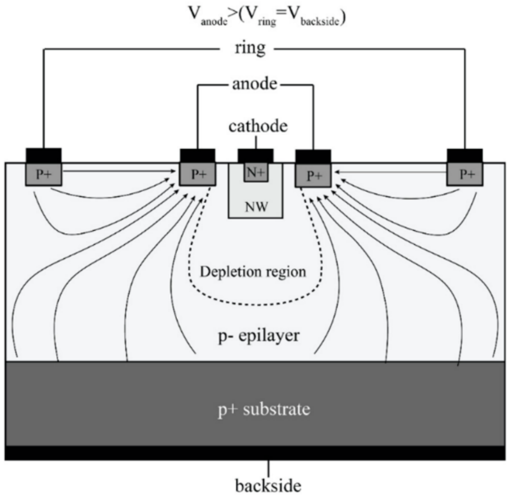
- **Other examples of field engineering:**

S. Shimada et al. (Sony)



A fine balance between breakdown and depletion

G. Jegannathan et al. (VUB)



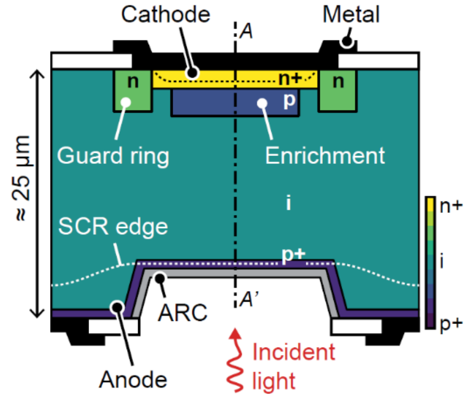
A charge-focusing technique with the assistance of a current

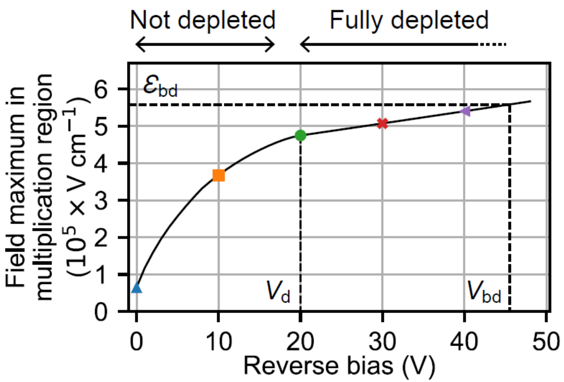
S. Shimada, et al., in *IEEE International Electron Devices Meeting (IEDM)*, 2021, pp. 446–449.
G. Jegannathan, et al., in *Silicon Photonics XVII. SPIE*, 2022, vol. 1*2006*, pp. p. 40–46.

A note on depletion and breakdown

- **Wide depletion region**
  => Potential spreads over large distance
    => Field strength is insensitive to bias
- **Consequences:**
  - Large operating voltage ⇔ Strong drift field
  - High excess bias V_e ⇔ High breakdown probability
  - Increased process sensitivity
  - Poor temperature coefficient

Reach-through SPAD

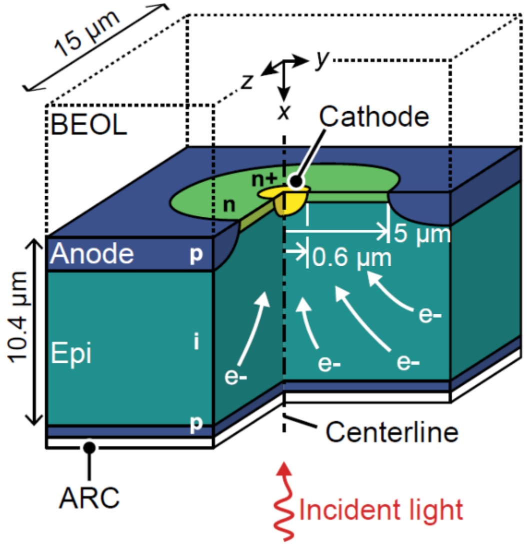


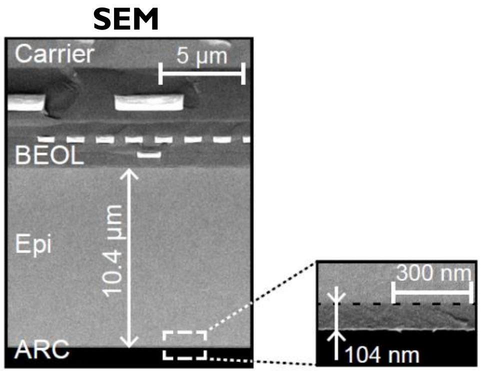


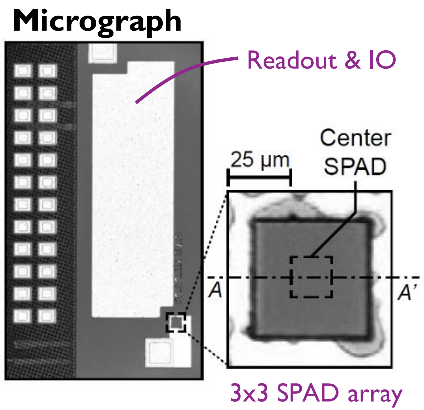
Contents

Proof-of-concept BSI device

- **Goal:**
  - High-performing sensor for d-ToF…
  - …by exploiting charge-focusing effect
- **Features:**
  - Silicon
  - Small spherical cathode
    => Field-line crowding
  - 10-µm-deep intrinsic epi
    => NIR sensitivity
  - BSI







Electric field

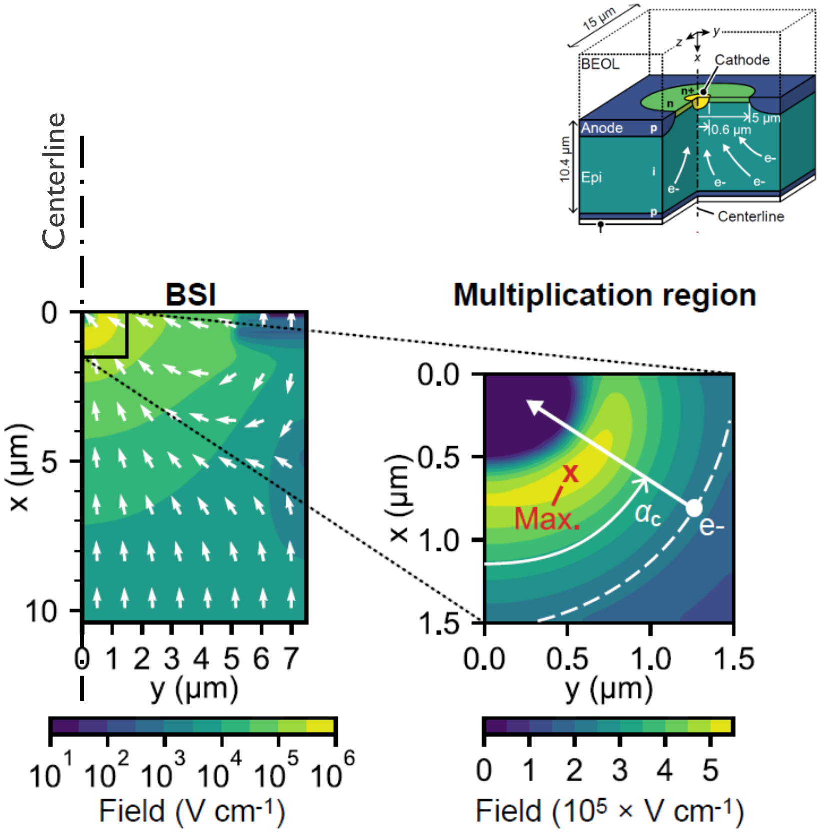
- **Spherically-uniform multiplication field around cathode due to field-line crowding**

+

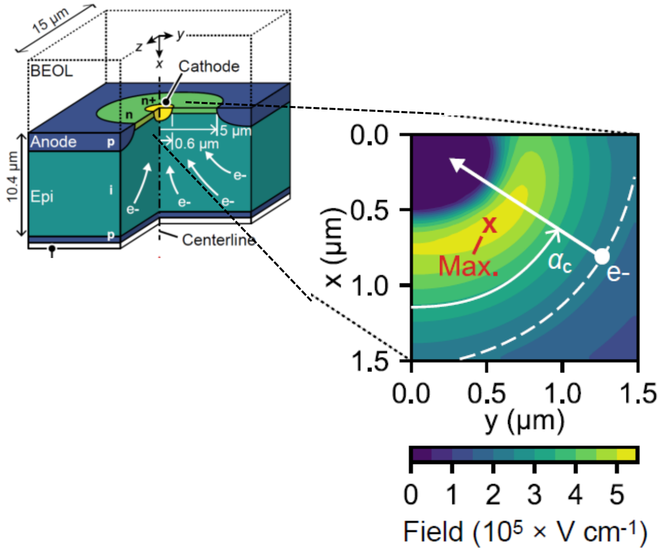
- **Charge-focusing drift field in epi**

+

- **The field reduced on top interface**

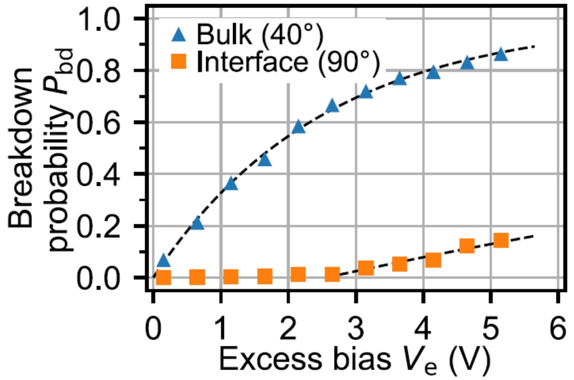


Electric field



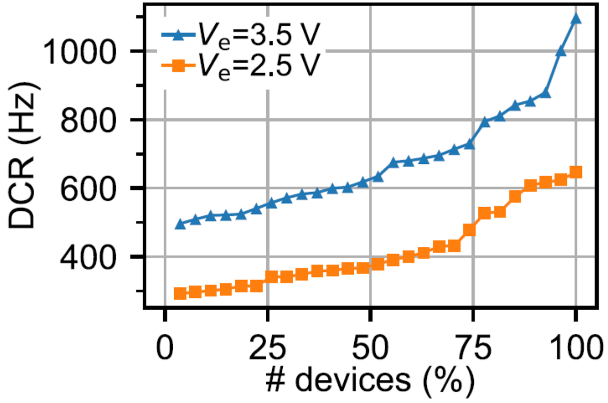
- **Charge-focusing effect**
  - Most carriers are funnelled through multiplication field
  - High PDE
  - Scalable

- **Multiplication field remains 'sensitive to applied bias'**
  - ⇒ Low excess bias required
  - ⇒ Low process sensitivity
  - ⇒ 33 mV/K temp. coeff.

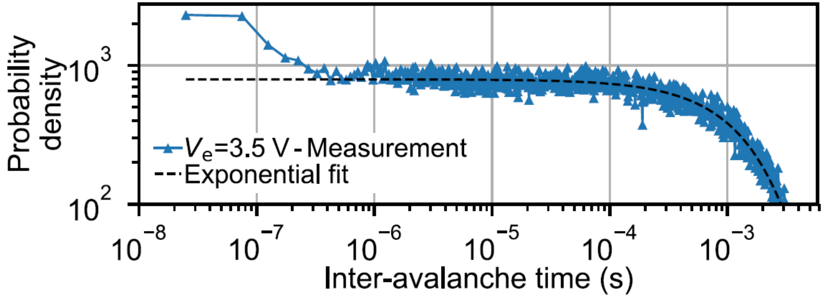


Performance (measured)

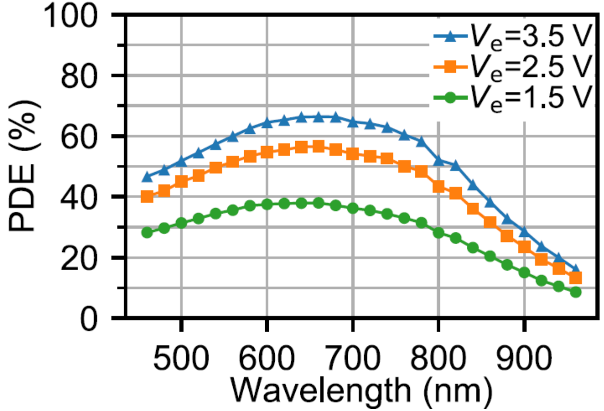
DCR



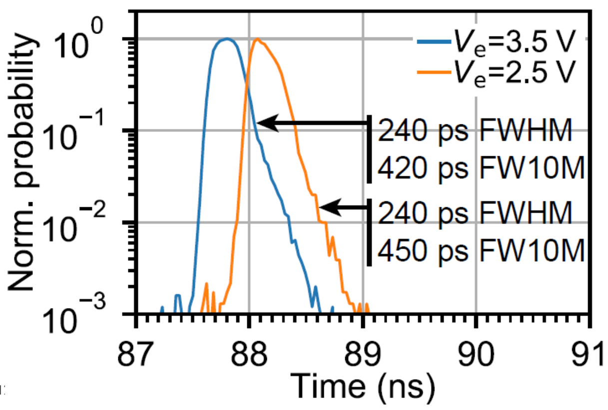
Afterpulsing (< 0.1%)



PDE



Jitter



Performance – NIR sensitive SPADs

	This work [1]	Shimada [2]	Morimoto [3]	Gullinatti [4]	Jegannathan [5]
Technology	BSI 130 nm	BSI 90 nm	BSI 90 nm	FSI	FSI 350 nm
Size	15 µm	6 µm	6.39 µm	50 µm	30 µm
Depth	10.4 µm	7 µm	6 µm	10 µm	14 µm
V_{bd} + V_e	67.4 + 3.5 V	22 + 3 V	30 + 2.5 V	30 + 20 V	49 + 2.5 V
PDE @ 905 nm	27%	33%	28%	20%	~25%
DCR @ 300K	640 Hz	19 Hz	1.8 Hz	3300 Hz	8×10^6 Hz
Timing FWHM	240 ps	137 ps	100 ps	95 ps	200 ps
Afterpulsing	<0.1%	<0.1%	-	2%	14%
Crosstalk	34%	0.5 %	-	0.2%	-

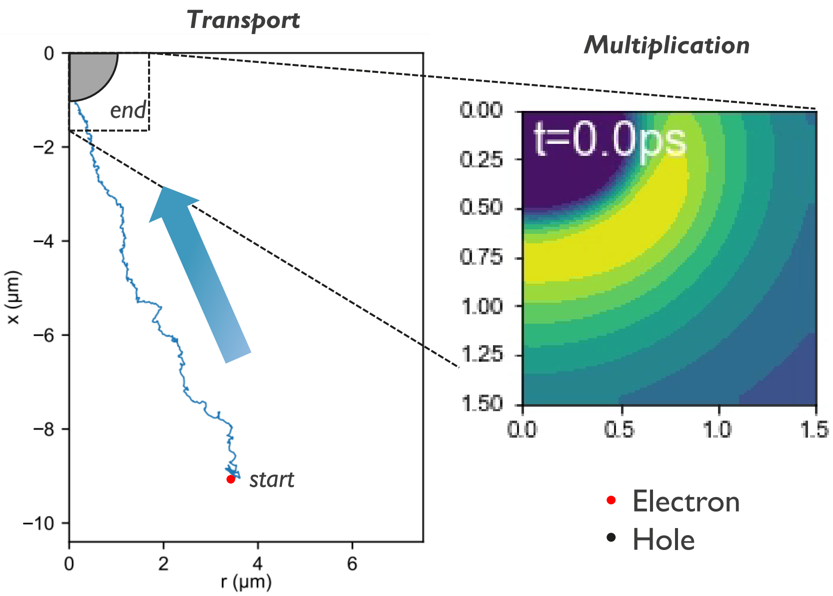
- **Proof-of-concept already performs well, but can be improved**:
  1. **Technology**: DTI, microlenses, metal reflector, scattering features [2,3]
     - PDE ↑ and crosstalk ↓
  2. **Scaling**
     - Pitch ↓ and V_{bd} ↓

[1] E. Van Sieleghem, et al., IEEE Transactions on Electron Devices, vol. 69, no. 3, pp. 1129–1136, 2022.
[2] S. Shimada, et al., in *IEEE International Electron Devices Meeting (IEDM)*, 2021, pp. 446–449.
[3] K. Morimoto, et al., in *IEEE International Electron Devices Meeting (IEDM)*, 2021, pp. 450–453.
[4] A. Gulinatti, et al.,*Optics Express*, vol. 29, no. 3, pp. 4559–4581, 2021.
[5] G. Jegannathan, et al., in *Silicon Photonics XVII. SPIE*, 2022, vol. 1*2006*, pp. p. 40–46.

Contents

Simulation methodology

- **How to accurately estimate SPAD performance?**
  1. Stochastically simulate single-carrier dynamics
  2. Combine behaviour of many individual carriers



E. Van Sieleghem, et al., in *International Image Sensor Workshop (IISW)*, 2021, pp. 49–52.

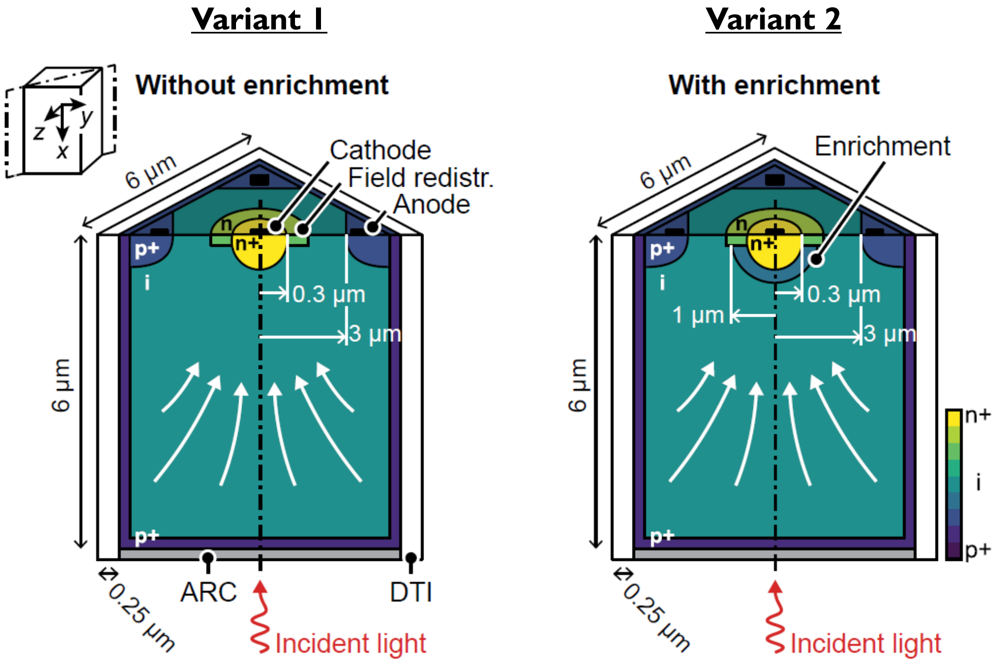
Contents

- Motivation
- Proof-of-concept charge-focusing SPAD
- Intermezzo: Simulation methodology
- **Scaled charge-focusing SPADs**
- Conclusion & outlook

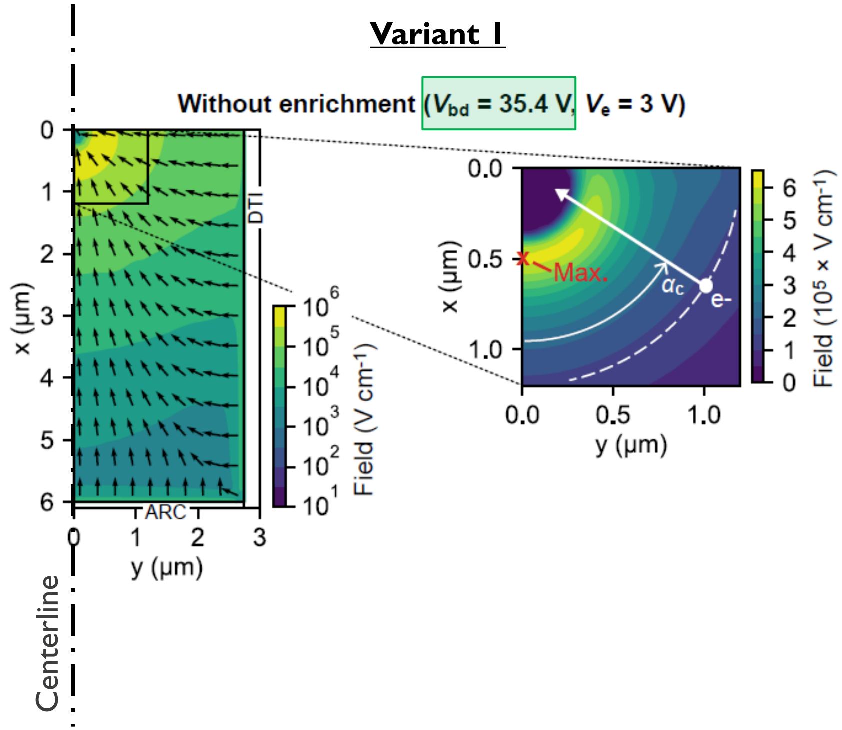
Scaled device design

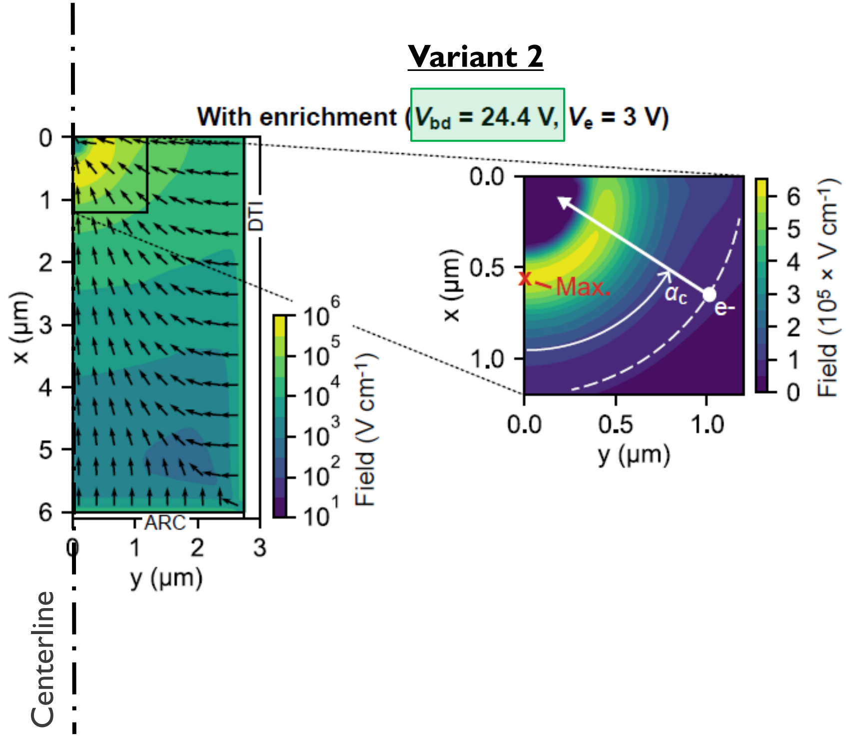
- **CF SPAD is inherently scalable!**
  Two design variants tested

- **Features**
  - Pitch 6 µm
  - Depth 6 µm
  - Reduced cathode radius
  - DTI
  - ‘P-enrichment’ (Optional)
  - No microlens or scattering layer yet



Electric field





Overall: Similar field & breakdown behaviour to 15 µm proof of concept

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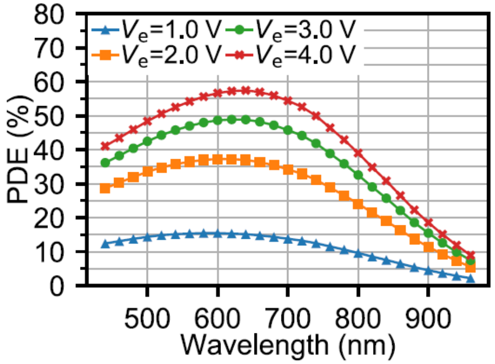
Performance (simulated)

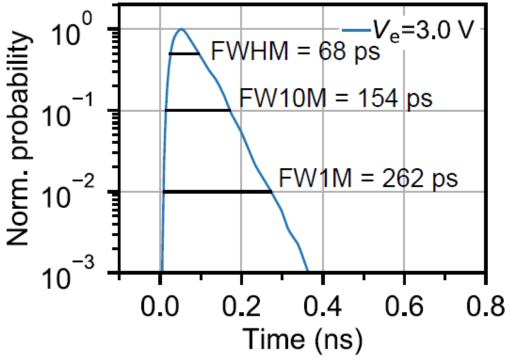
Variant 1

Without enrichment (V_{bd} = 35.4 V)

PDE

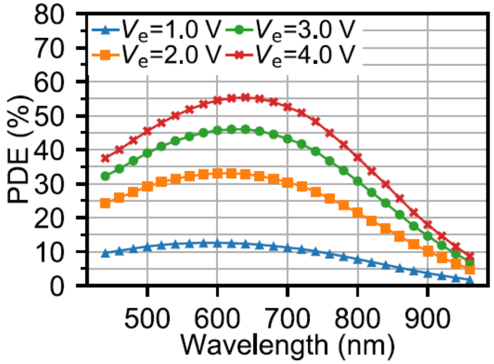


Jitter

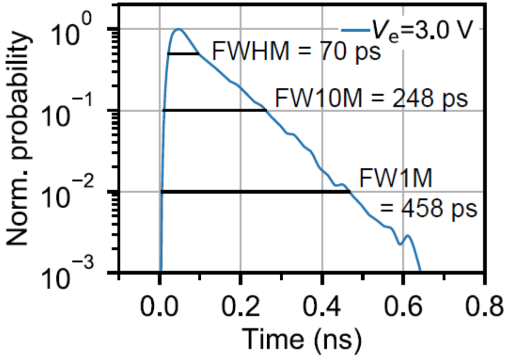


Variant 2

With enrichment (V_{bd} = 24.4 V)

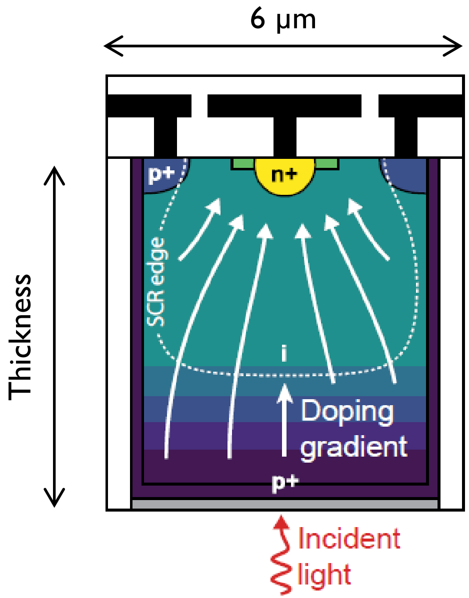


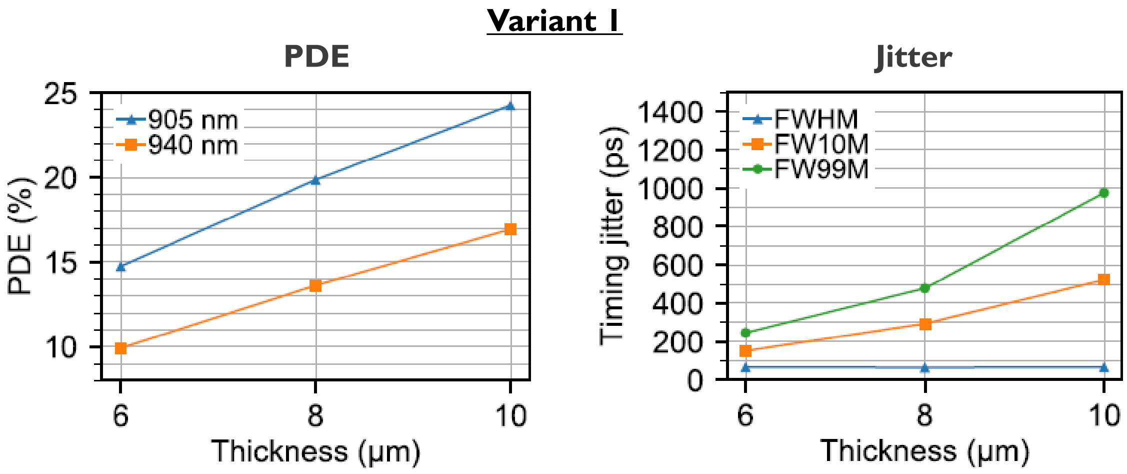
Reminder:
No microlens or scattering layer yet!



Absorption volume extension

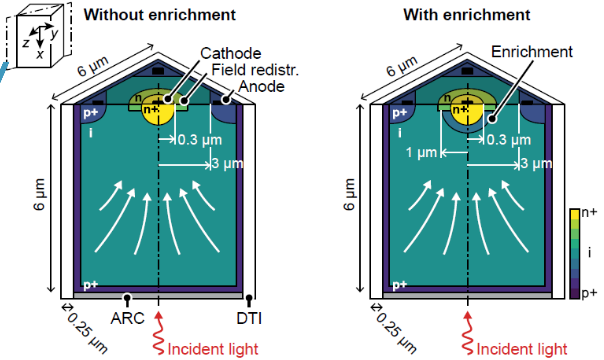
- **Doping gradient provides drift field in regions that would otherwise be neutral**





Reminder:
No microlens or
scattering layer yet!

Expected performance overview



Variant 1 **Variant 2**

	Without enrichment	With enrichment
Technology	BSI 130 nm	BSI 130 nm
Features	Charge focusing, DTI, Metal reflector, *[Doping gradient]**	Charge focusing, DTI, Metal reflector, *[Doping gradient]**
SPAD size	6 µm	6 µm
SPAD depth	6 µm *[8 µm]**	6 µm *[8 µm]**
$V_{bd}+V_e$	35.4+3 V	24.4+3 V
PDE @ 905 nm†	15% *[20%]**	14% *[18%]**
Tunneling noise	$<$ 1 Hz	$<$ 1 Hz
Timing FWHM @ 905 nm	68 ps *[66 ps]**	70 ps *[78 ps]**
Timing FW10M @ 905 nm	154 ps *[302 ps]**	248 ps *[444 ps]**
Junction capacitance	0.3 fF	0.3 fF

[. . .]* With an extended absorption volume and tuned doping gradient.

†Without optical microlenses (84% DTI fill factor) and without light trapping.

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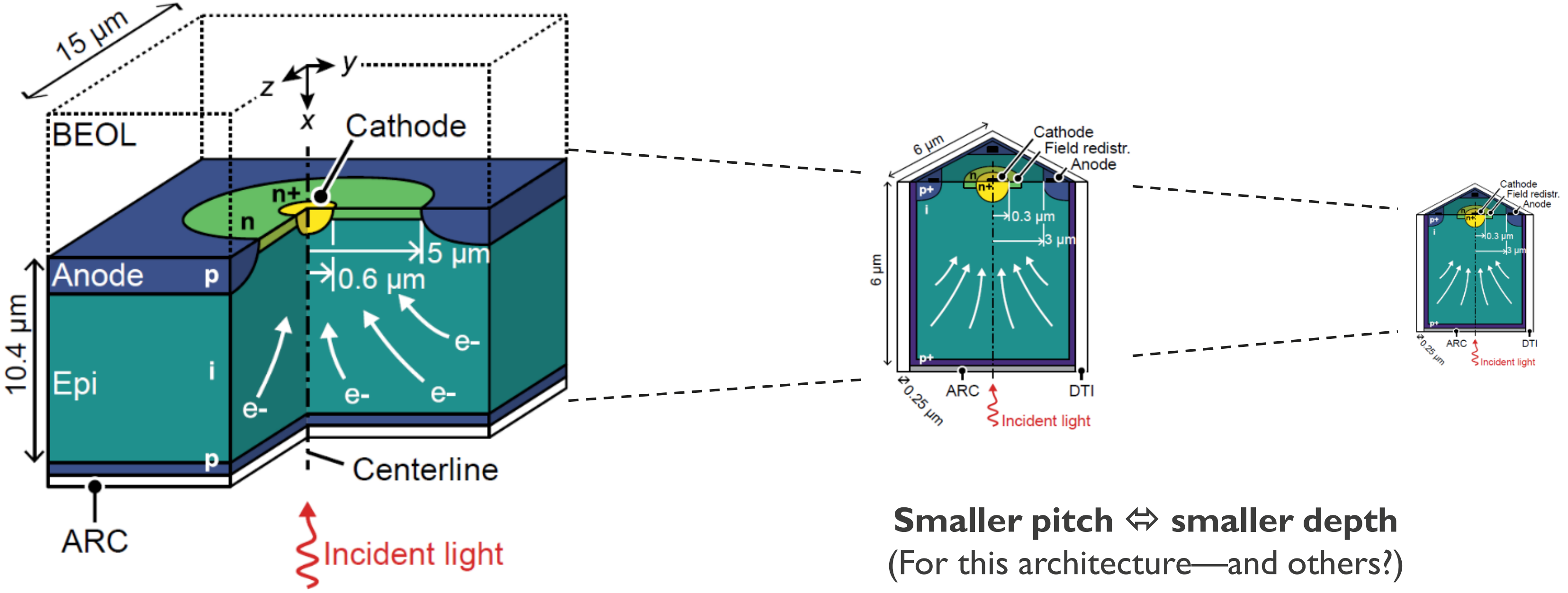
Where does the scaling end?



Smaller pitch ⇔ smaller depth
(For this architecture—and others?)

The application sets the trade-off…

Contents

Conclusion & Outlook

- **SPADs** are becoming an important technology for **d-ToF LIDAR applications**, but **array integration w/ high PDE** remains challenging

- **Our solution: Charge focusing BSI SPADs**
  - State-of-the-art PDE
  - Scalable, low excess bias, good timing resolution, ...

- **Future work**
  - Improve performance through scaling (V_{bd}, noise, ...)
  - Dense array integration w/ deep trench isolation

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ARENBERG DOCTORAL SCHOOL
Faculty of Engineering Science

Near-Infrared Enhanced Silicon Single-Photon Avalanche Diodes for Direct Time-of-Flight Applications

Edward Van Sieleghem

Supervisor:
Prof. dr. Chris Van Hoof

Dissertation presented in partial fulfillment of the requirements for the degree of Doctor of Engineering Science (PhD): Electrical Engineering

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