Charge-Focusing SPAD Image Sensors for Low Light Imaging Applications

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Canon Inc.

Kazuhiro Morimoto

Outline

- Background & Motivation
- Proposal & Simulation
- Experimental Results
- Summary & Future Perspectives

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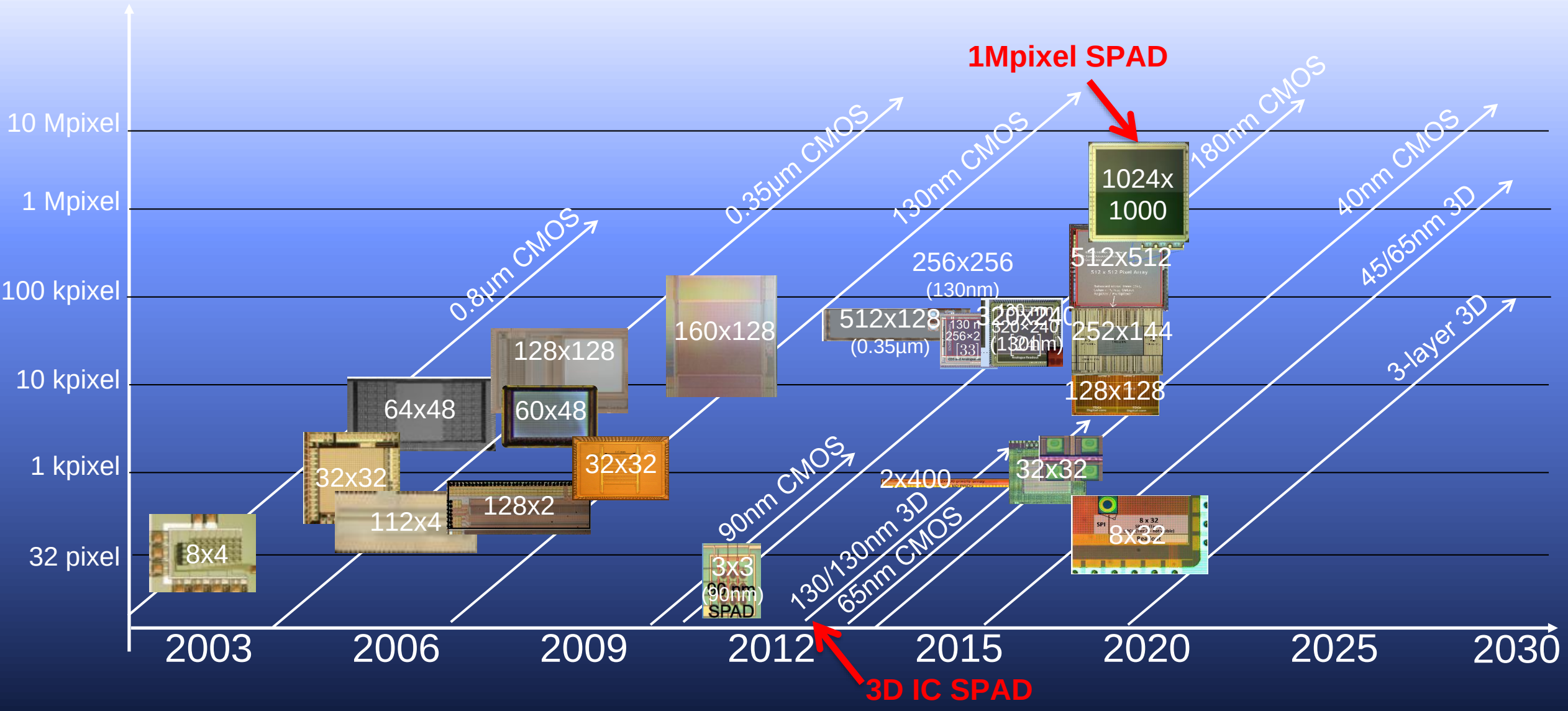
Scaling of SPAD Arrays

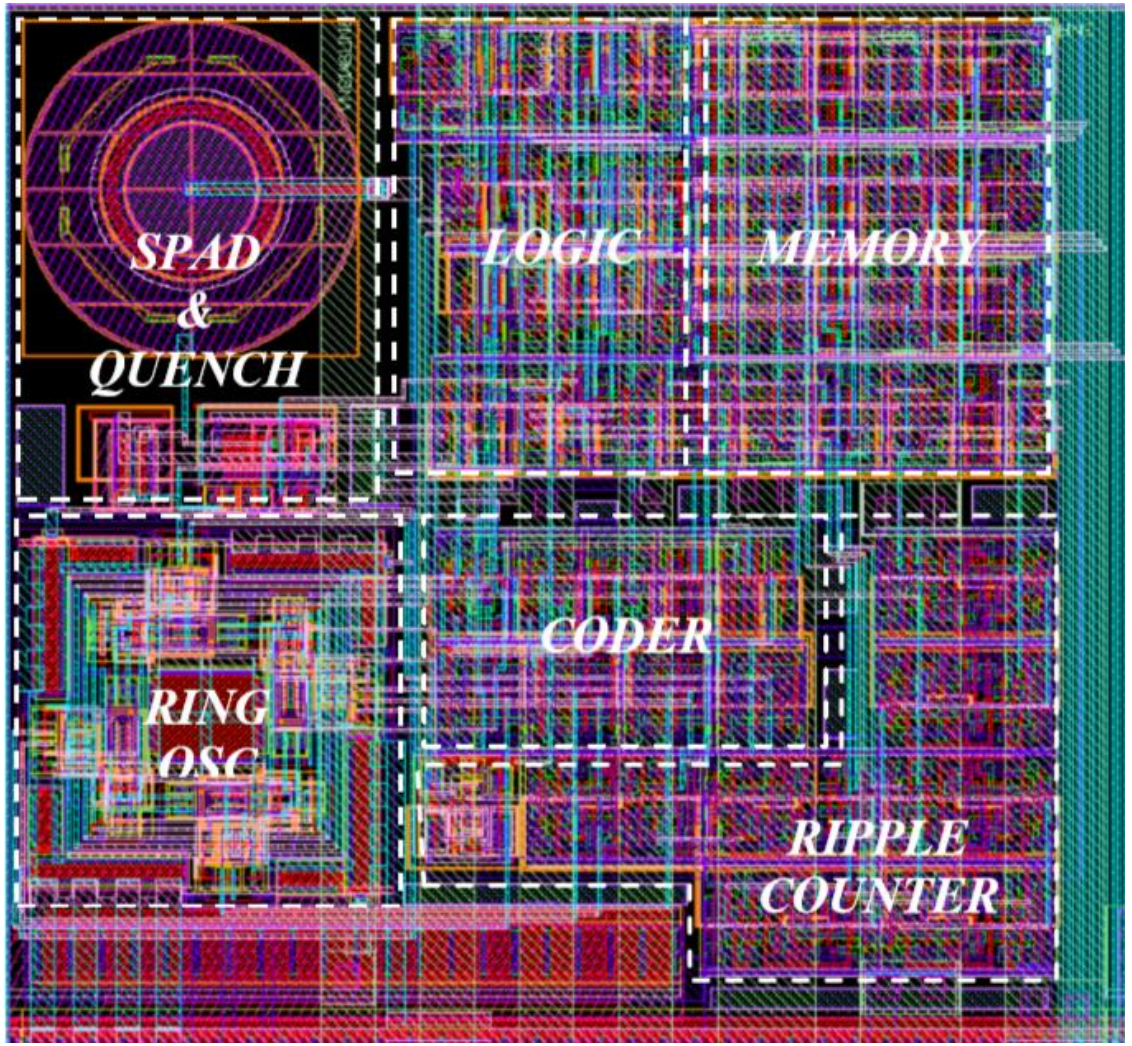


Frontside-illuminated (FSI) SPAD Pixels

SPAD and pixel circuit share a limited pixel area

Megaframe (2009)

- 32 × 32 pixels
- Pixel pitch = 50 µm
- Fill factor = 1.2%
- 580 Transistors / pix



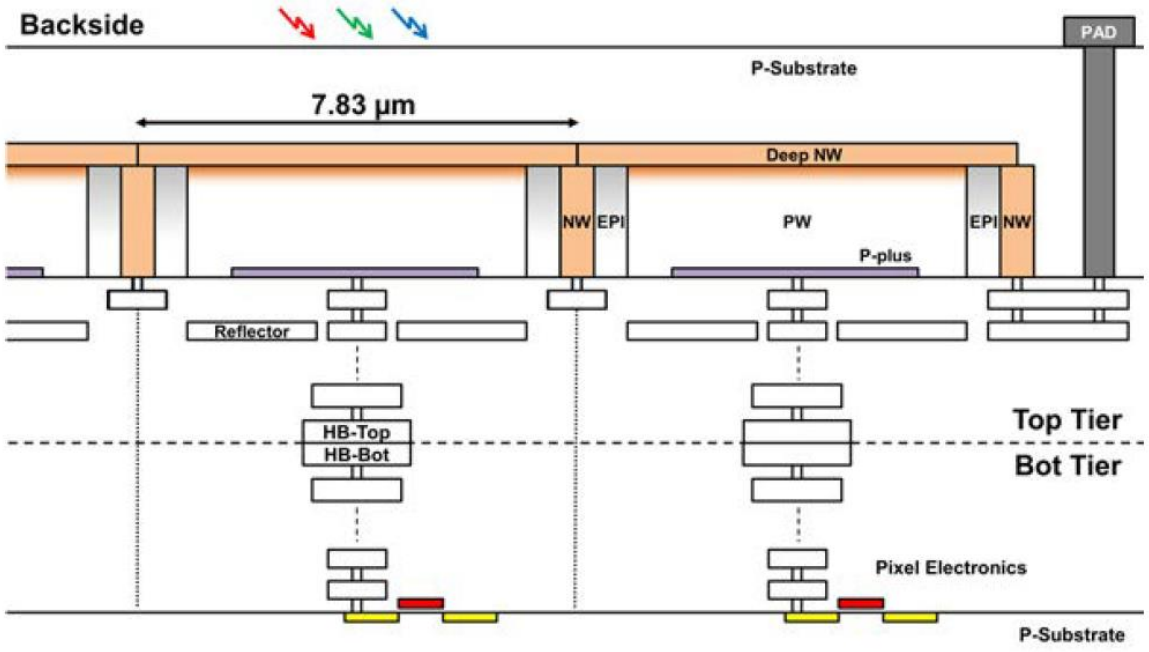
50 µm

J. Richardson *et al.*, CICC (2009),
M. Gersbach *et al.*, ESSCIRC (2009),
D. Stoppa *et al.*, ESSCIRC (2009)

Technology Trend: 3D Stacking

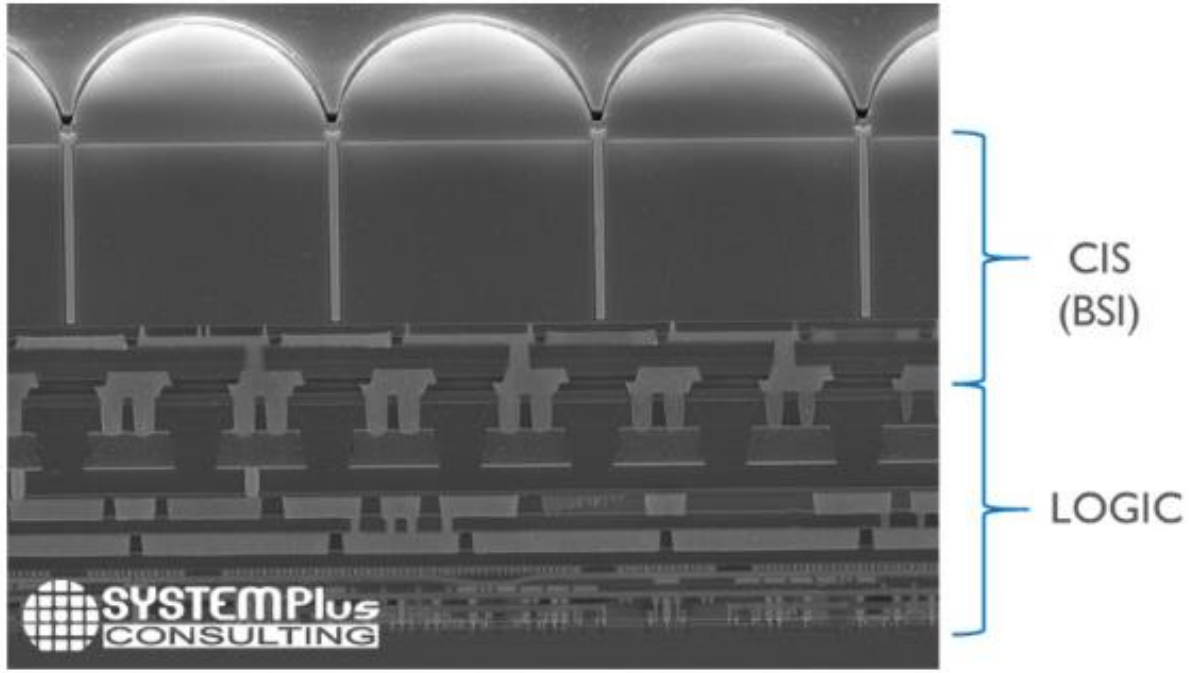
Academy and industry are striving for BSI 3D-stacked SPAD arrays

The University of Edinburgh / STM (2016)



T. Al Abbas *et al*., IEDM (2016)

Apple / Sony (2020)



https://www.i-micronews.com/with-the-apple-ipad-lidar-chip-sony-landed-on-the-moon-without-us-knowing/

SPAD Pixel Miniaturization

➢ **Benefits:**

- Compact system, reduced cost
- High spatial resolution
- High dynamic range
- Low DCR, afterpulsing, timing jitter
- Low power consumption

➢ **Challenges:**

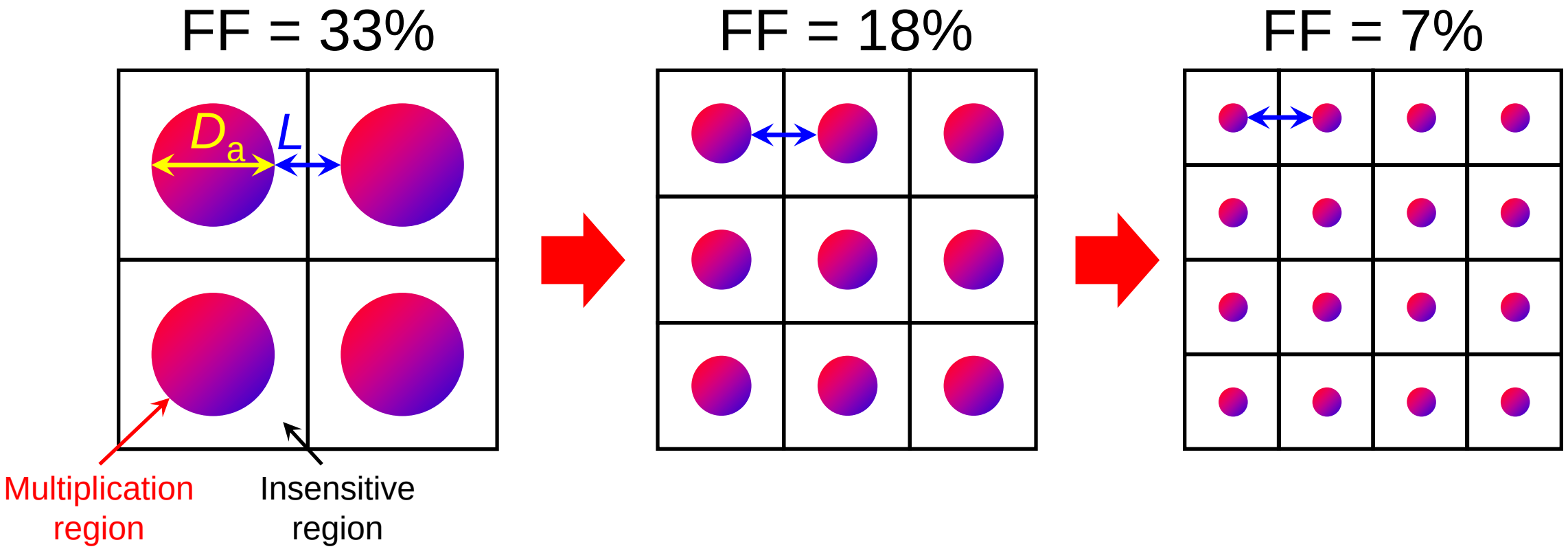
- Limited fill factor
- Limited PDP, PDE
- High crosstalk

Challenge in SPAD Pixel Miniaturization

Pixel miniaturization degrades fill factor (FF)

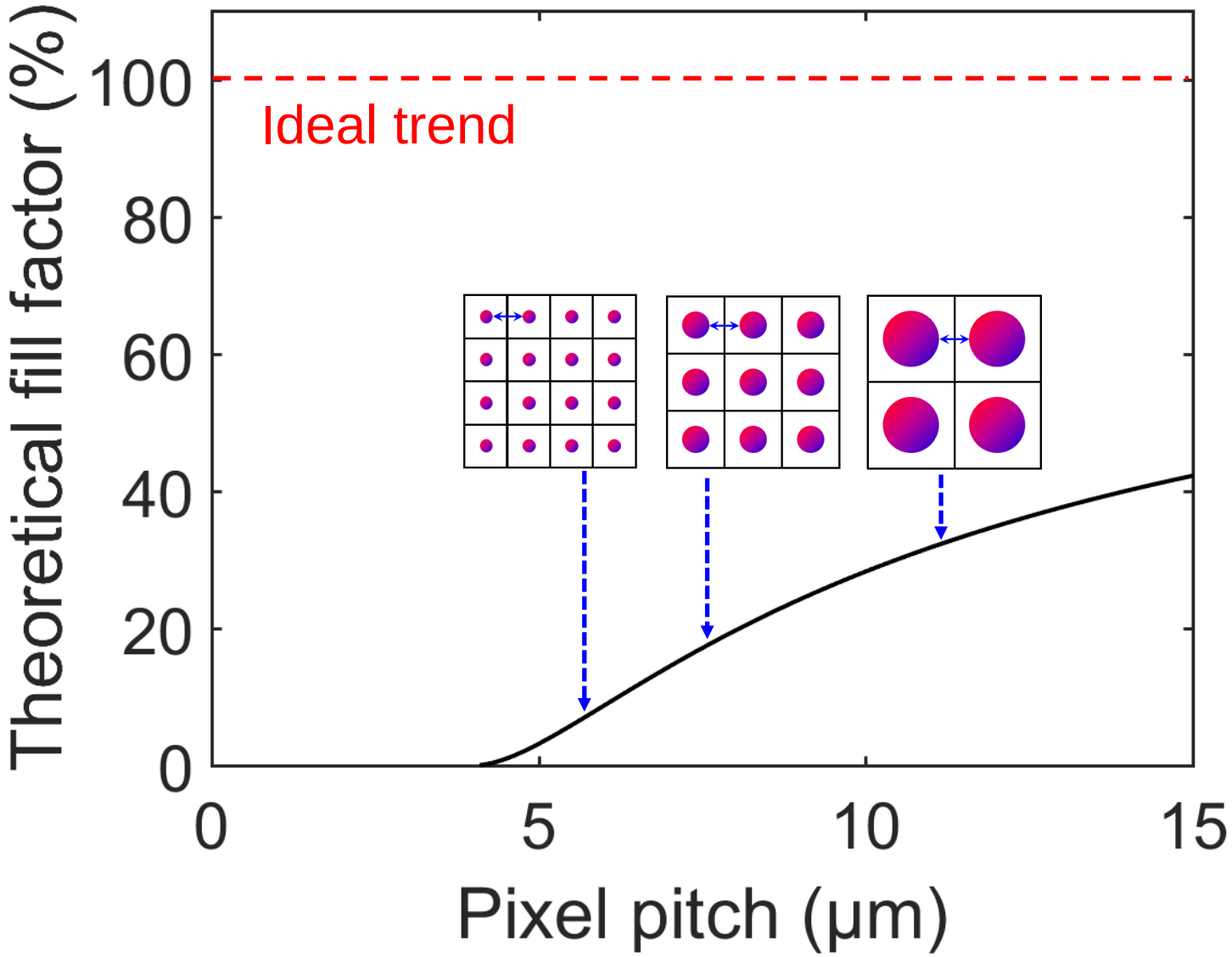
Pixel pitch = $D_a + L$

Unscalable !



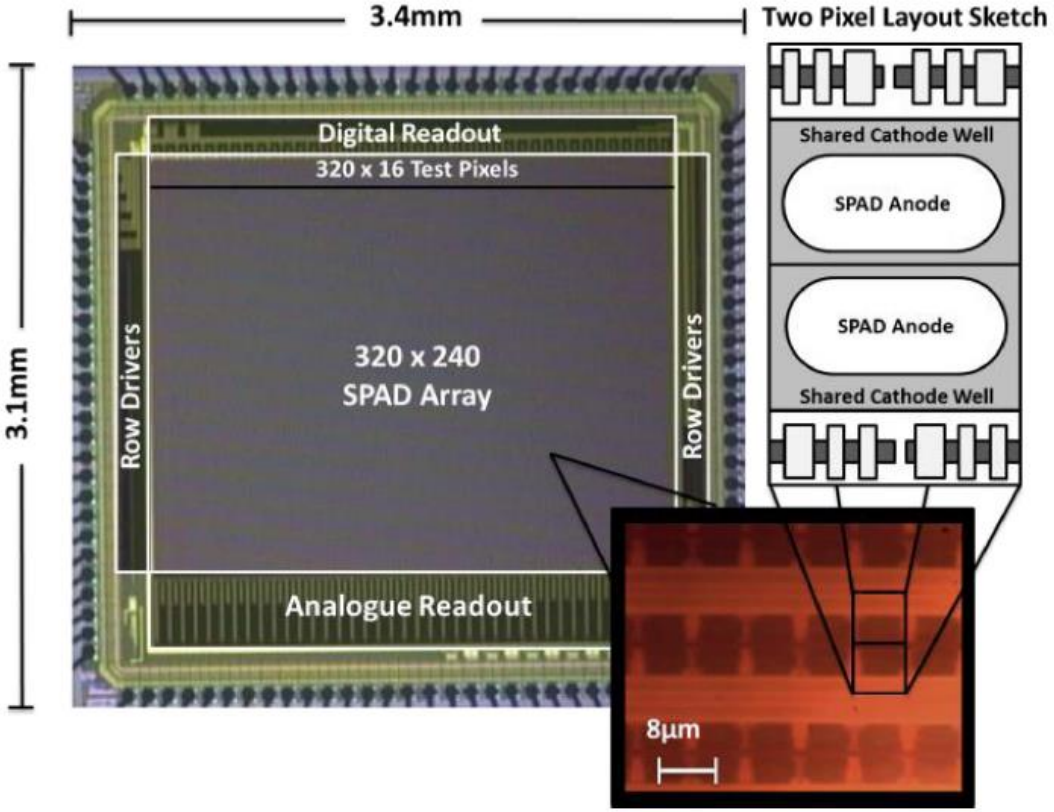
Challenge in SPAD Pixel Miniaturization

Pixel miniaturization degrades fill factor (FF)

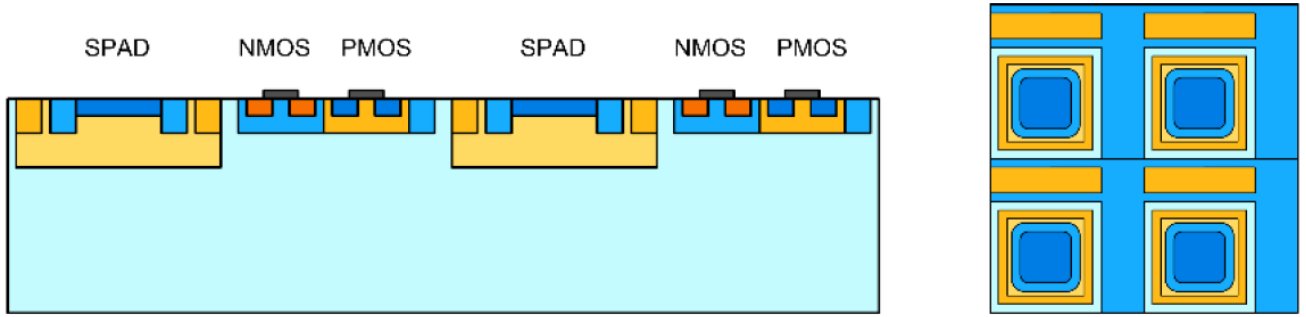


Well Sharing

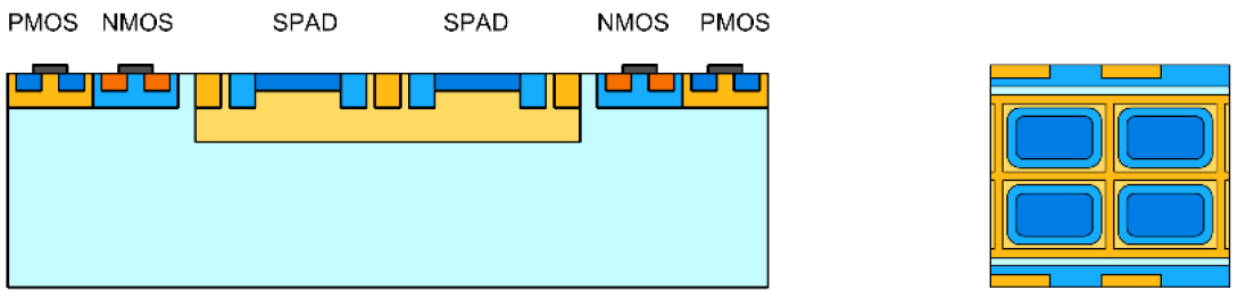
Sharing isolation well to enhance FF



No sharing



Well sharing

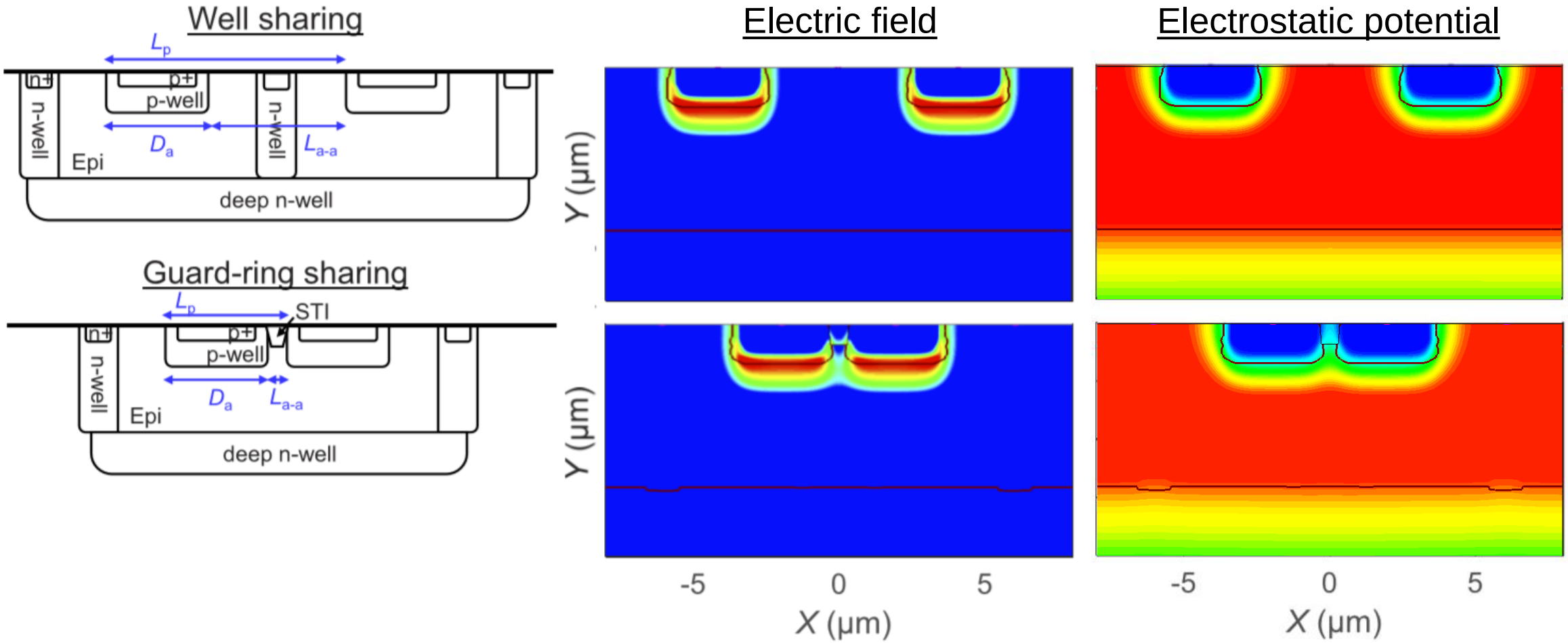


N. A. W. Dutton *et al*., TED, 63(1) (2016)

M. Perenzoni *et al*., Sensors, 16(5), 745 (2016)

Guard-Ring (GR) Sharing

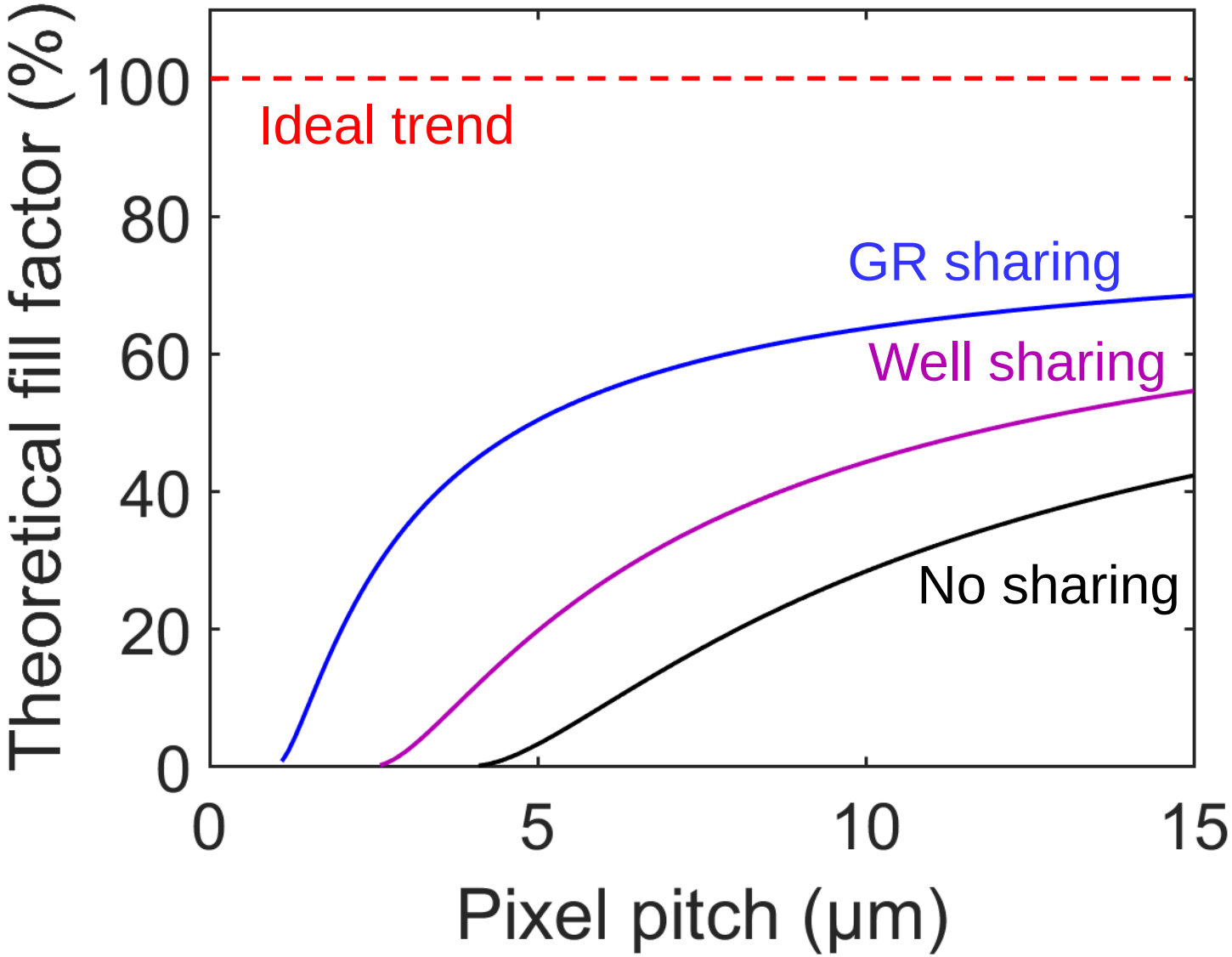
Eliminating isolation well and sharing GR to achieve 2.2 μm-pitch pixel



K. Morimoto *et al*., Opt. Express, 28(9), 13068 (2020)

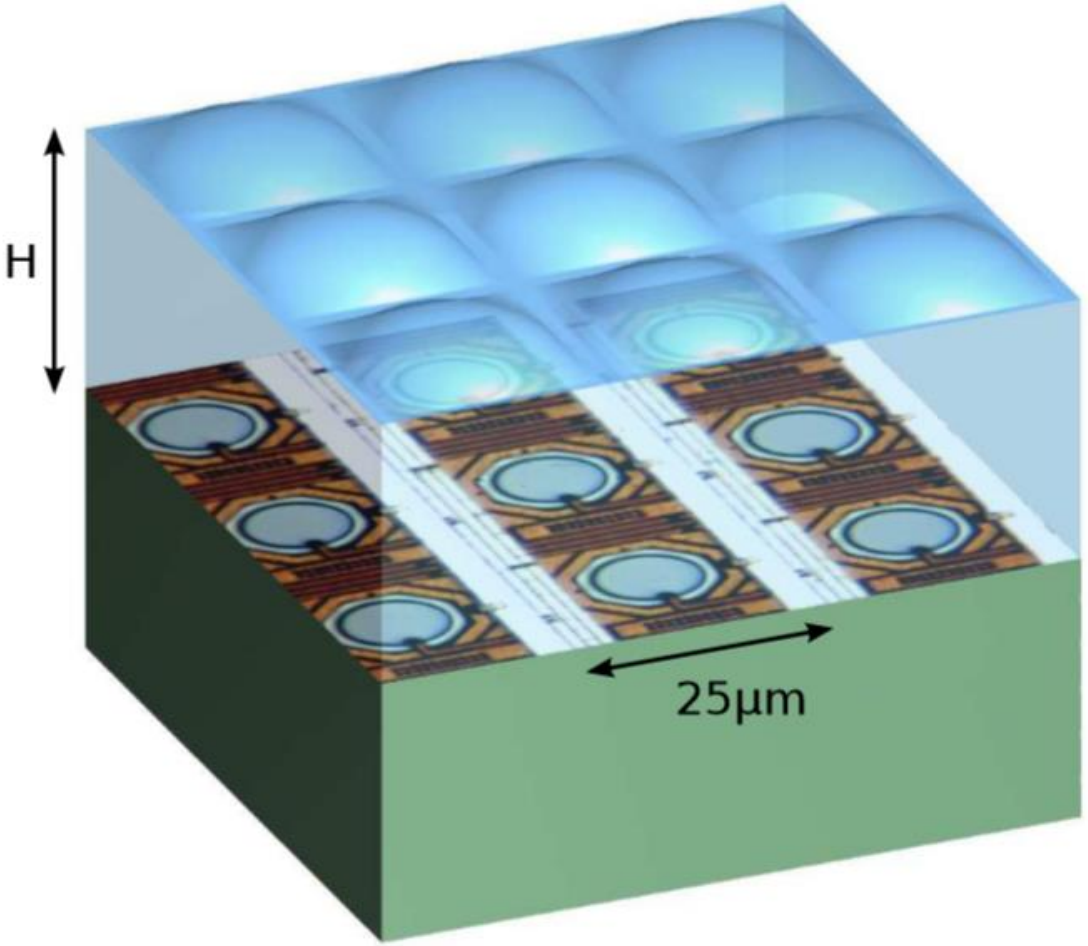
FF Trends for “Shared” SPADs

"Sharing" improves FF, but still far from ideal trend



On-Chip Microlens (EPFL / USZ)

Optically focusing light to virtually enhance the active area



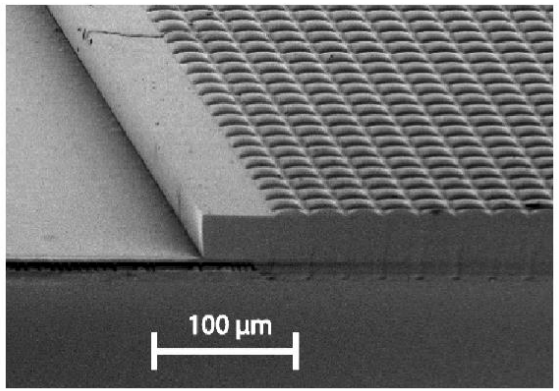
J. M. Pavia *et al*., Opt. Express 22(4) (2014)

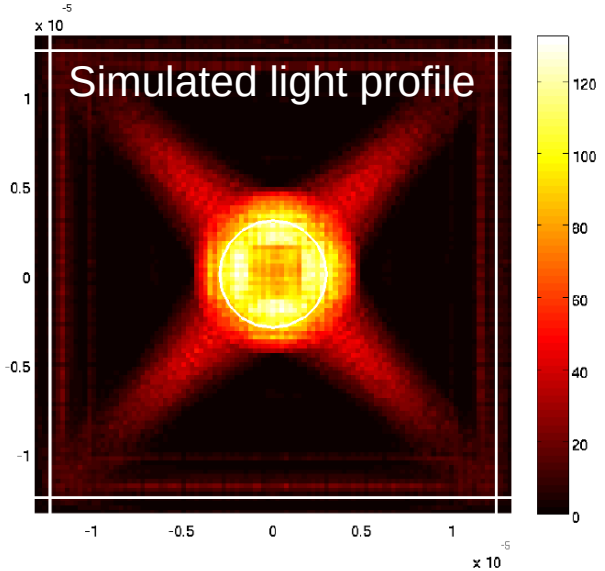
■ Advantage

- Enhanced effective fill factor (>10 ×)

■ Issues

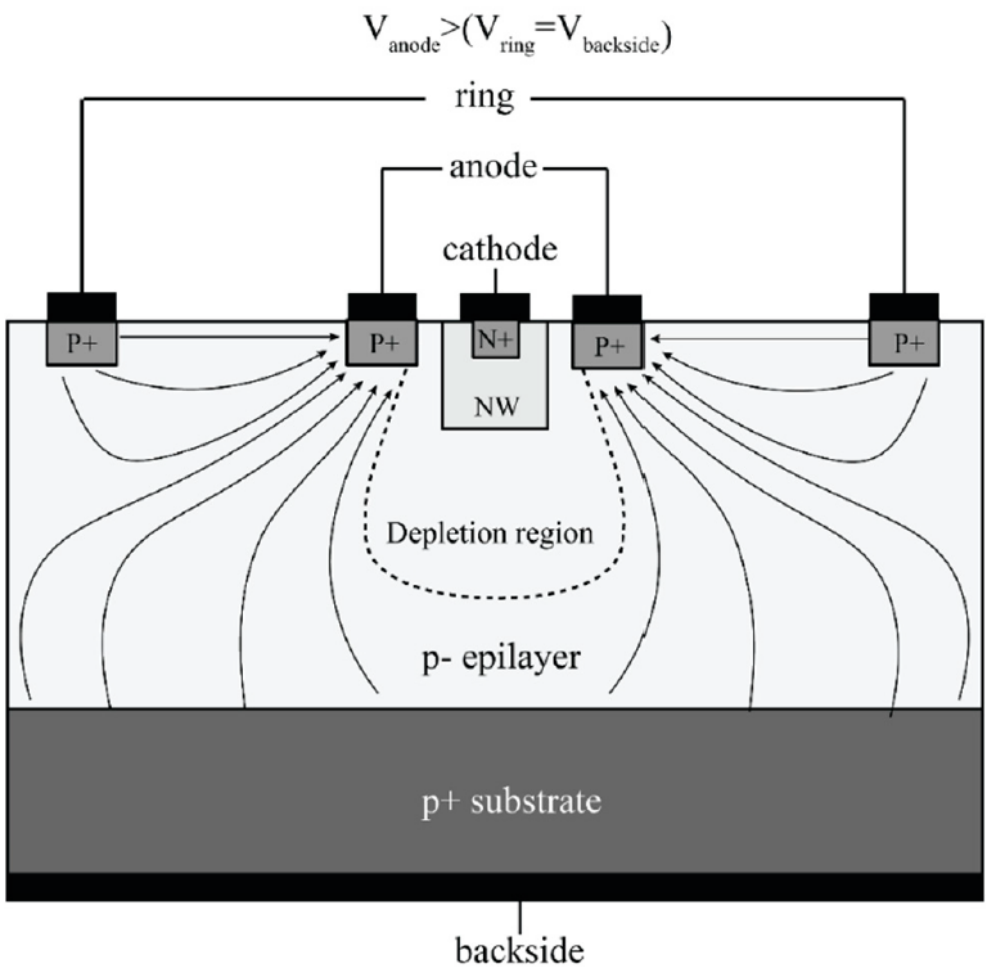
- Less effective for too small active area; small f-number lenses; tilted light





Current-Assisted SPAD (Vrije Universiteit Brussel)

Photocharges focused to multiplication region assisted by current biasing



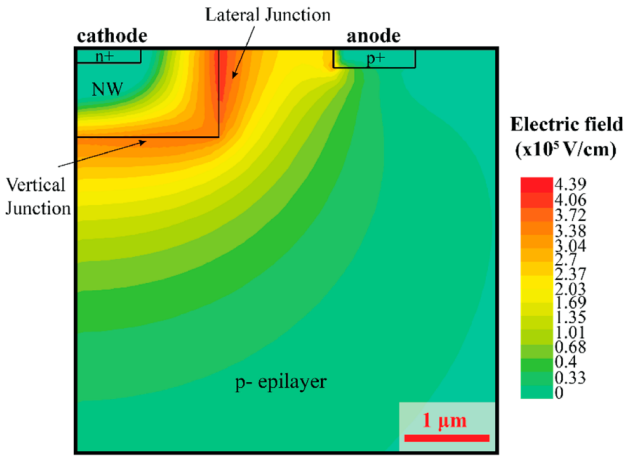
G. Jegannathan *et al.*, Appl. Sci. 10(6), 2155 (2020)

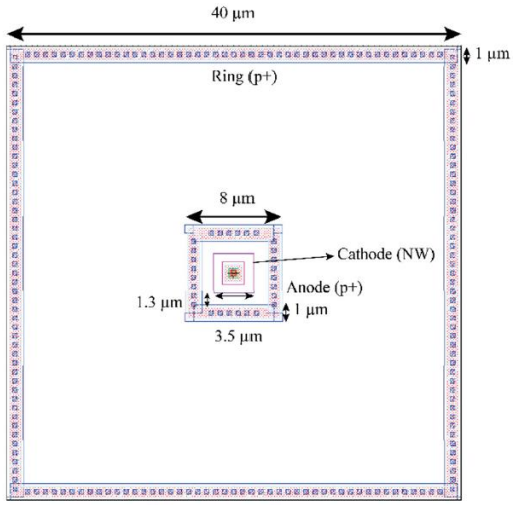
■ Advantage

- Large photo-conversion volume (potentially higher PDE)

■ Issues

- Constant current (>10 µA/pix)
- Large DCR (>1 Mcps/pix)
- Not scalable (currently 40 µm-pitch)





Objective

To propose and verify next-gen. SPAD concept to achieve:

- Scalability (pixel pitch $\leq$ 6 µm)
- High FF (up to 100%)
- Low noise (DCR, afterpulsing, crosstalk)
- Flexible choice of optics

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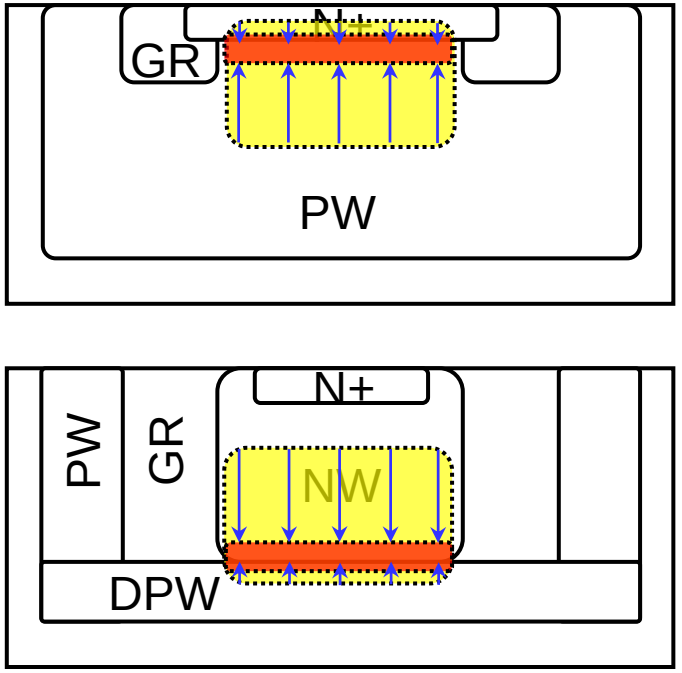
Conventional SPAD Devices

■ Conventional SPADs



: Multiplication region

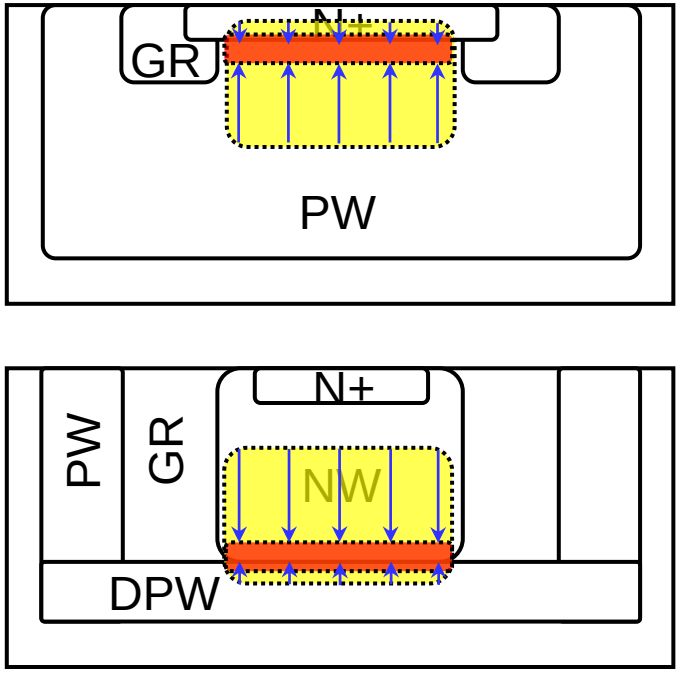
: Photo-sensitive region

: Photo-charge path

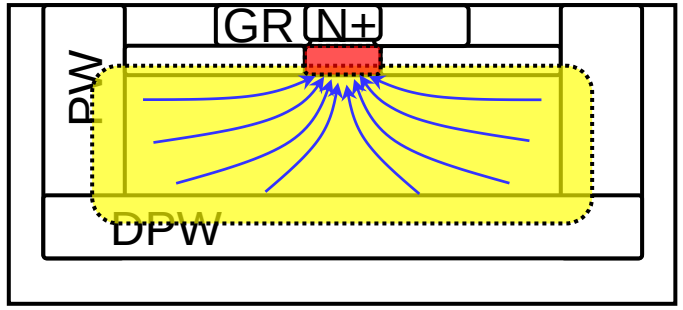
- Only vertical photo-charge collection
- Multiplication area = Photo-sensitive area
- Trade-off between DCR and PDE

Proposal of Charge-Focusing SPAD

■ Conventional SPADs



■ Charge-Focusing SPAD



: Multiplication region

: Photo-sensitive region

: Photo-charge path

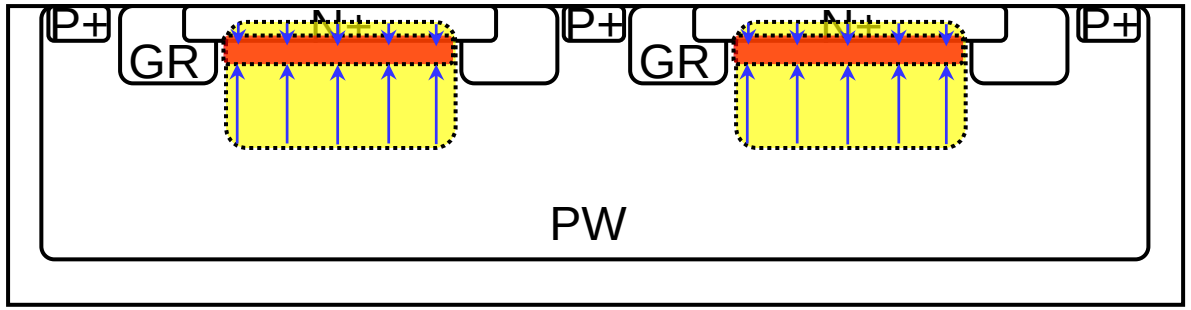
- Only vertical photo-charge collection
- Multiplication area = Photo-sensitive area
- Trade-off between DCR and PDE

- Vertical + horizontal photo-charge collection
- Multiplication area << Photo-sensitive area
- Low DCR & high PDE

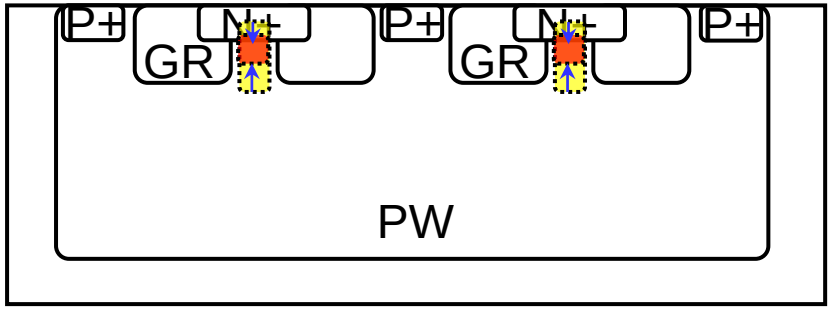
Advantages of Our Technology

1. High PDE for miniaturized pixel array

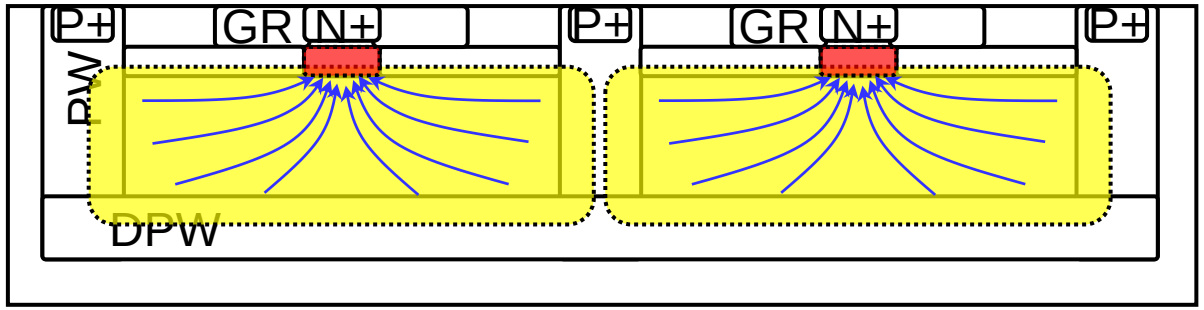
■ Conventional SPAD

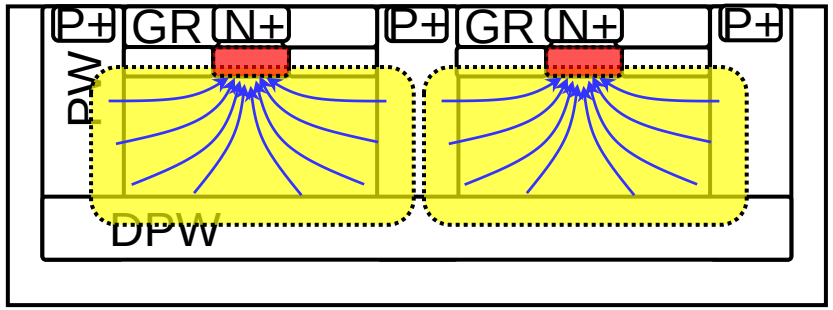


Pixel miniaturization



■ Charge-Focusing SPAD

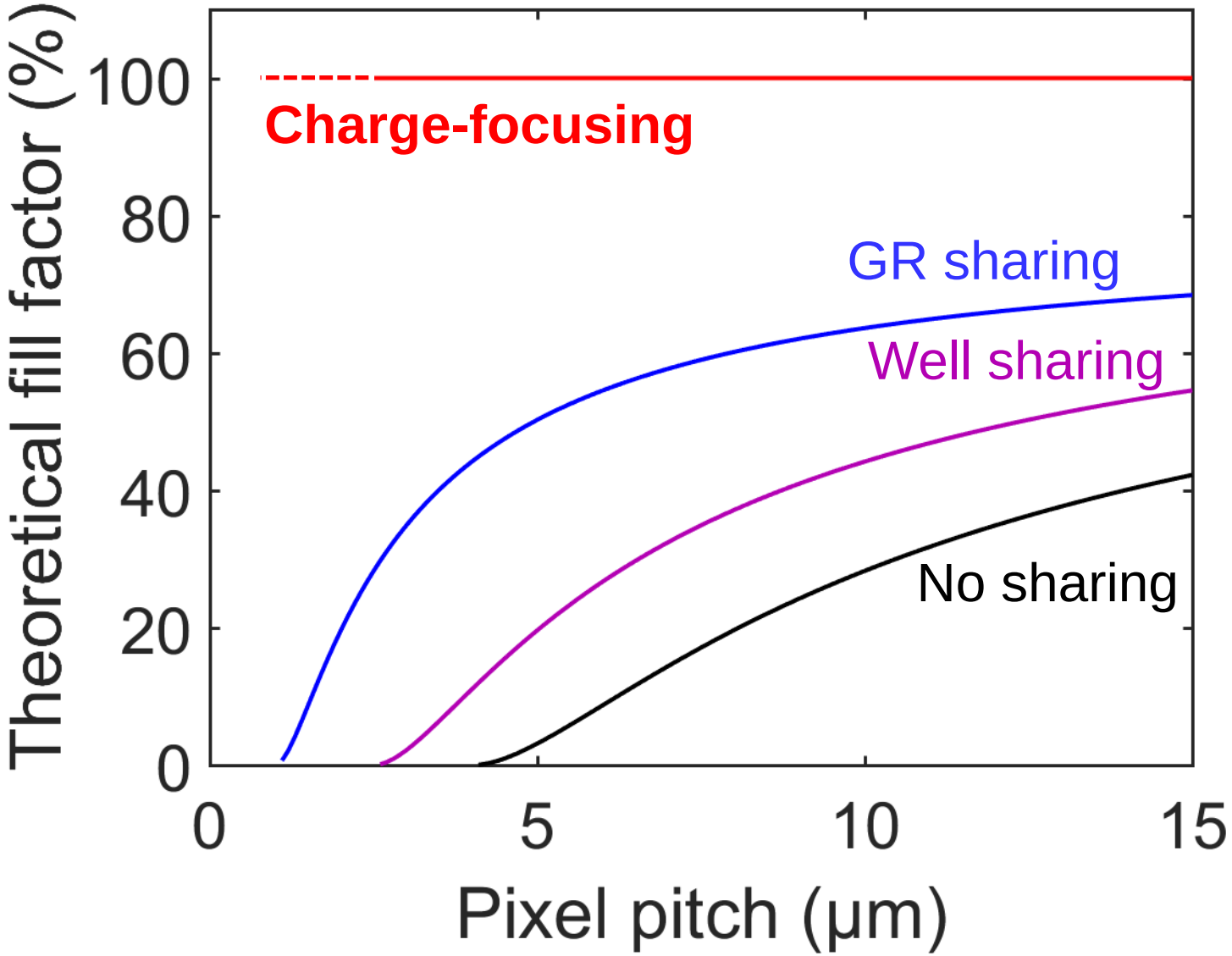




- Poor fill factor & PDP for small pixels
- Near-100% fill factor for small pixels

Advantages of Our Technology

1. High PDE for miniaturized pixel array



Advantages of Our Technology

2. Miniaturized multiplication area

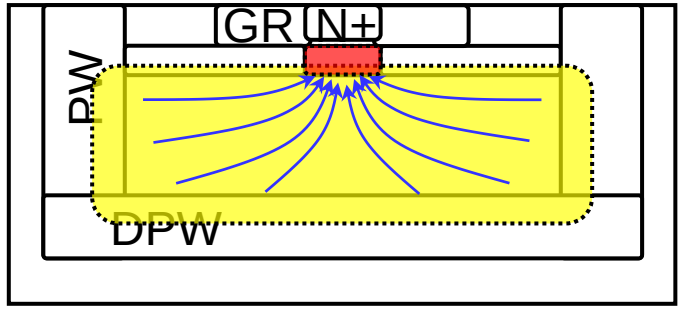
- Low DCR (DCR density*<0.02 cps/μm^2)
- Low hot pixel population (<1%)

3. Extended photo-sensitive area

- High PDP (>60% for visible light)
- High fill factor (Near-100%)

4. Small p-n junction capacitance

- Low afterpulsing probability
- Low light emission crosstalk
- Low power consumption
- Short dead time



: Multiplication region

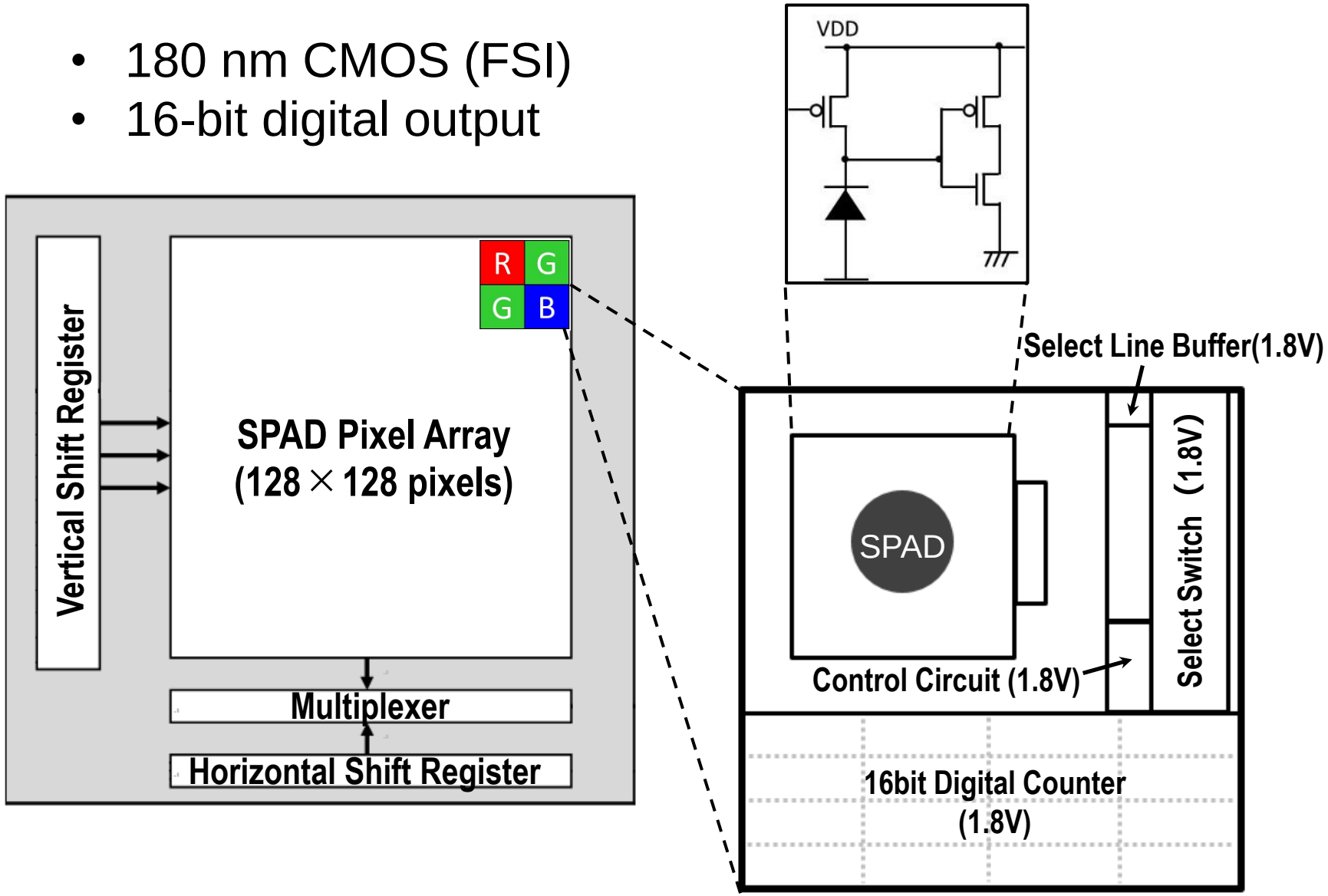
: Photo-sensitive region

: Photo-charge path

*Room temperature DCR per unit photo-sensitive area

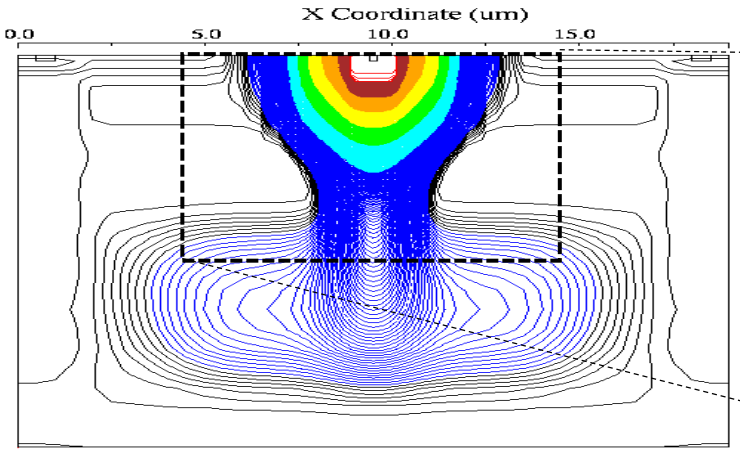
Proof-of-Concept SPAD Image Sensor

- 180 nm CMOS (FSI)
- 16-bit digital output

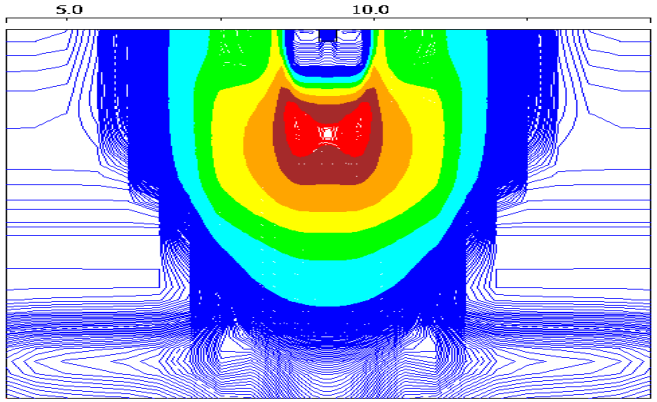


SPAD Pixel Design

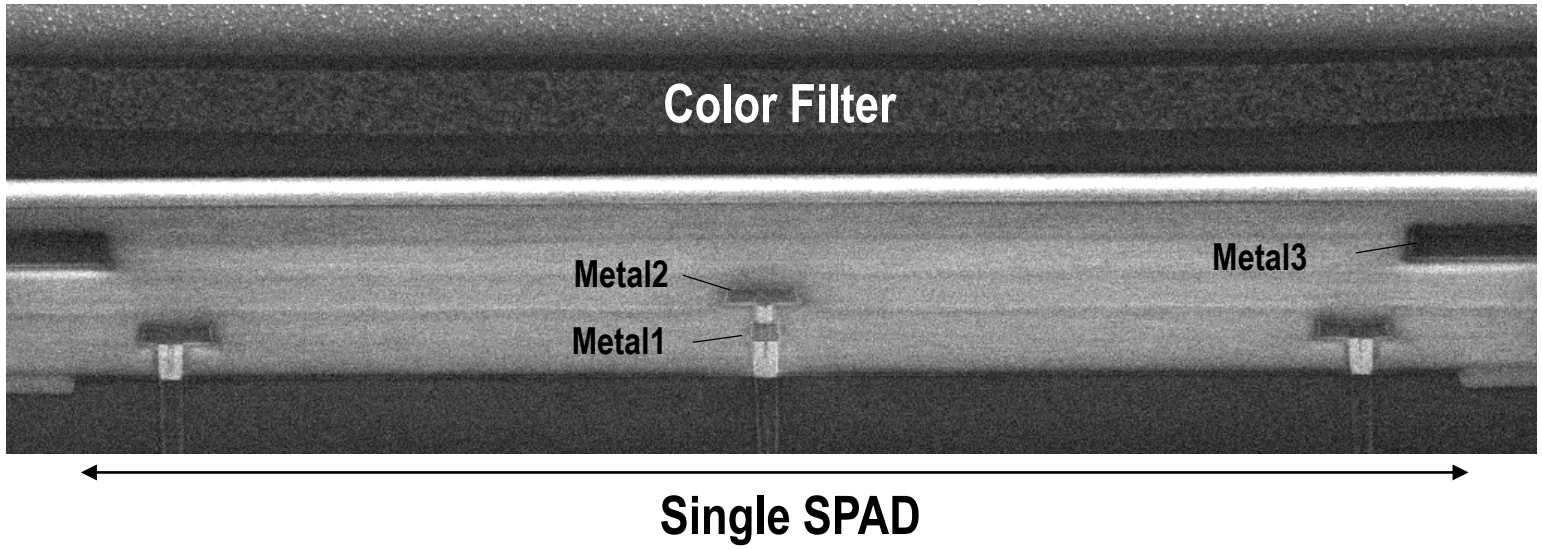
Electrostatic potential sim.



Electric field sim.



Cross-sectional SEM image



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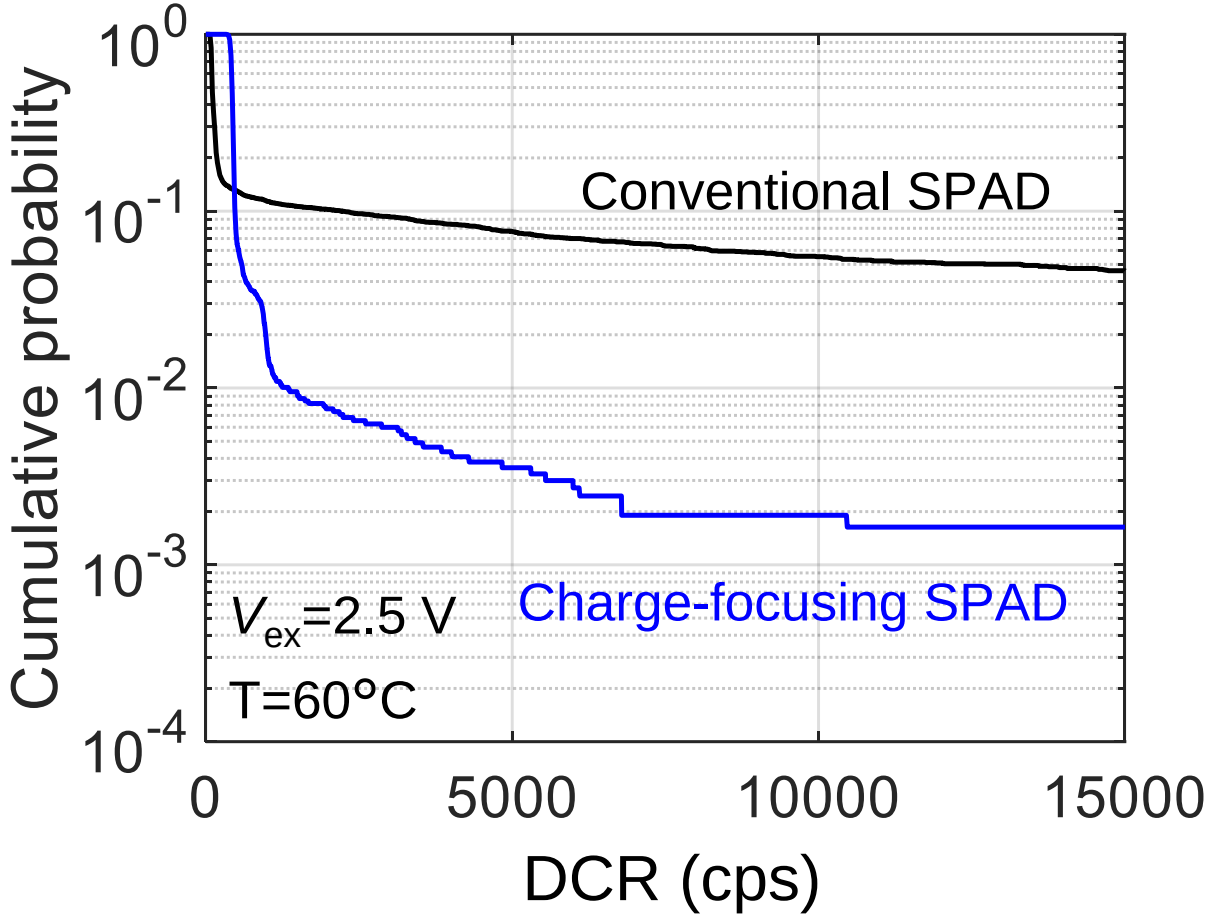
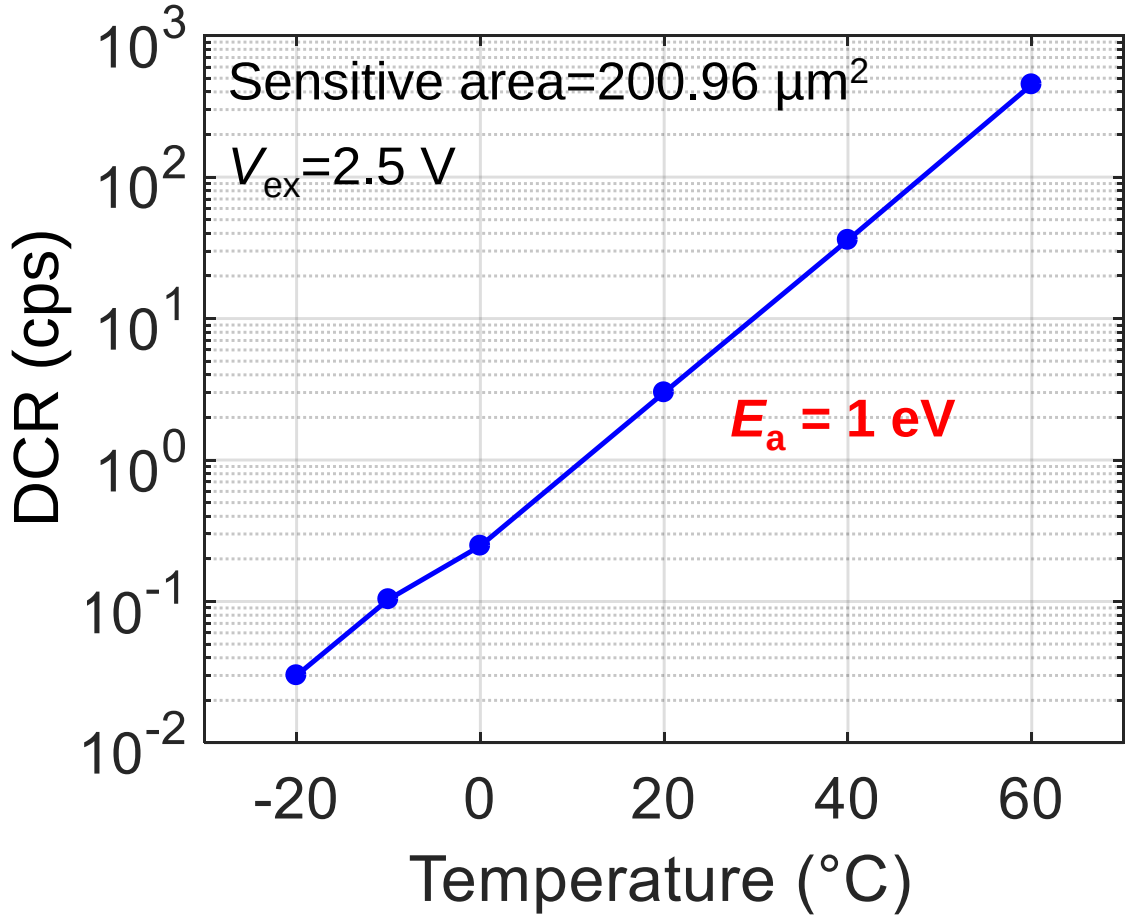
Dark Count Rate (DCR)

Hot pixel population < 1%, DCR = 3 cps, DCR density = 0.015 cps/μm² (at RT)

Hot pixel population

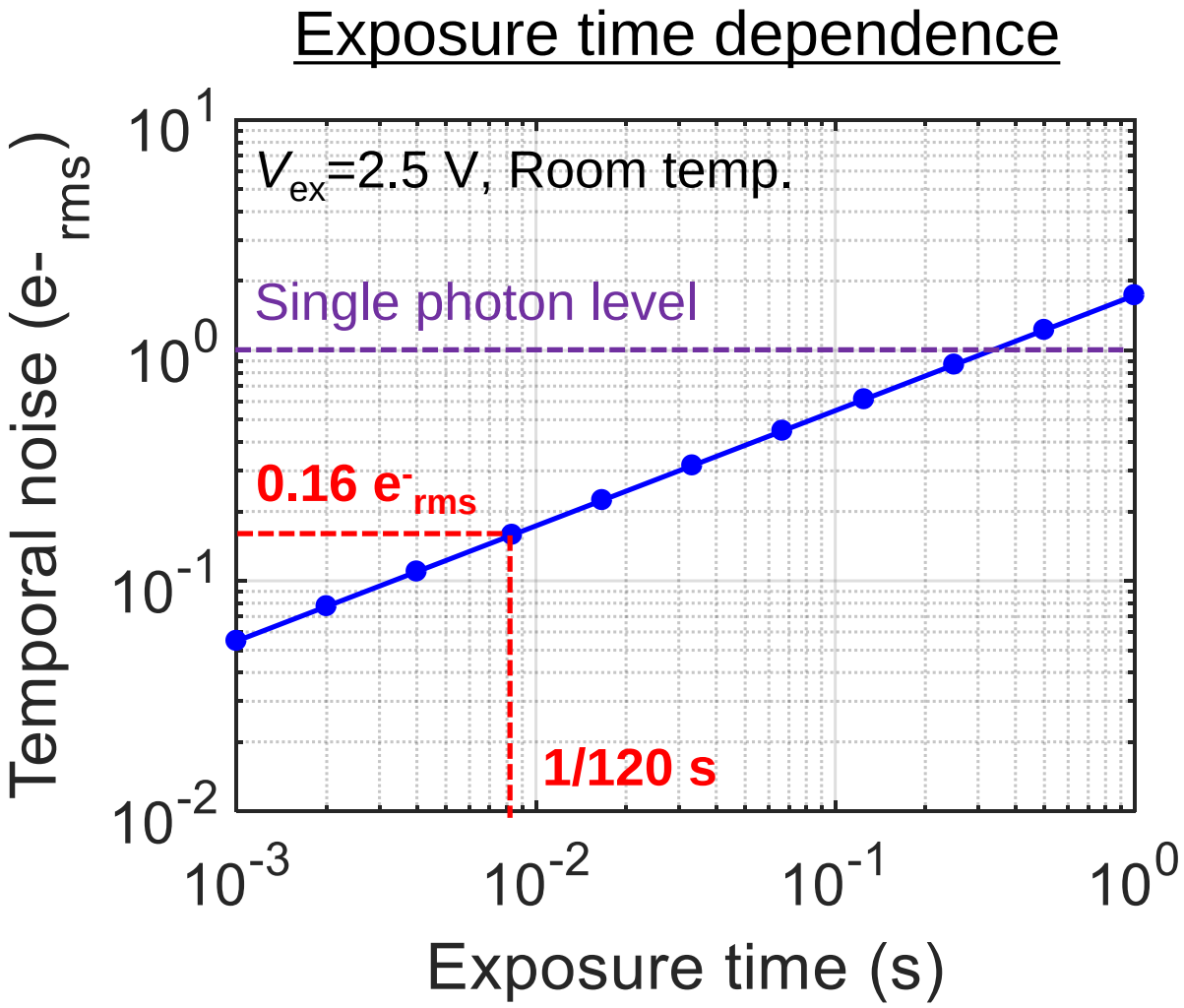


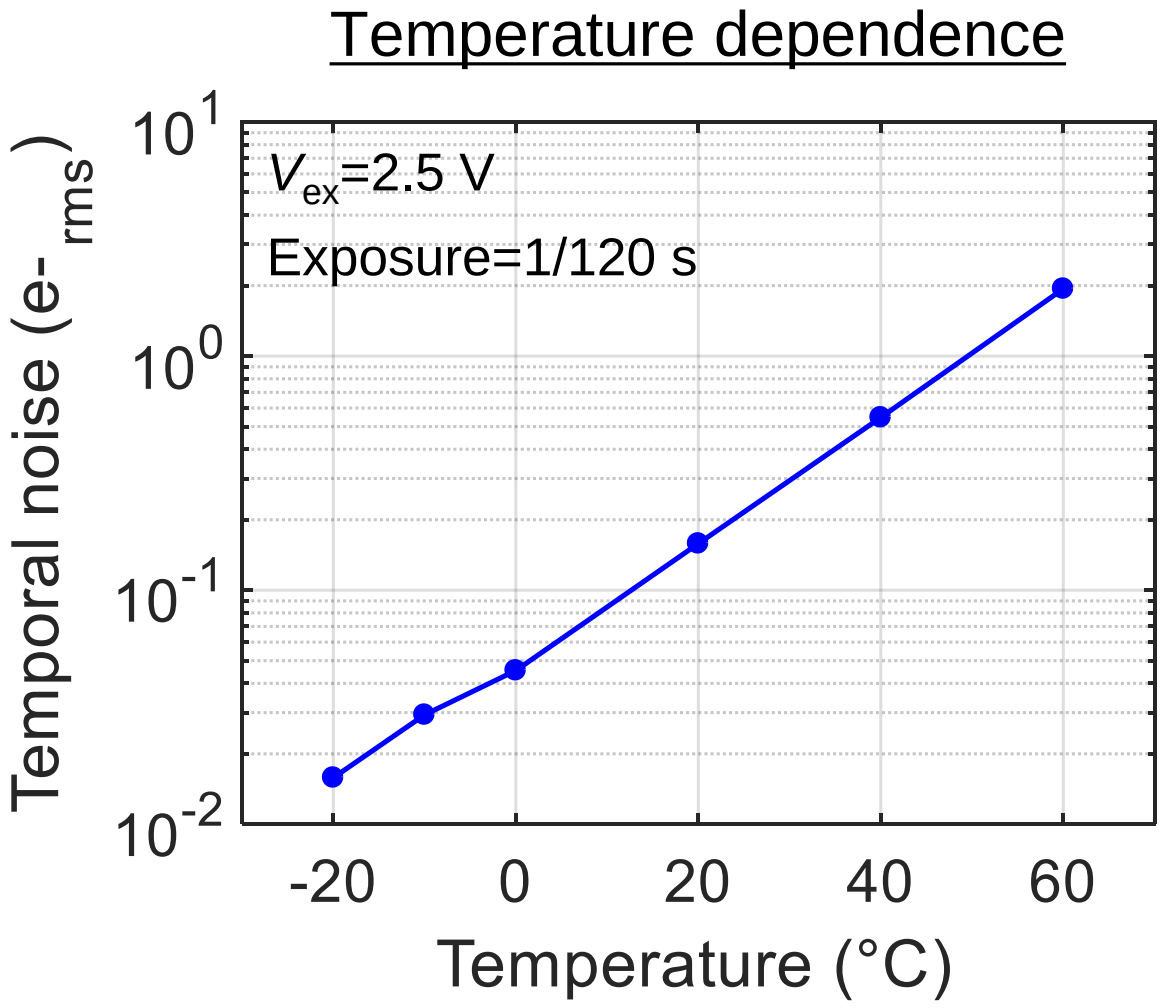
T dependence of median DCR



Temporal Noise

Input referred noise = 0.16 e^-_{rms} at video frame rate

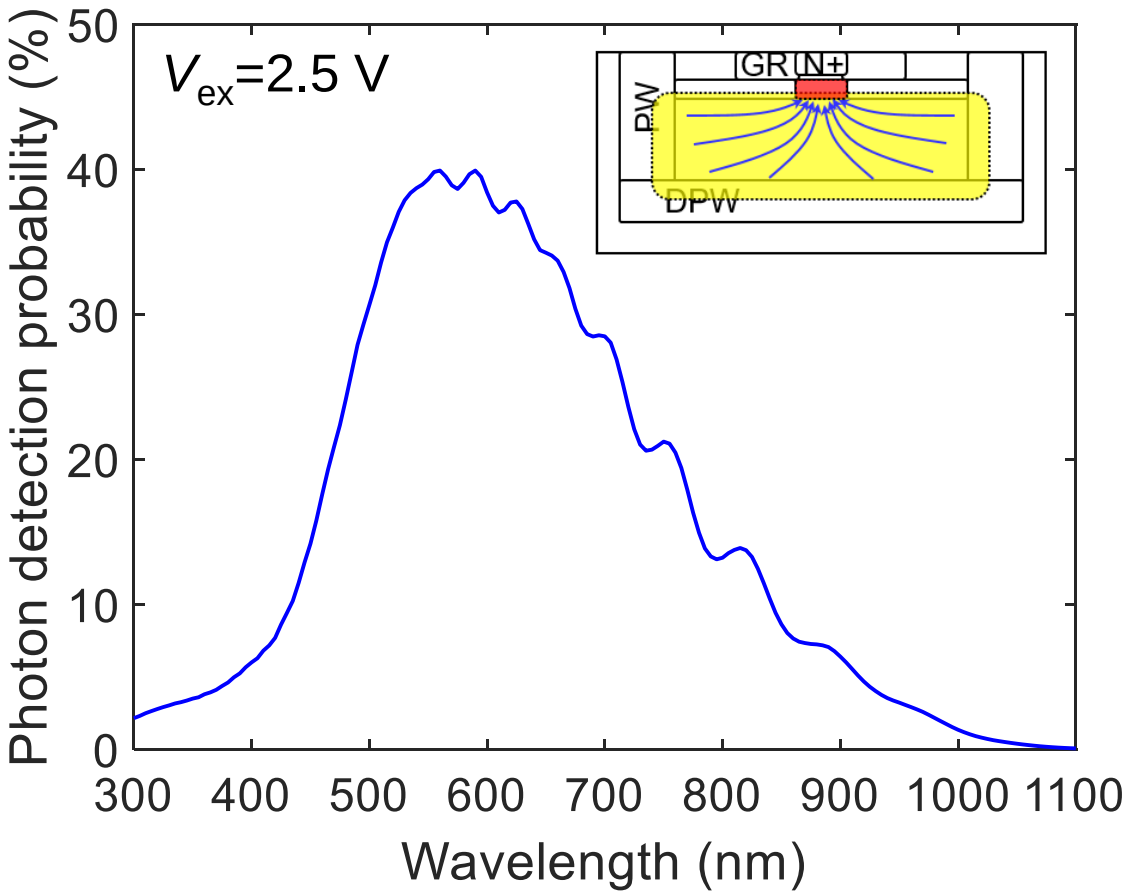




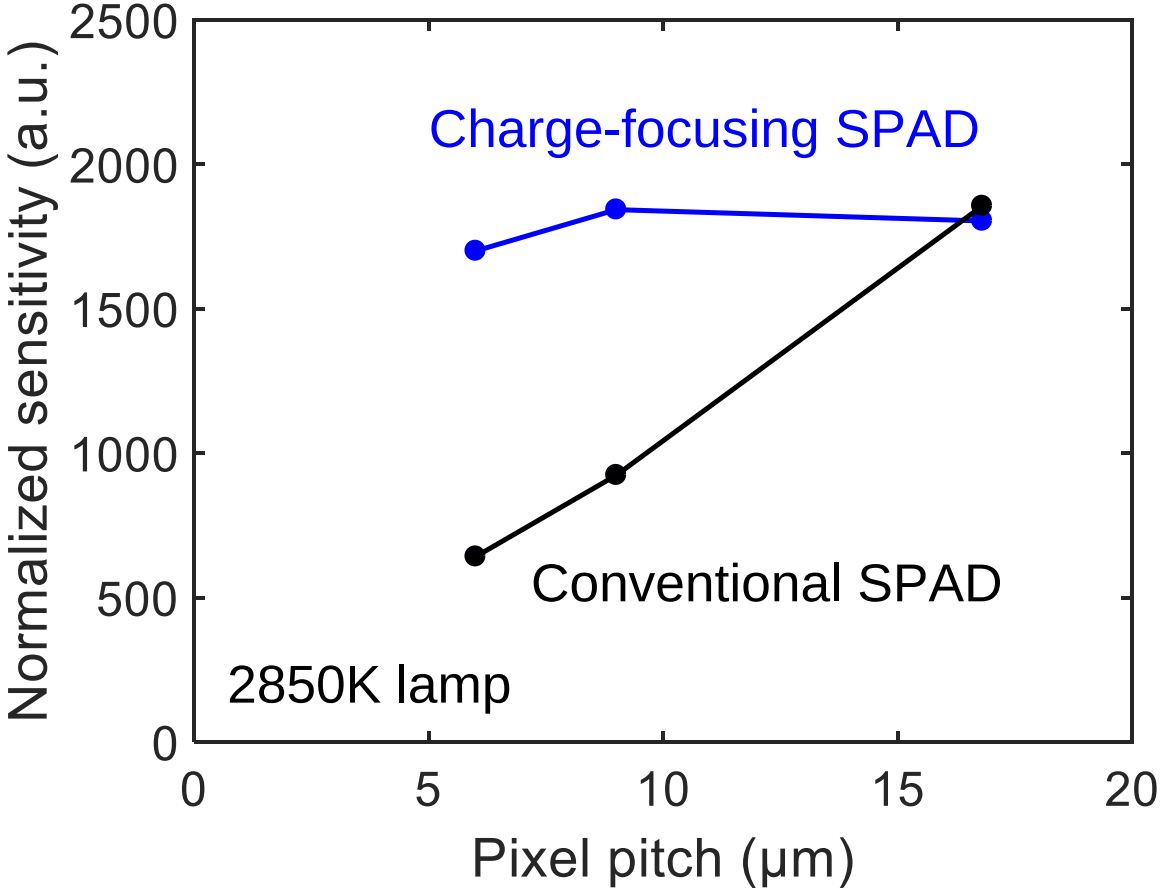
PDP and Sensitivity

Max. PDP=40%, no sensitivity degradation up to 6 μm pixel

Wavelength dependence



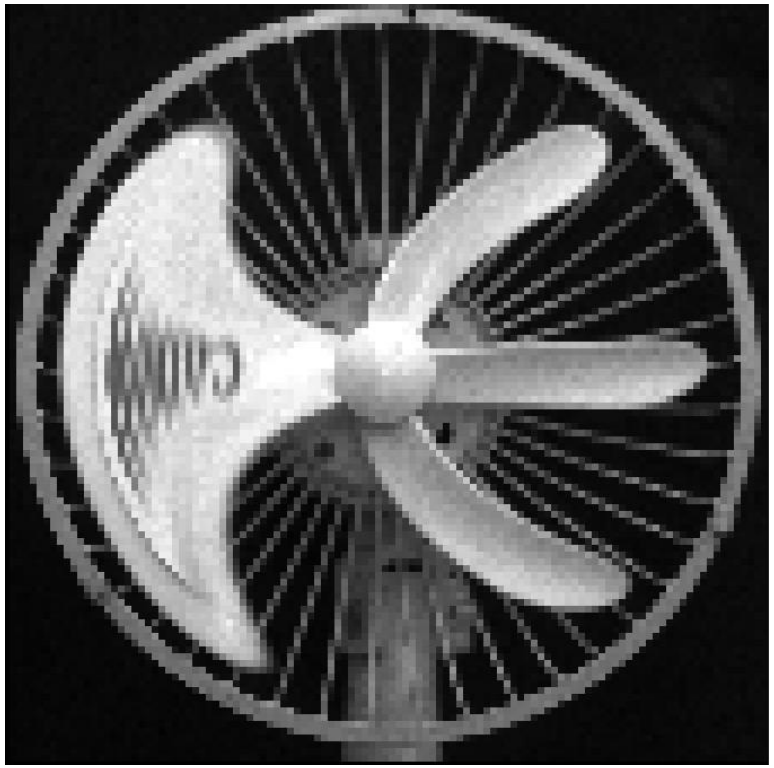
Pixel pitch dependence



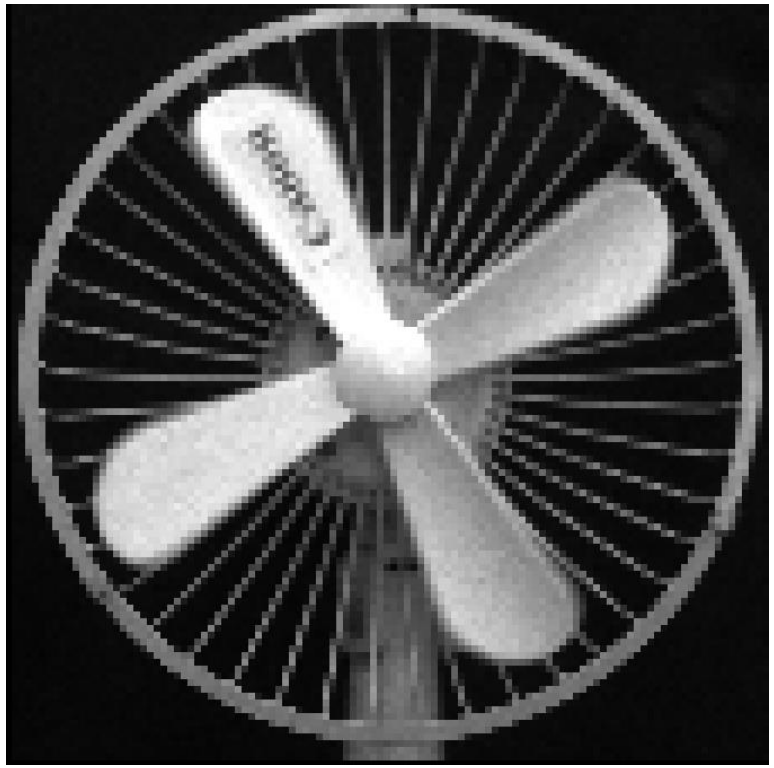
Rolling / Global Shutter Imaging

Operation confirmed in rolling and global shutter modes

Rolling shutter mode



Global shutter mode



Photon-Counting RGB Imaging

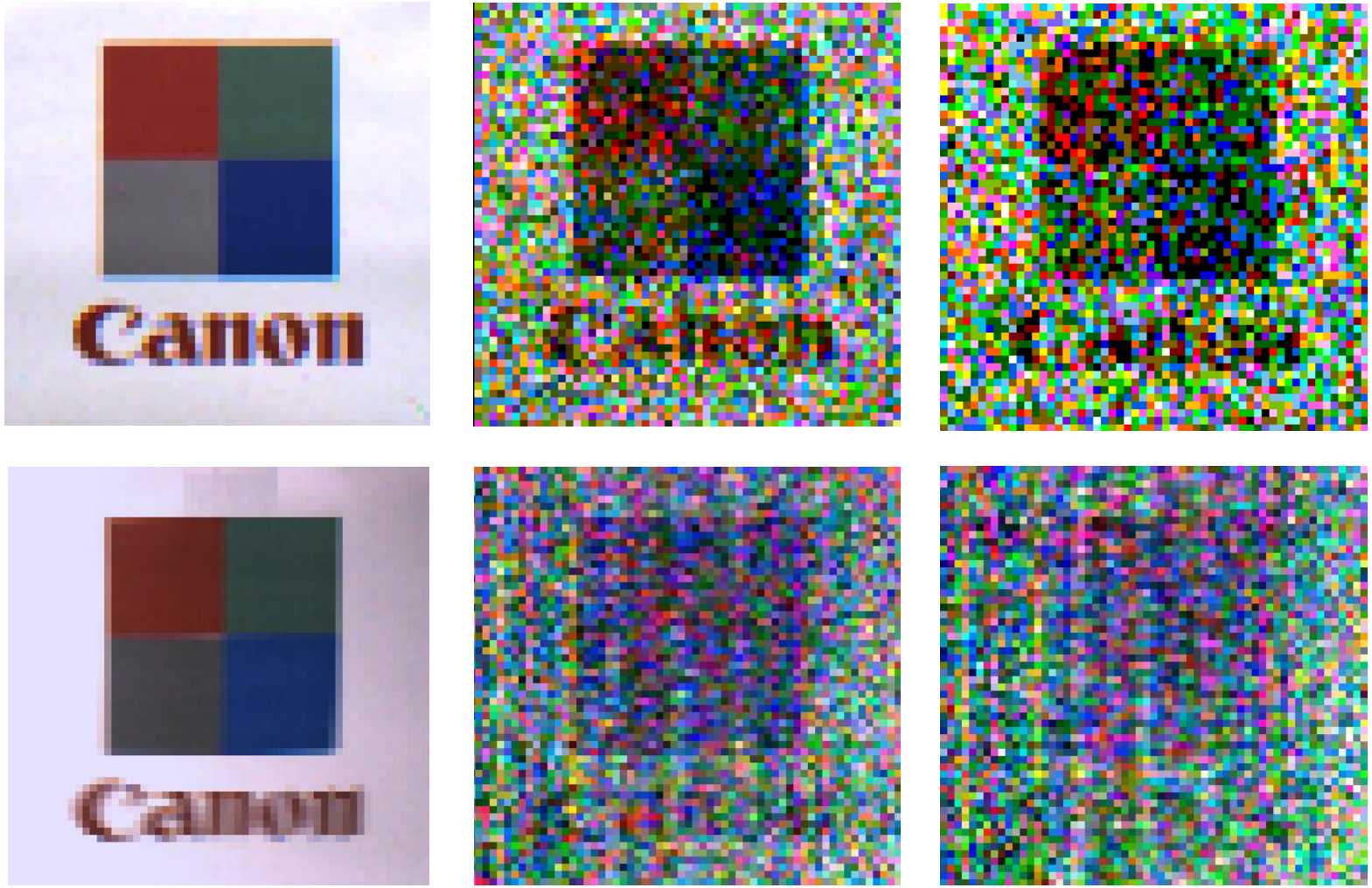
Single-photon-sensitive color imaging is demonstrated

RGB Color SPAD

Temporal noise = 0.16 e^-_{rms}

CMOS imager

Temporal noise = 2.1 e^-_{rms}



Highlight **Signal = 1 photon** **Signal = 0.5 photon**

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State-of-the-Art Comparison

	This work	Ulku, et al 2018	Hirose, et al 2019	Ma, et al 2017	Seo, et al 2015
Type	SPAD	SPAD	VAPD	CMOS	CMOS
Process technology	180 nm FSI	180 nm FSI	65 nm FSI	45/60 nm BSI	110 nm FSI
Pixel pitch (μm)	84	16.38	6.0	1.1	11.2×5.6
Pixel array size (H×V)	128×128	512×512	400×400	1024×1024	312×512
Pixel output (bit)	16	1	-	3	-
Operation voltage (V)	3.3/-26.5	-	3.3/-29	-	3/25
Photodiode area (μm^2)	200.96	28.2	25.2	1.21	-
Max. PDP (%)	40	50	-	80	-
DCR density* ($cps/\mu m^2$)	**0.015**	0.26	2.77	<0.16	-
Temporal noise* (e^-_{rms})	**0.16**	-	-	0.21	0.27
DSNU (e^-_{rms})	0.2	-	-	-	-
PRNU (%)	**1.7**	-	-	>2.6	-
Electronic shutter	**GS/RS**	GS/RS	RS	RS	RS
On-chip color filter	**w/**	w/o	w/o	w/o	w/o

*At room temperature

Summary

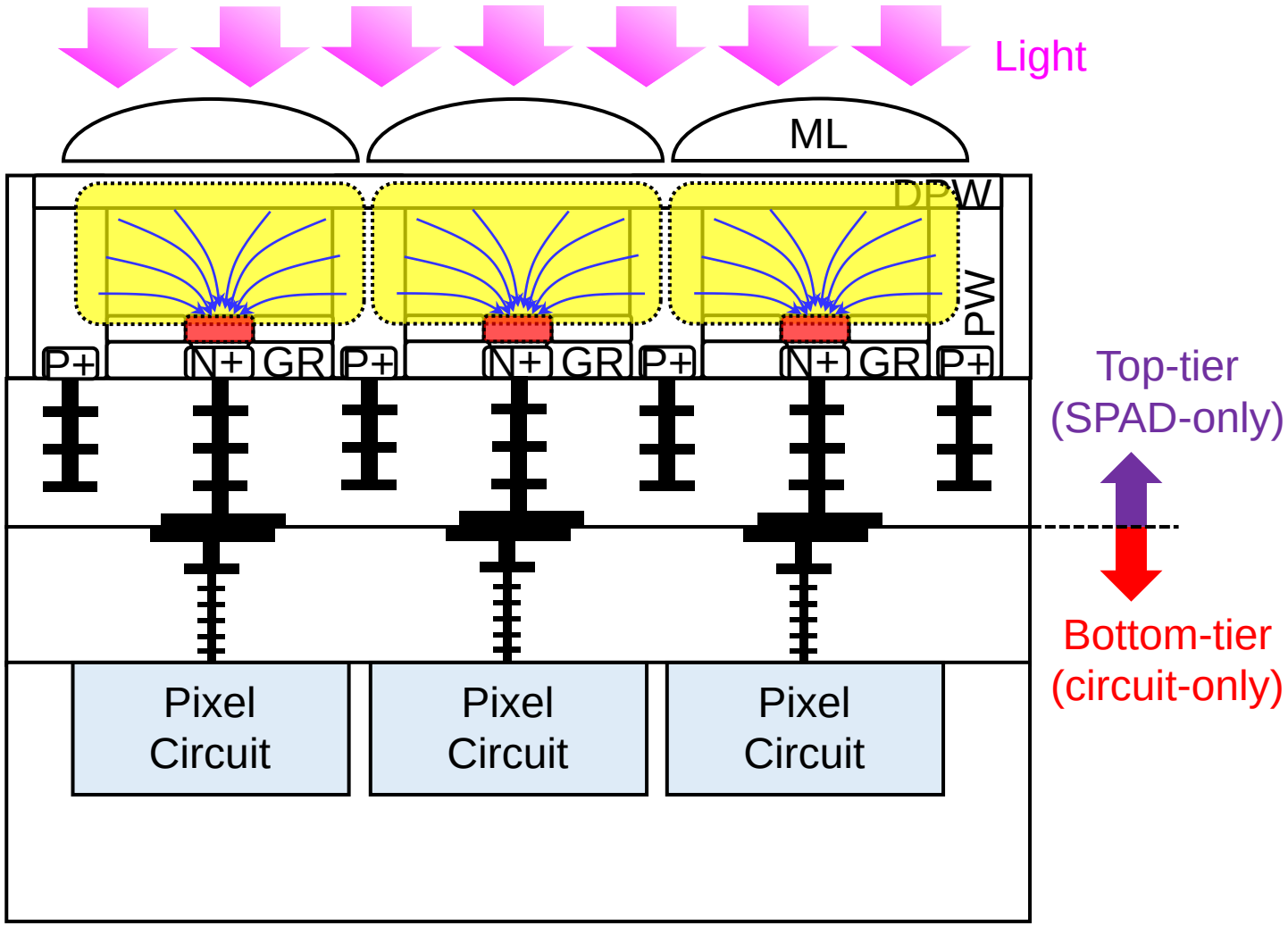
We proposed next-gen. SPAD concept to achieve:

- Scalability (pixel pitch $\leq$ 6 µm)
- High FF (up to 100%)
- Low noise (DCR, afterpulsing, crosstalk)
- Flexible choice of optics

Proof-of-concept SPAD sensor demonstrated:

- DCR density = 0.015 cps/µm^2 (lowest ever reported)
- Temporal noise = 0.16 e^-_{rms} (at 120 fps)
- Max. PDP = 40% (up to 6 µm)
- Single-photon-sensitive RS/GS and RGB color imaging

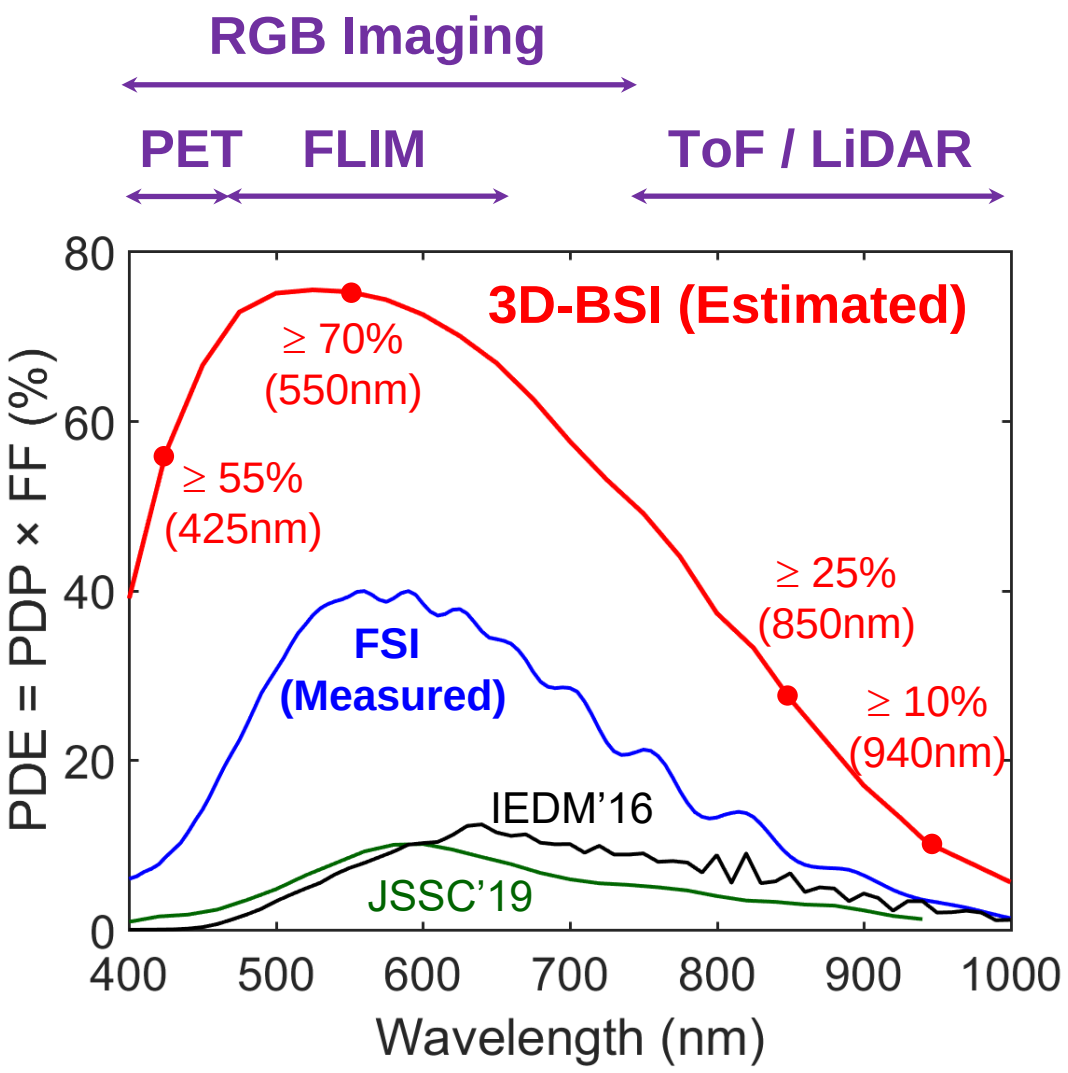
3D-BSI Charge-Focusing SPAD Array



Target Specifications

	This work (FSI)	Target Specs (BSI)
Type	SPAD	SPAD
Process technology	180 nm FSI	**3D-BSI**
Pixel pitch (μm)	84	**≤ 7**
Pixel array size (H×V)	128×128	**≥ 1Mpix**
Pixel output (bit)	16	-
Operation voltage (V)	3.3/-26.5	3.3/-26.5
Photodiode area (μm^2)	200.96	≤ 50
Max. PDP (%)	40	**≥ 70**
DCR density (cps/μm^2)	0.015	0.015
Temporal noise (e^-_{rms})	0.16	**≤ 0.08**
DSNU (e^-_{rms})	0.2	< 0.2
PRNU (%)	1.7	1.7
Electronic shutter	GS/RS	GS/RS
On-chip color filter	w/	w/

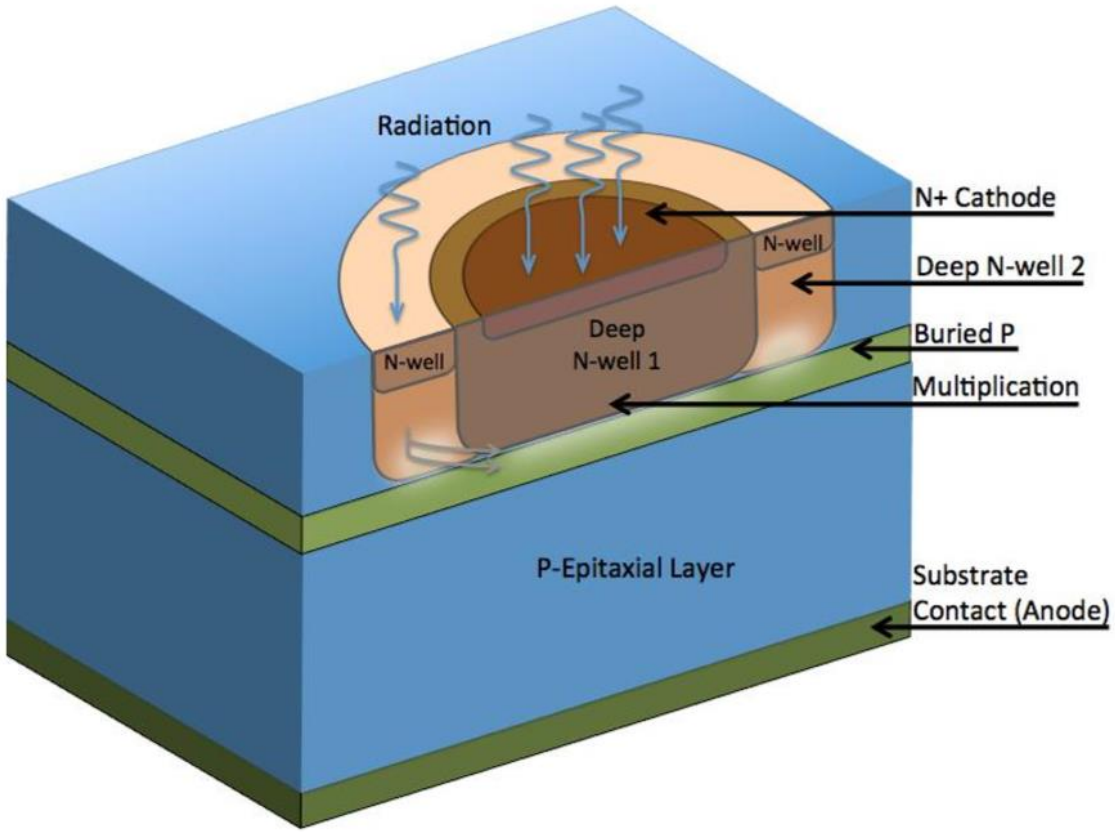
Broad spectrum for wider apps



Supplementary Materials

Electrical Microlens (TU Delft)

Using lateral avalanche propagation to virtually enhance the active area

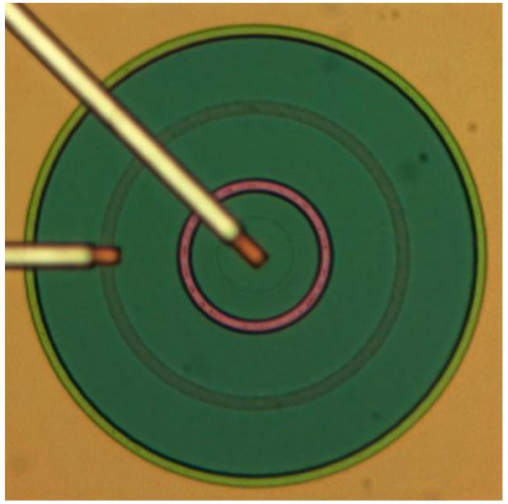


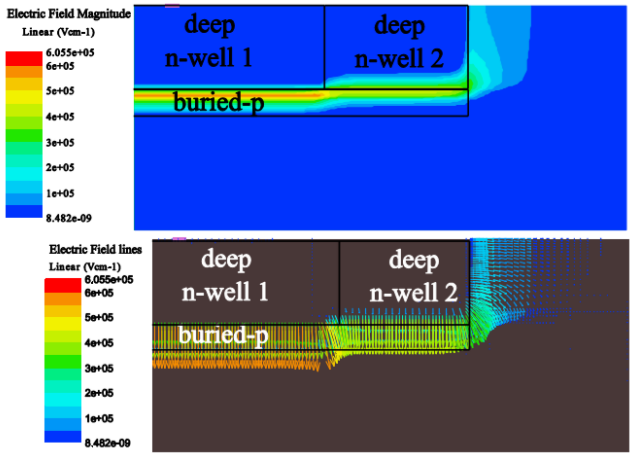
■ Advantage

- Electrically tunable active area

■ Issues

- Large DCR (>0.1 Mcps/pix)
- FF still limited by guard-ring / isolation





C. Veerappan *et al*., IISW2013 (2013)