SONY

A Challenge for 3 µm SPAD Pixel Using Embedded Metal Contact on Deep Trench Pixel Isolation

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Sony Semiconductor Solutions Corporation

13th June, 2022

The International SPAD Sensor Workshop

Outline

1. Overview of Sony's SPAD technology
2. A Challenge for shrinking the pixel size
3. Prototyping
4. Conclusions

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1. **Overview of Sony's SPAD technology**
2. A Challenge for shrinking the pixel size
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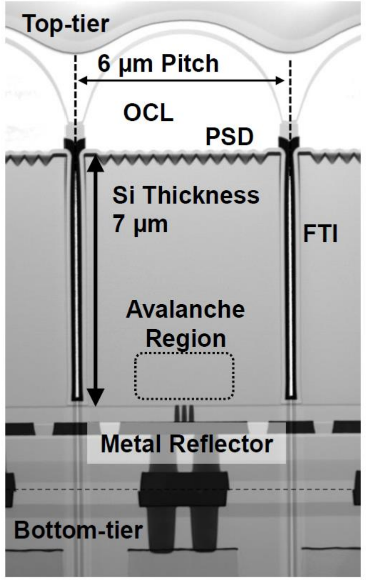
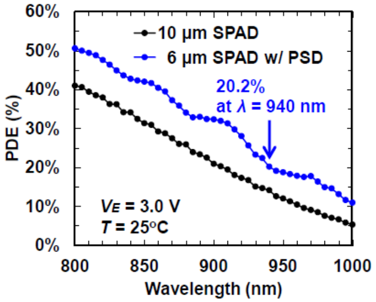
Overview of Sony's SPAD technology

SPAD pixel

Back-illuminated Stacked Pixel down to 6 µm

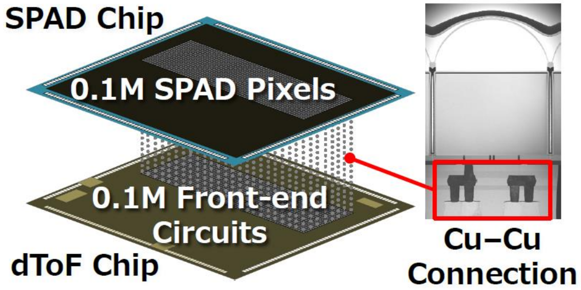


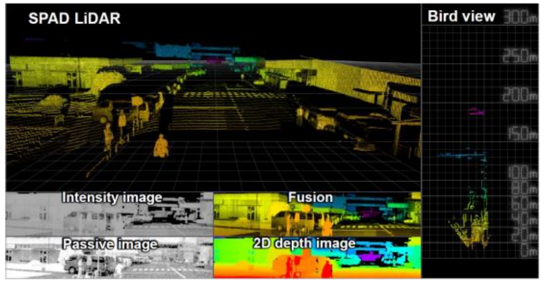


[1] S. Shimada *et al*., IEDM 2021
[4] K. Ito *et al*., IEDM 2020

SPAD LiDAR

Long distance and high-accuracy ranging system

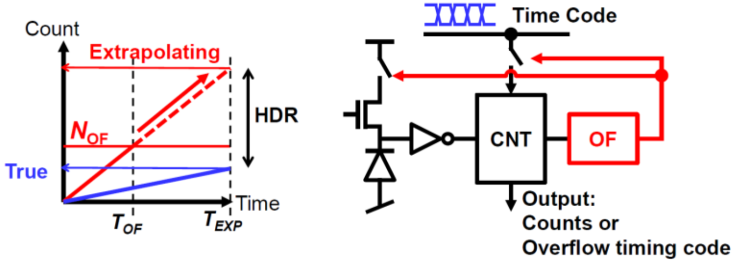




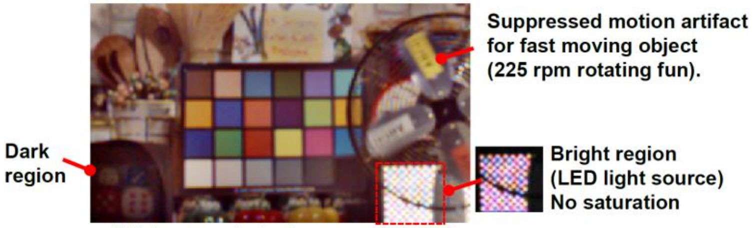
[5] O. Kumagai *et al*., ISSCC2021

SPAD photon counting

High-dynamic range and high-speed imaging



HDR image capture at 250 fps



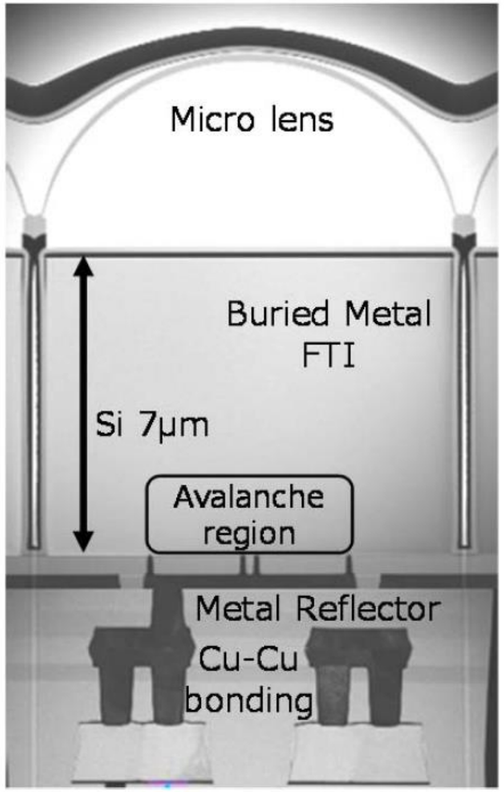
With tone reproduction for representing HDR image

[2] J.Ogi *et al*., ISSCC 2021
[3] J. Ogi *et al*., ISSW 2021

- Down to 6 µm pixel technology with relatively large PDE
- SPAD sensors combining the pixel and advanced circuit design.

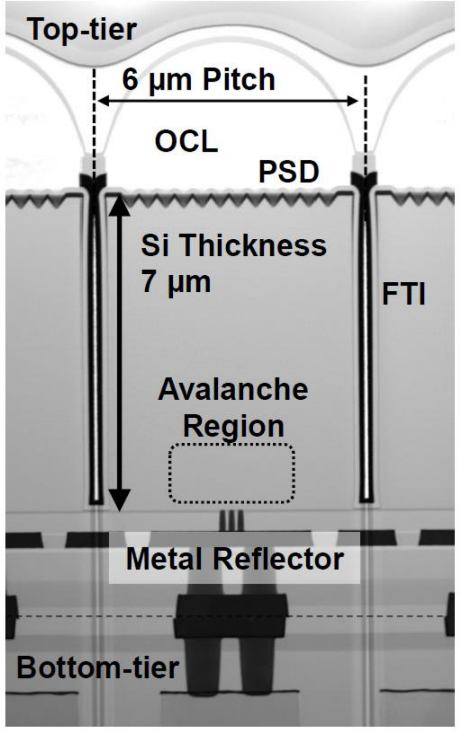
Pixel technology

10 µm

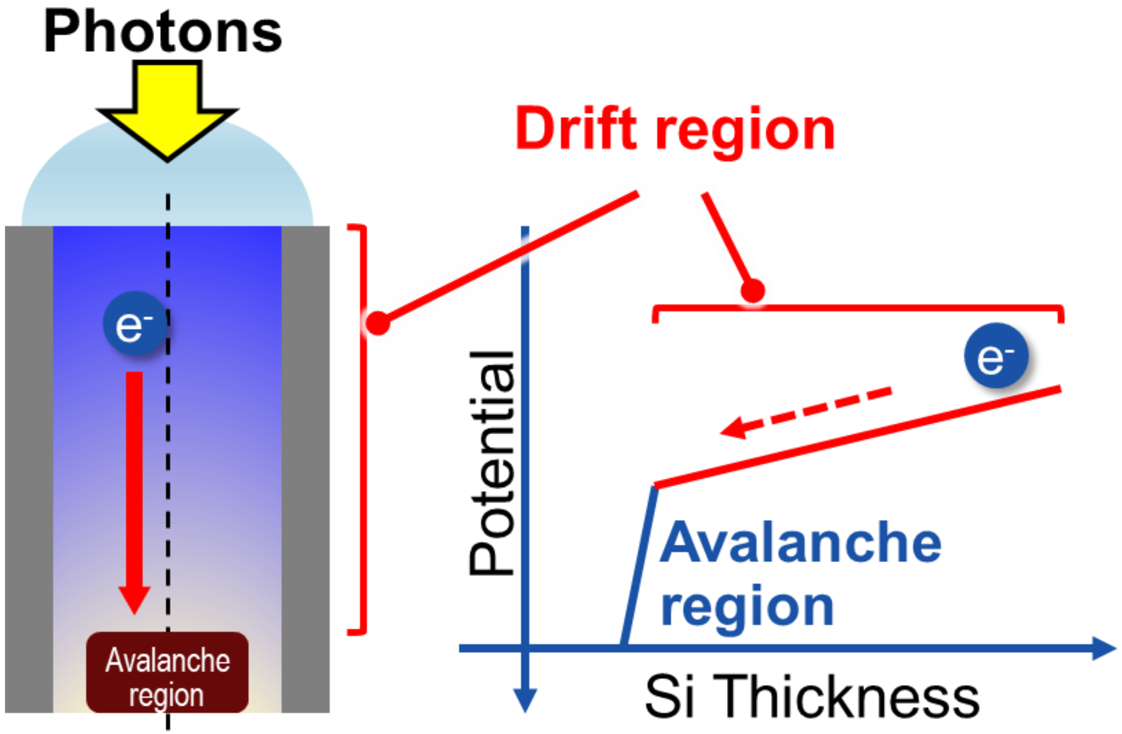


[4] K. Ito *et al*., IEDM 2020

6 µm

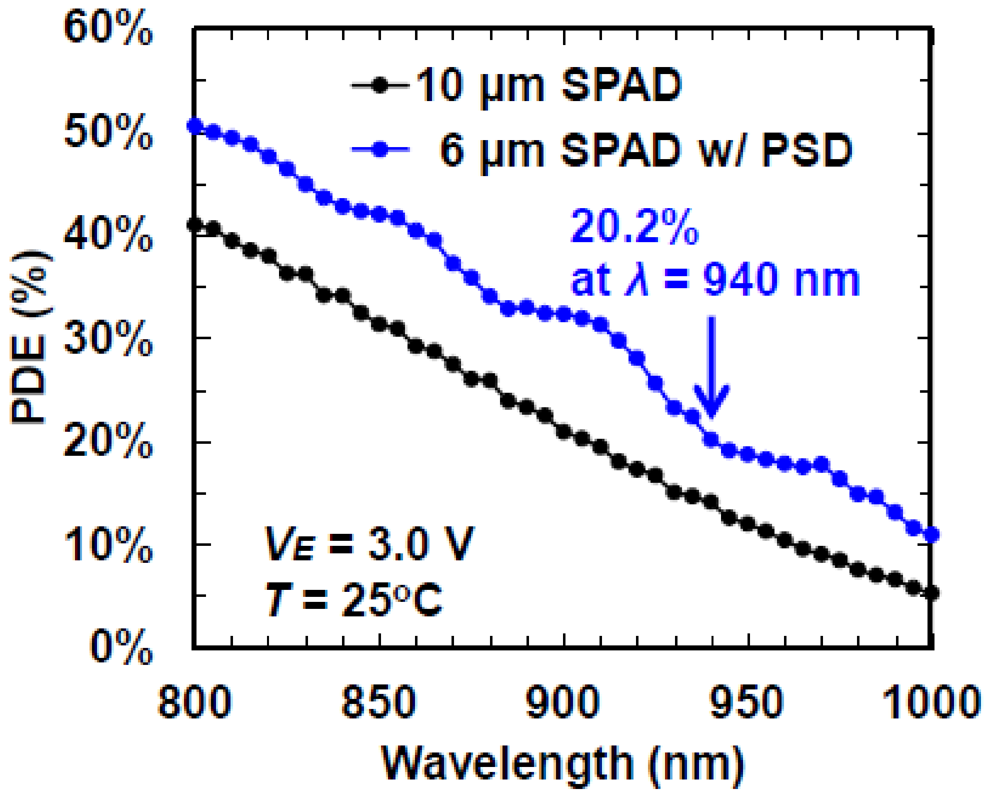


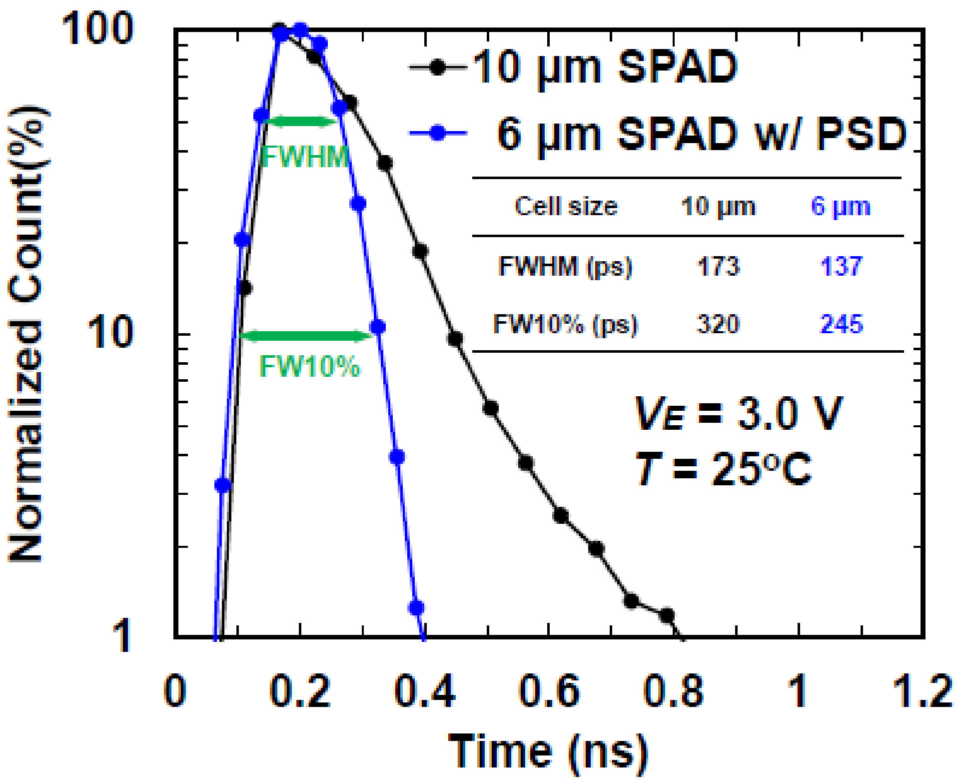
[1] S. Shimada *et al*., IEDM 2021



- High fill-factor owing to the back-illuminated stacked structure.
- High PDE without timing jitter degradation by optimizing the potential slope

Pixel technology

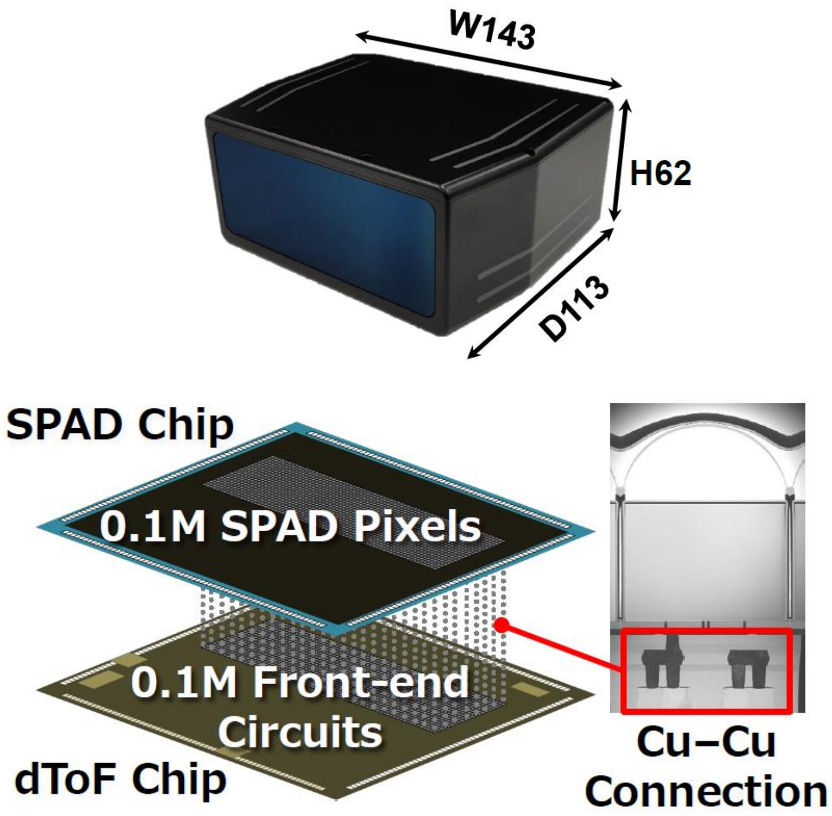


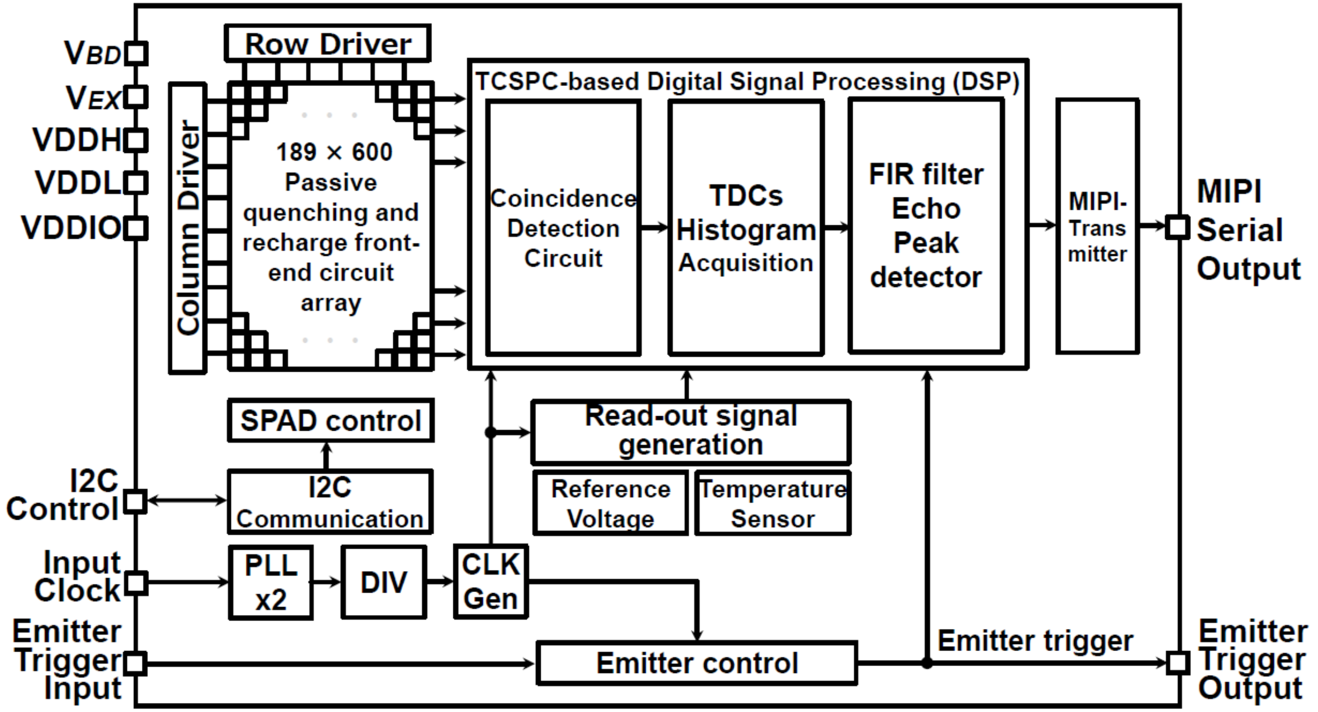


[1] S. Shimada *et al*., IEDM 2021

- PDE is above 20 % at 940 nm of wavelength
- Timing jitter is less than 150 psec of FWHM

LiDAR system

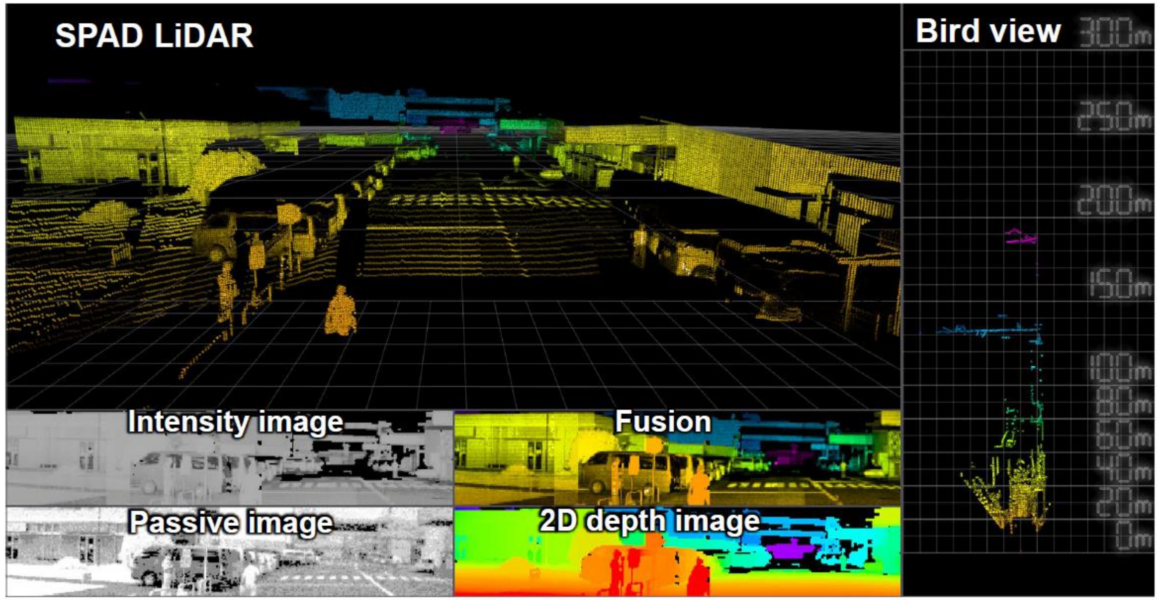


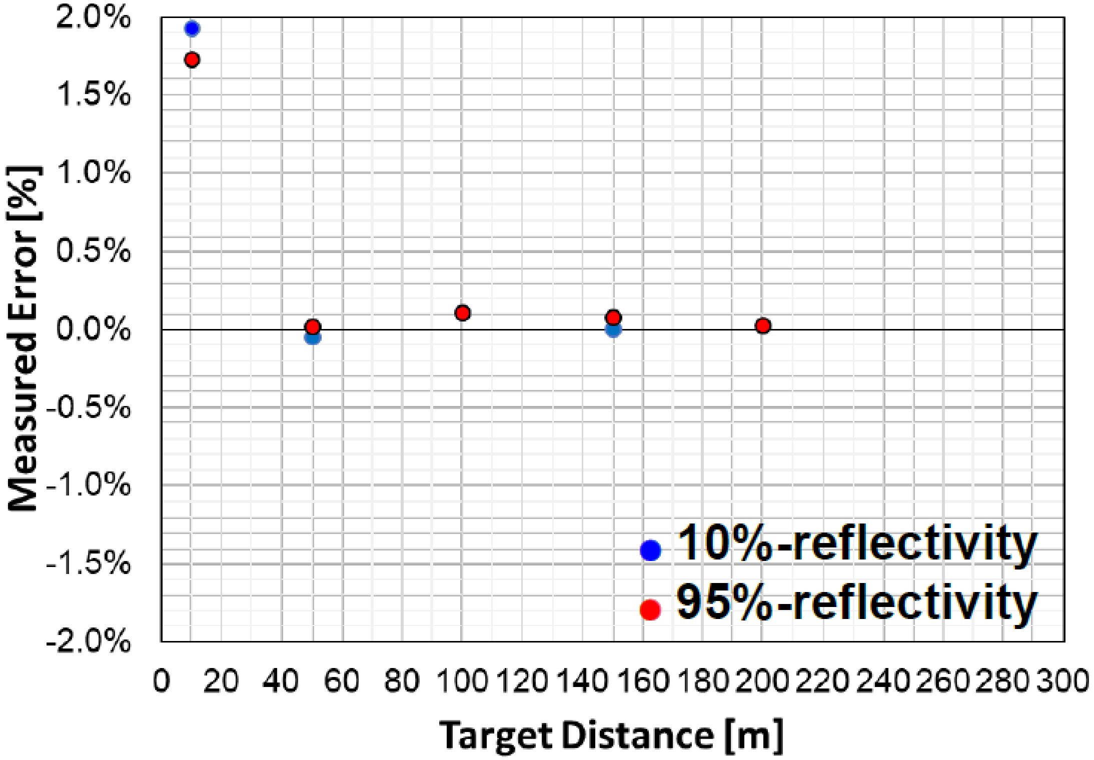


[5] O. Kumagai *et al.*, ISSCC2021

- A SPAD Direct Time-of-Flight Depth Sensor has been developed for automotive LiDAR applications
- High-sensitivity depth sensors make it possible to measure long distances

LiDAR system

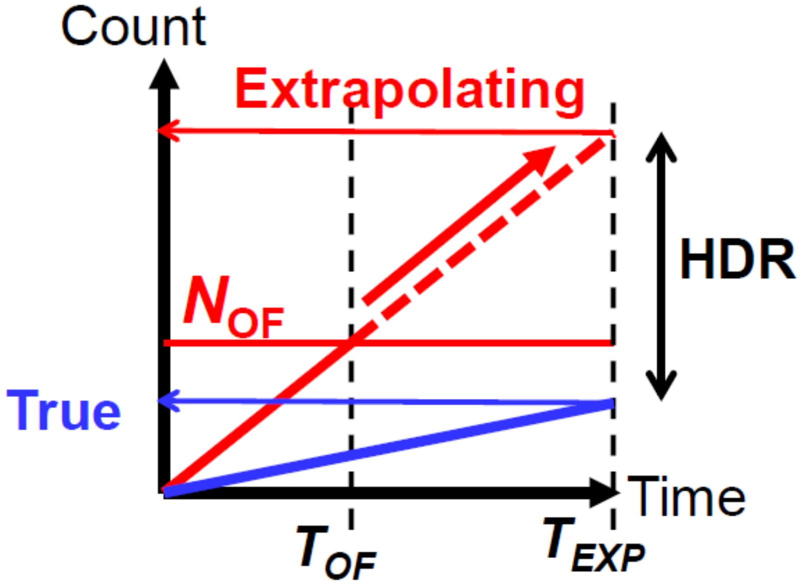


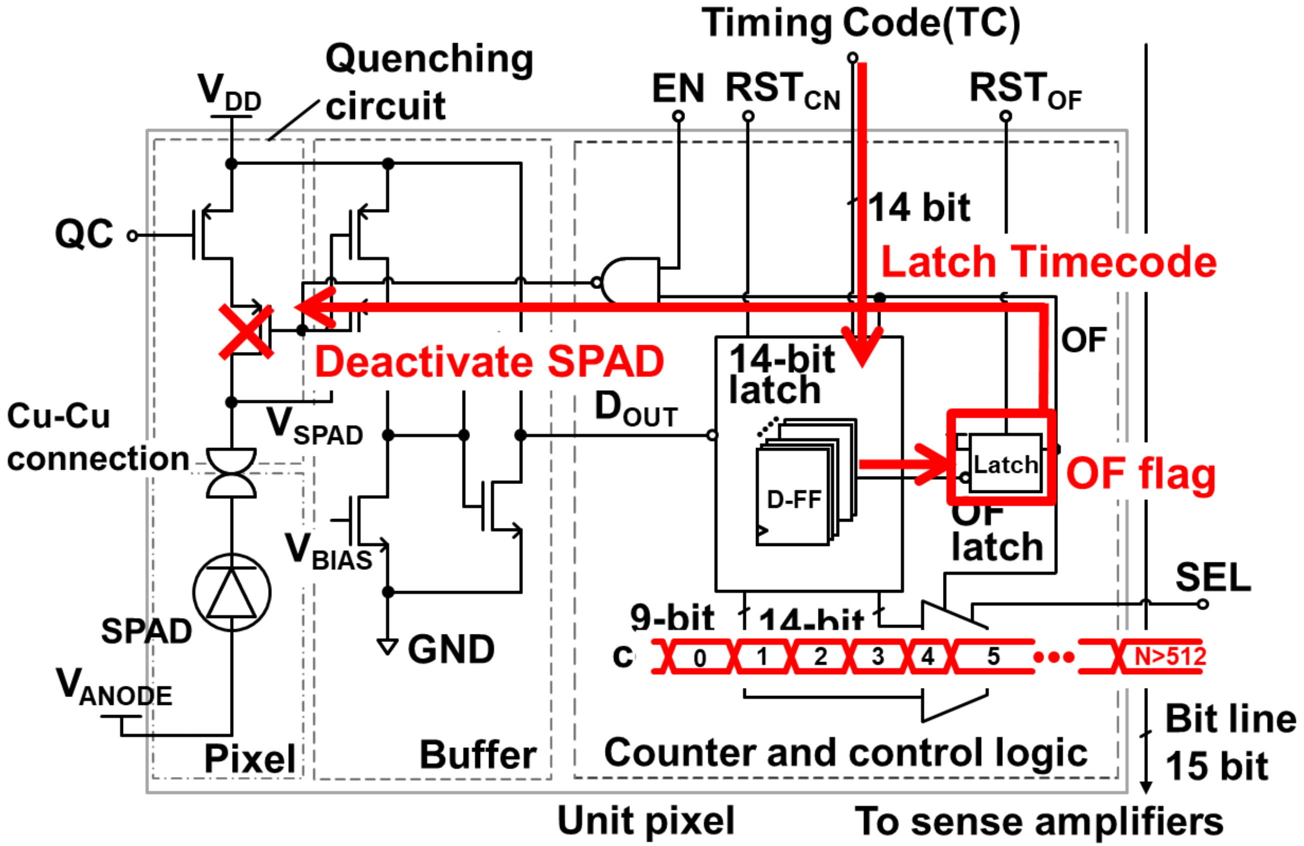


[5] O. Kumagai *et al.*, ISSCC2021

- The LiDAR is capable of detecting objects 150m ahead at day light with poor object detection ratio, even if the reflectance is less than 10%

Photon counting image sensor

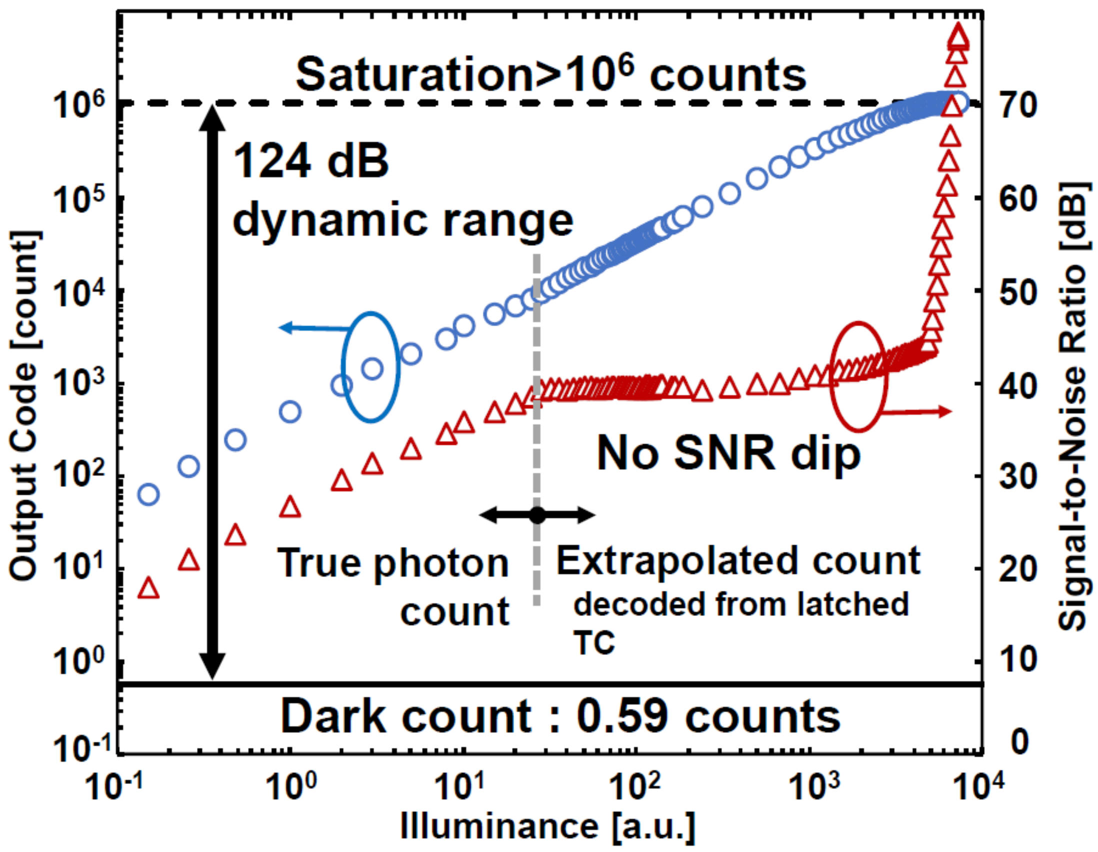




[2] J.Ogi *et al.*, ISSCC 2021
[3] J.Ogi *et al.*, ISSW 2021

- SPAD Photon counting Image sensor created by introducing extrapolating photon count to reduce in-pixel counter bit and power consumption in a pixel

HDR image capture



HDR image capture at 250 fps

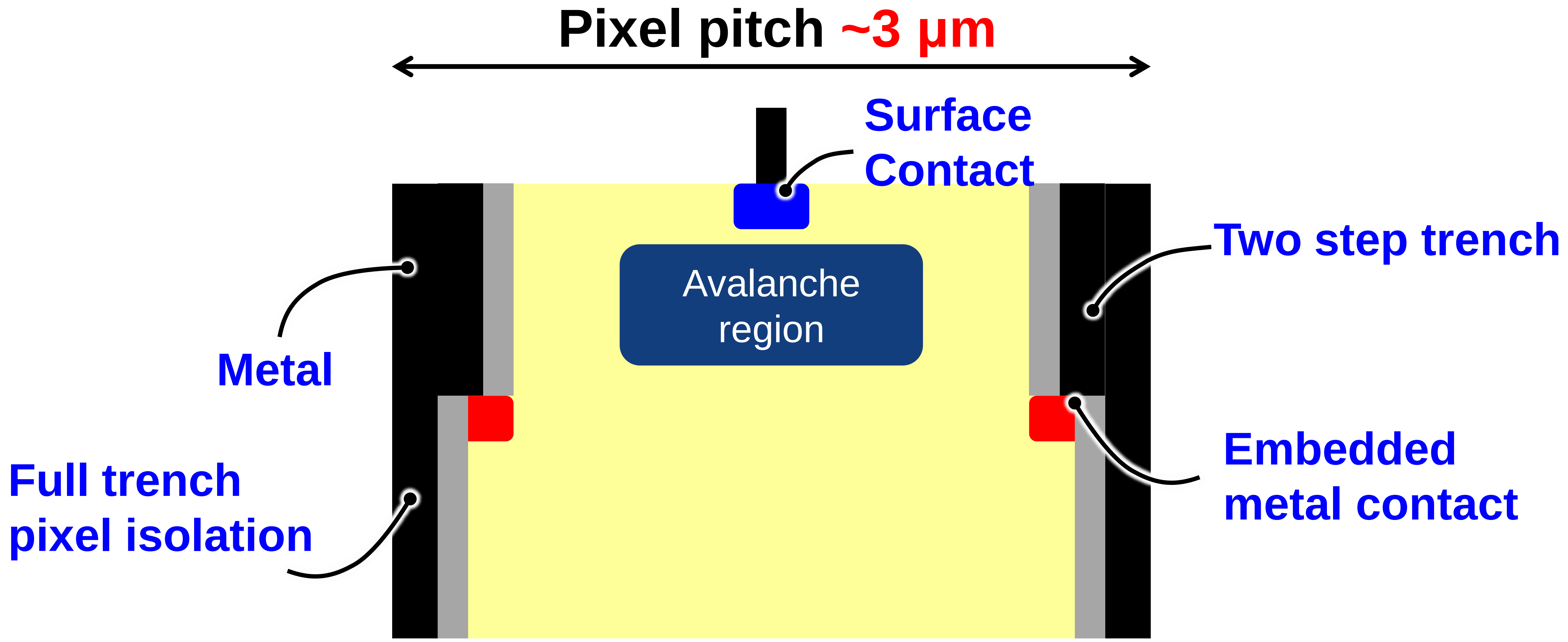
[2] J.Ogi *et al.*, ISSCC 2021
[3] J.Ogi *et al.*, ISSW 2021

- 250 fps and 124 dB HDR was achieved only with the 9-bit in-pixel counter

Outline

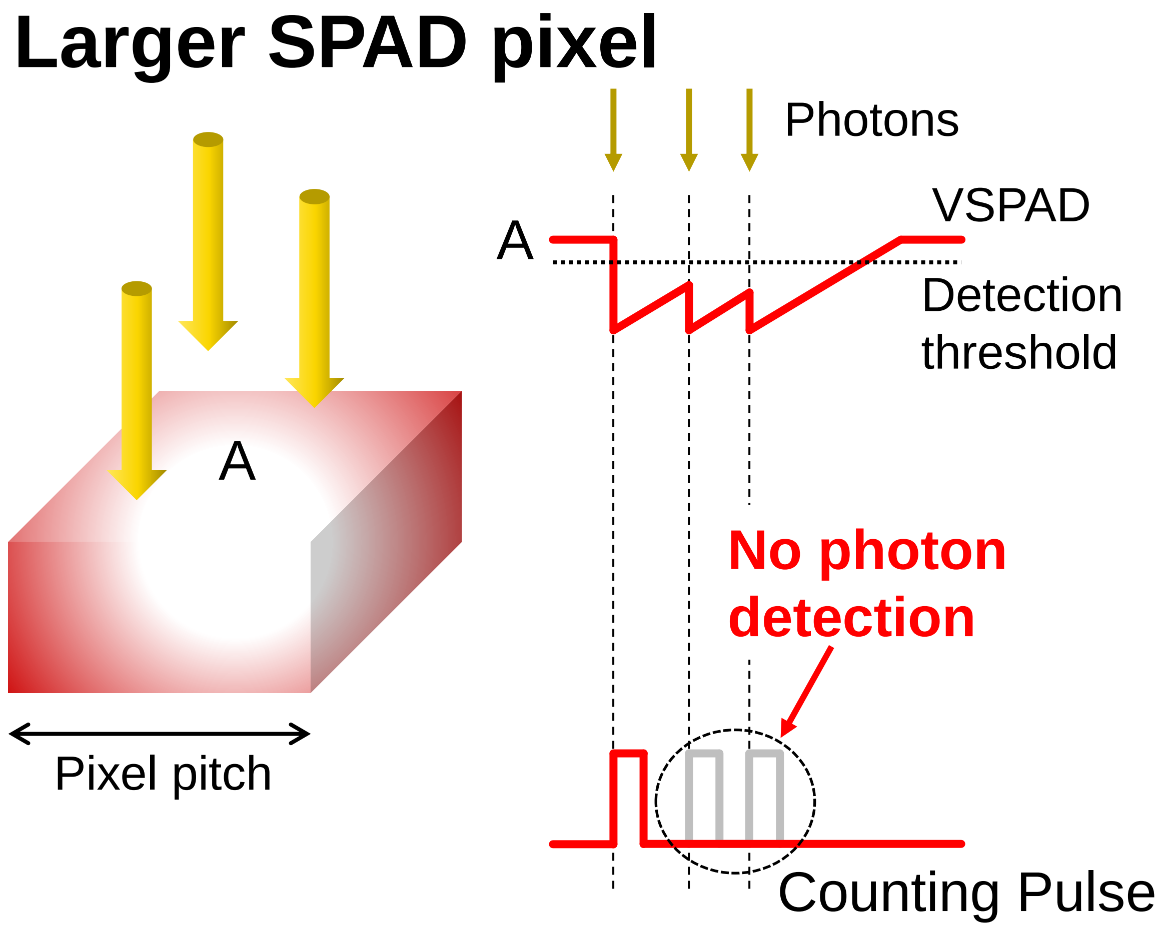
1. Overview of Sony’s SPAD technology
2. A Challenge for shrinking the pixel size
    1. Motivation
    2. Pixel structure
    3. Potential design
3. Prototyping
4. Conclusions

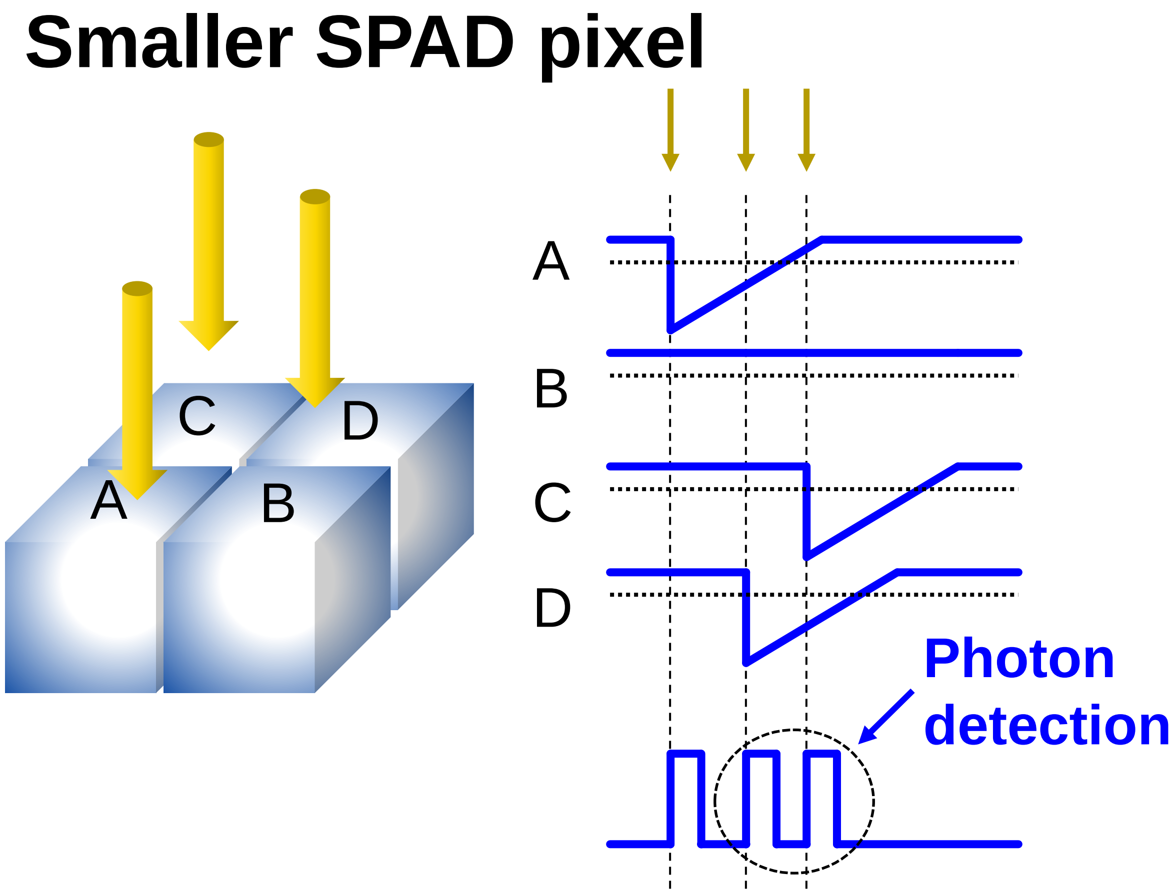
A challenge for shrinking the pixel size



- We challenge to shrink the SPAD pixel size to 3 µm by introducing a new SPAD pixel structure - Embedded metal contact on deep trench pixel isolation -

Motivation behind shrinking the pixel size

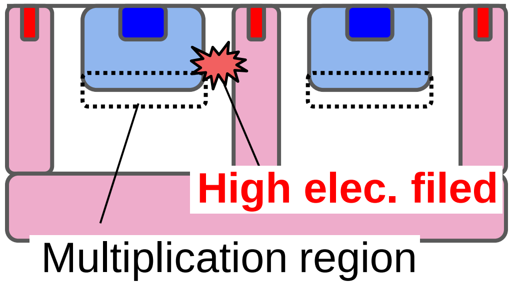
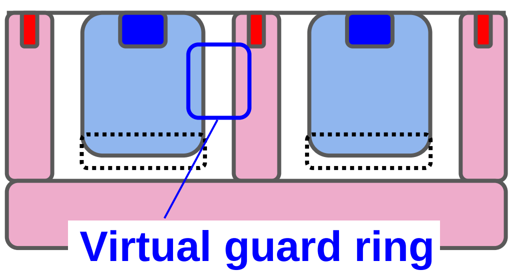
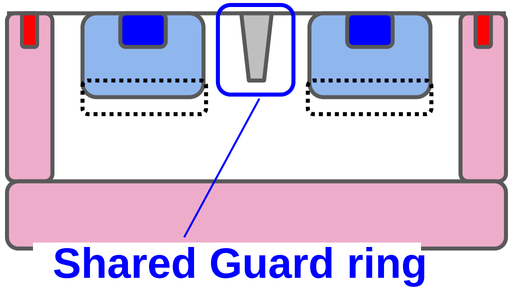
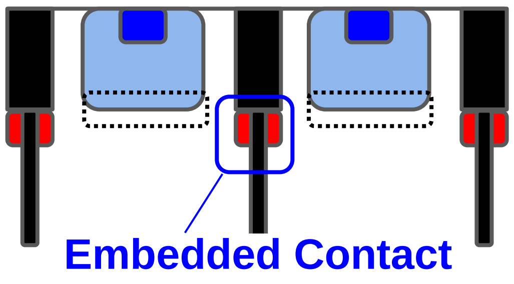




- A small pixel contributes to improve the SPAD sensor characteristics under high light illumination, such as, photon counting saturation.

Small pixel technology

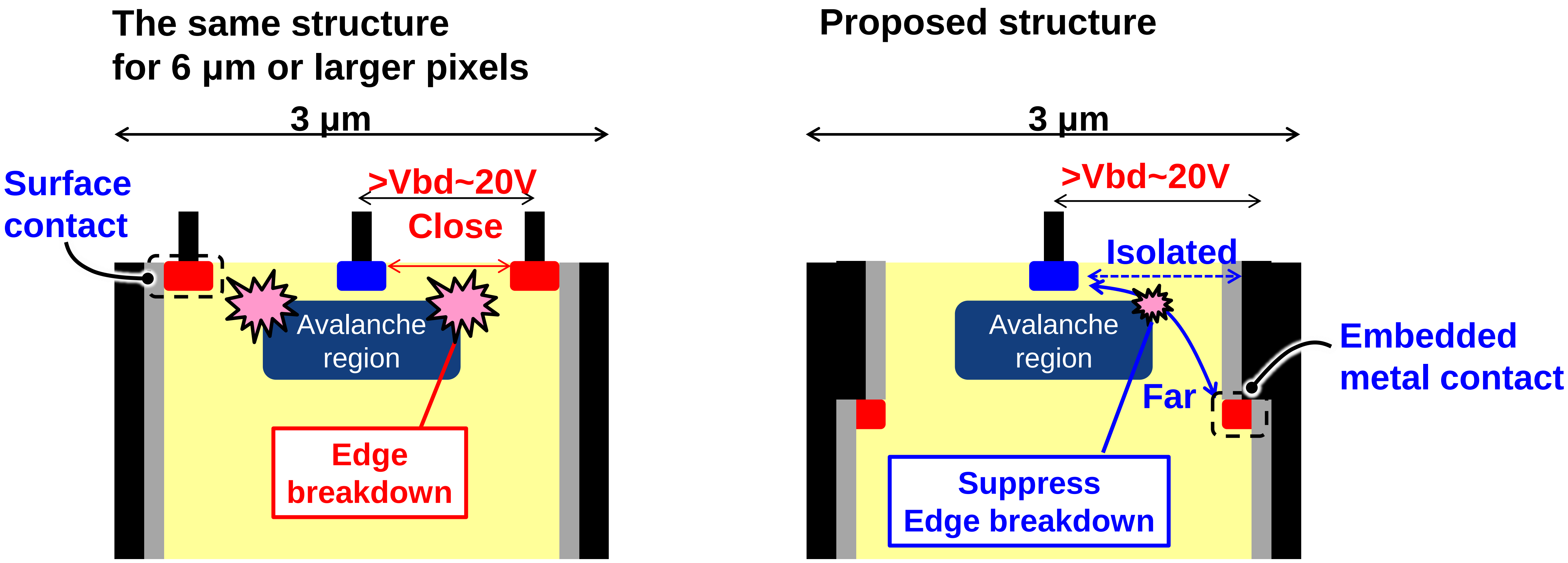
N+ P+ STI
N-well P-well Metal

	[6] Well sharing (Conventional)	[7] Virtual guard ring	[6] Guard-ring Sharing	**This work Embedded contact**
				
Electric field at pixel edge	High	Low	Low	Low
Vbd variation	Small	Large	Small	Small
Well impedance	Low	Low	High	Low
Fabrication	Simple	Simple	Little complicated	Complicated

[6] K. Morimoto *et al* Optic Express Apr, 2020
[7] Z. You *et al*.,, ISSW2017

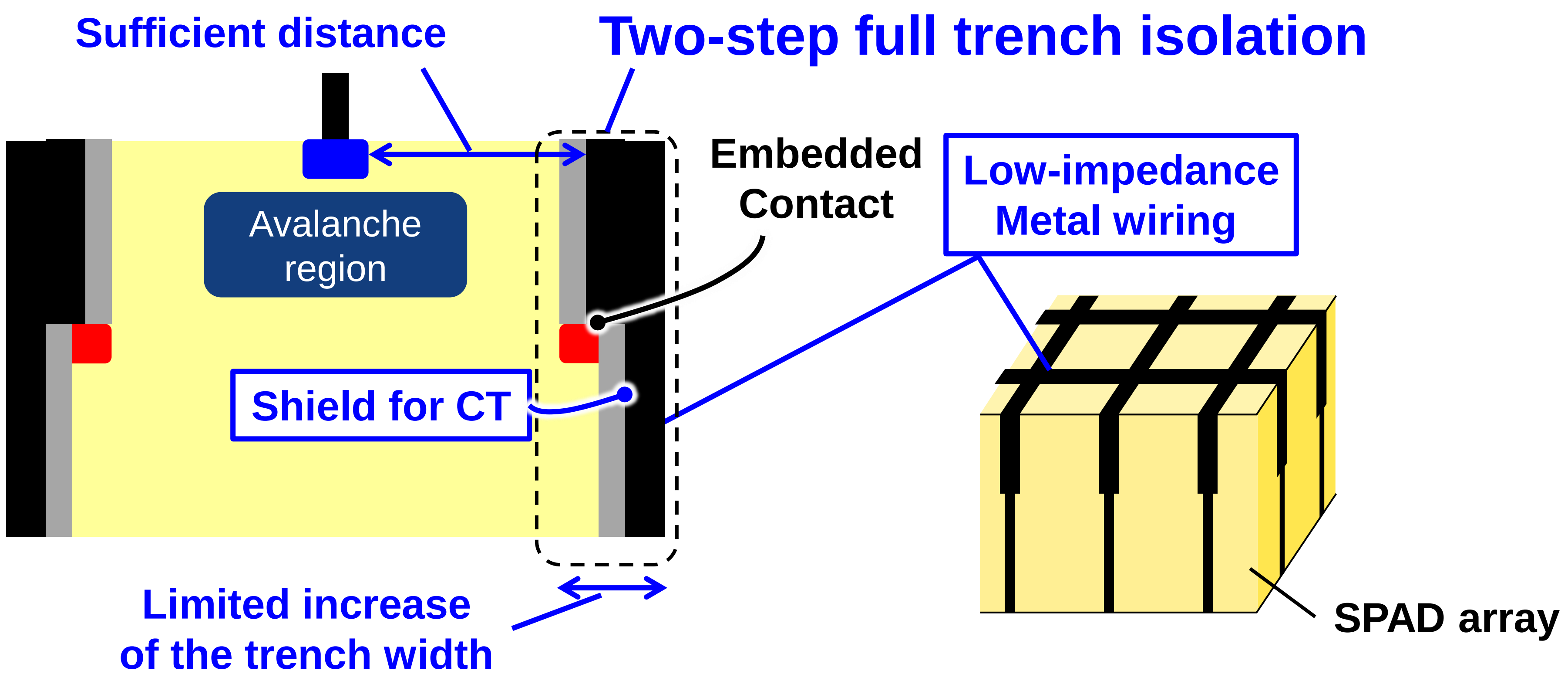
- Electric filed on the pixel edge must be decreased for a small pixel.
- The embedded metal contact is introduced with improved guard ring design

Embedded metal contact structure



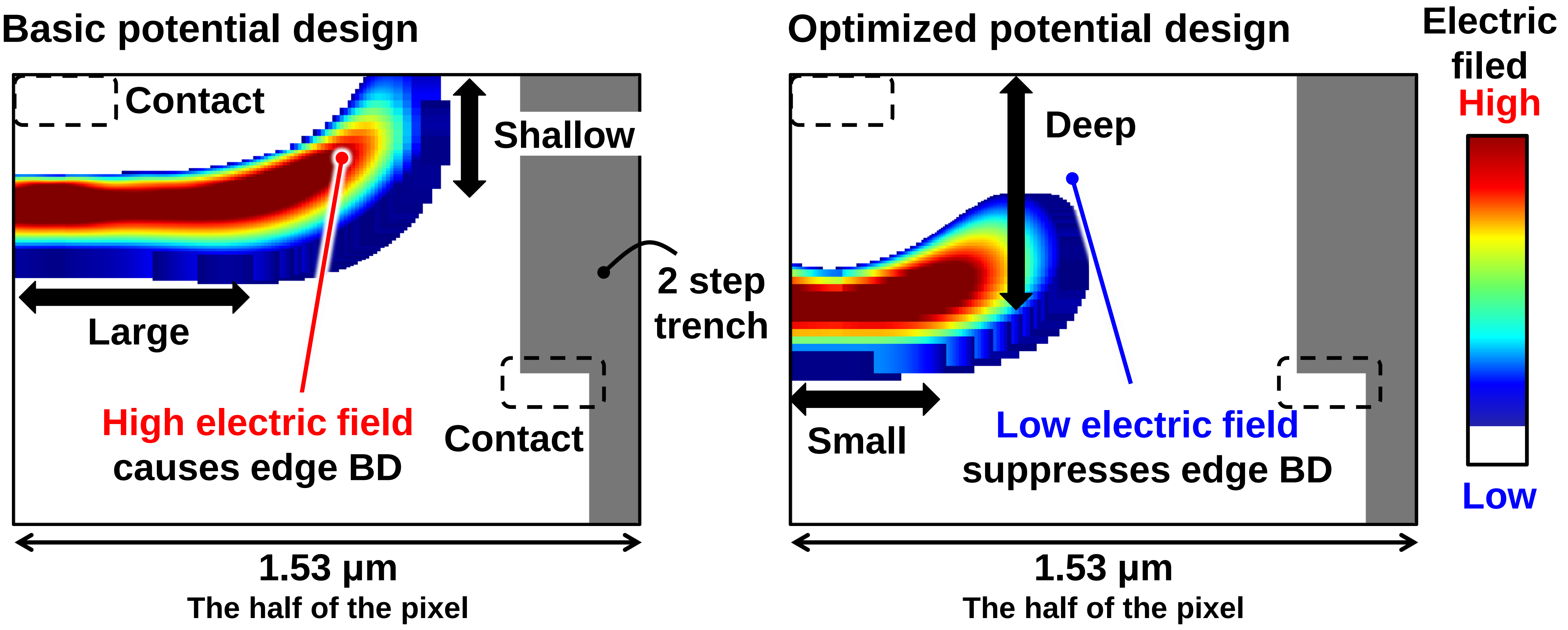
- The metal contact is embedded in the two-step deep trench isolation
- The embedded metal contact separates the anode and cathode region in a vertical direction

Two-step full trench isolation structure



- The two-step trench isolation has an advantageous trench width for combining the embedded contact and optical shield for cross talk suppression.
- The embedded metal is also used as a low impedance metal wiring.

Improvement of avalanche region design



- Small and deep avalanche region reduces the electric field around the pixel surface and suppress edge breakdown.

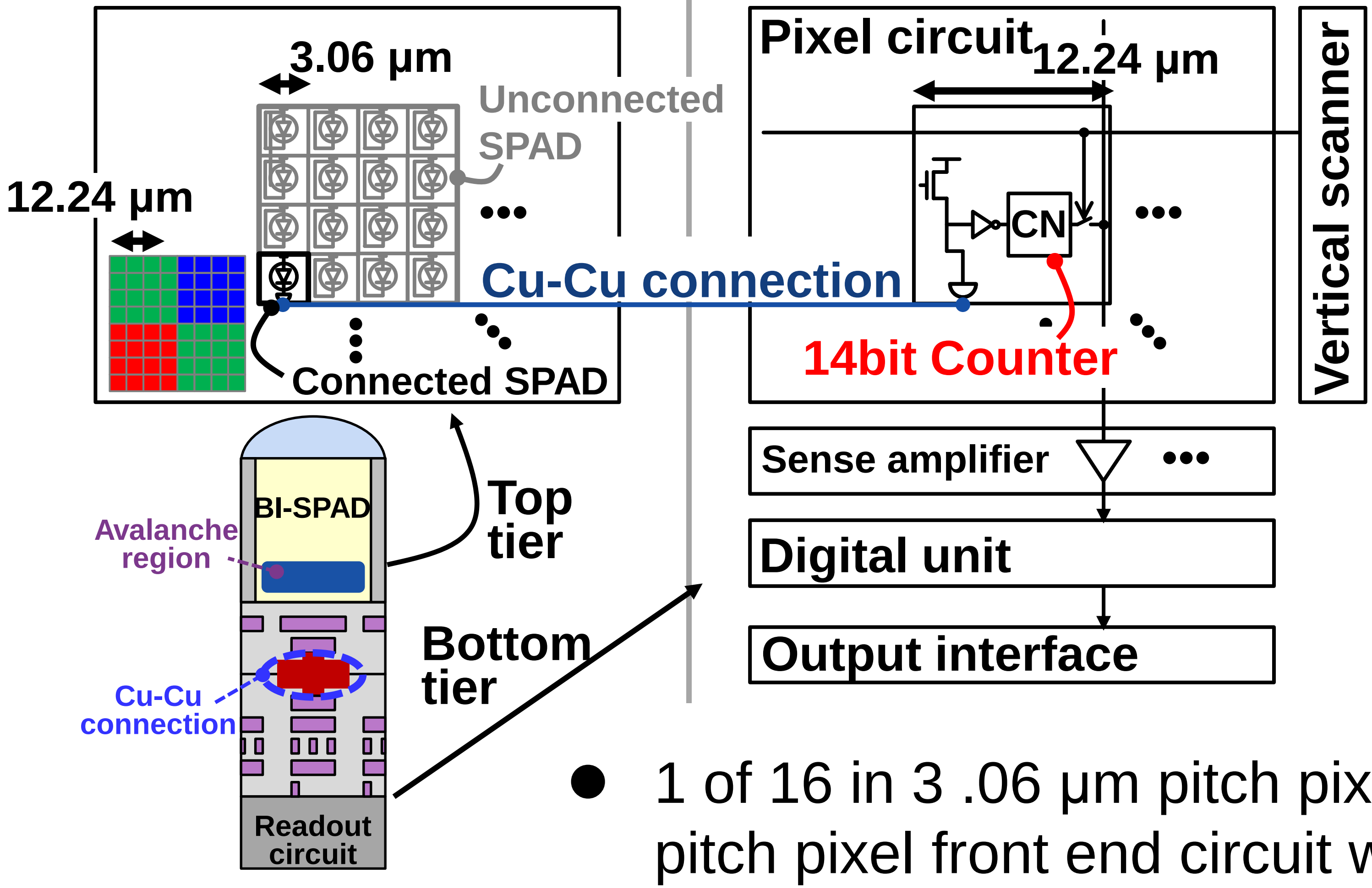
Outline

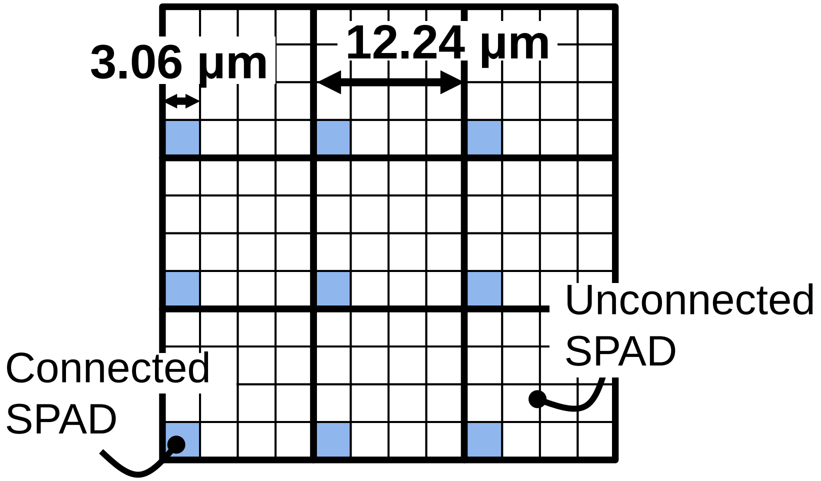
1. Overview of Sony's SPAD technology
2. A Challenge for shrinking the pixel size
3. Prototyping
    1. Chip design
    2. Multiplication and dark count rate (DCR)
    3. Photon detection efficiency (PDE)
    4. Cross Talk (CT) Probability
    5. Captured image with photon counting circuit
4. Conclusions

Prototyping for the proof of concept

Top tier: 90nm BI-SPAD pixel array

Bottom tier: 40-nm CMOS Readout circuit

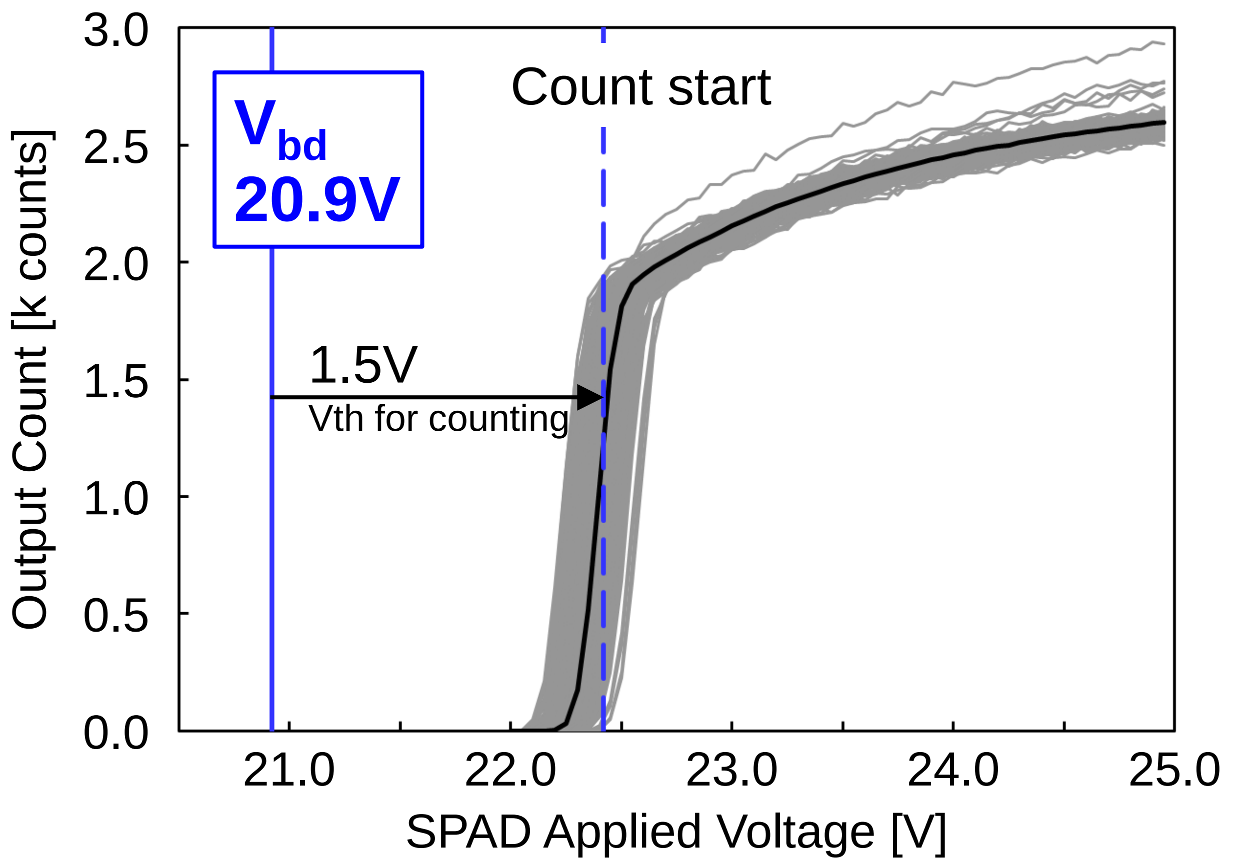


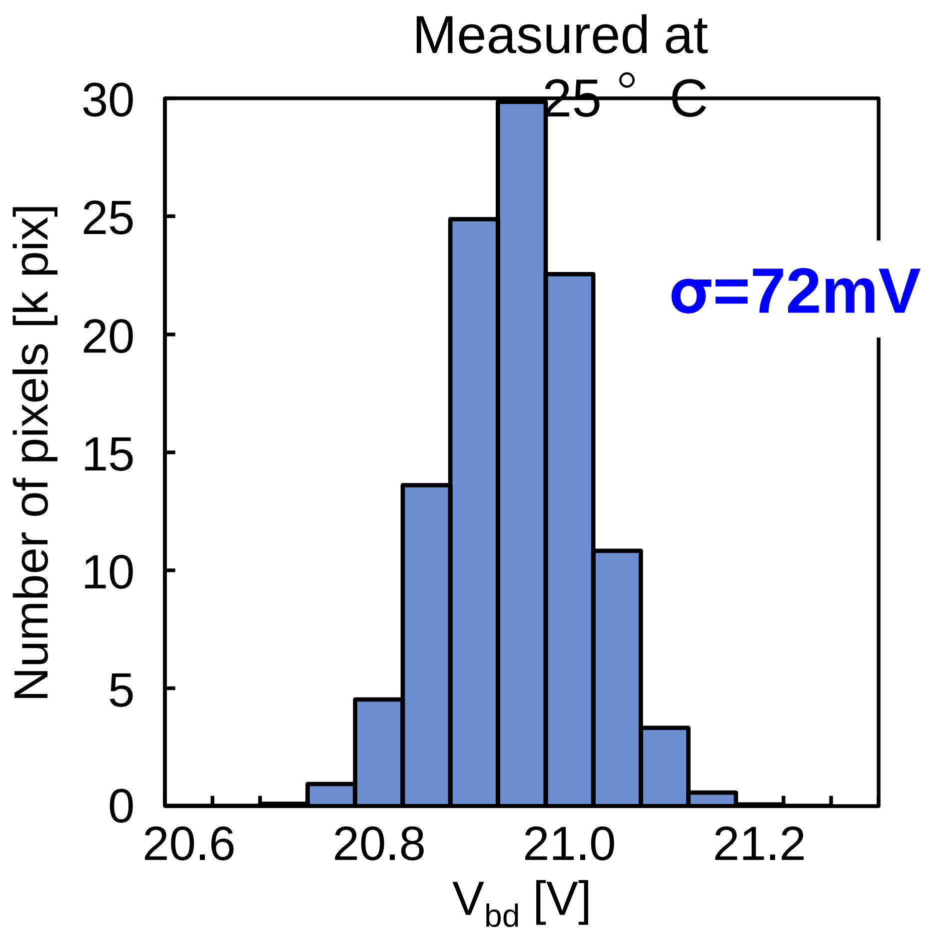


	Physical	Readout
Pixel pitch	3.06 µm	12.24 µm
Array size	640^{H} x 1056^{V}	160^{H} x 264^{V}

- 1 of 16 in 3 .06 µm pitch pixel array connects to 12.24 µm pitch pixel front end circuit with 14-bit in-pixel counter.

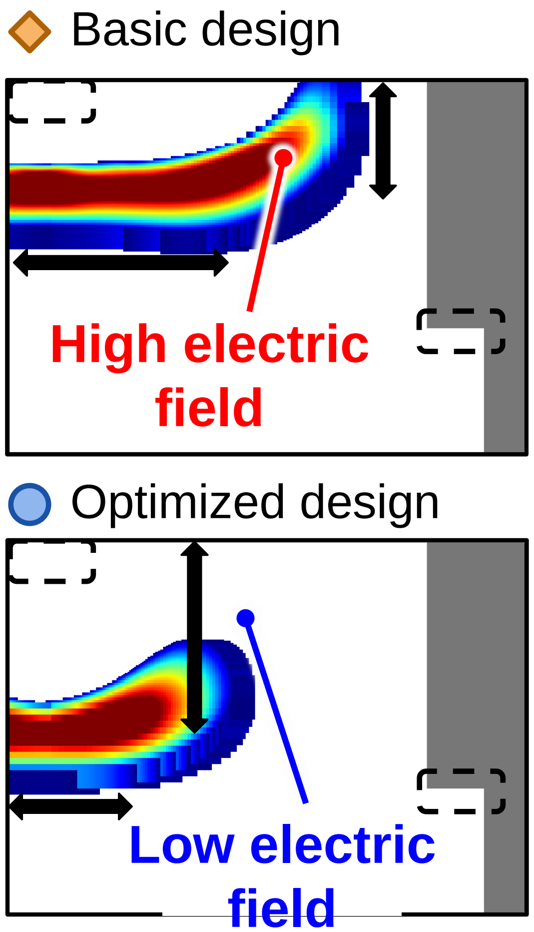
Breakdown characteristics

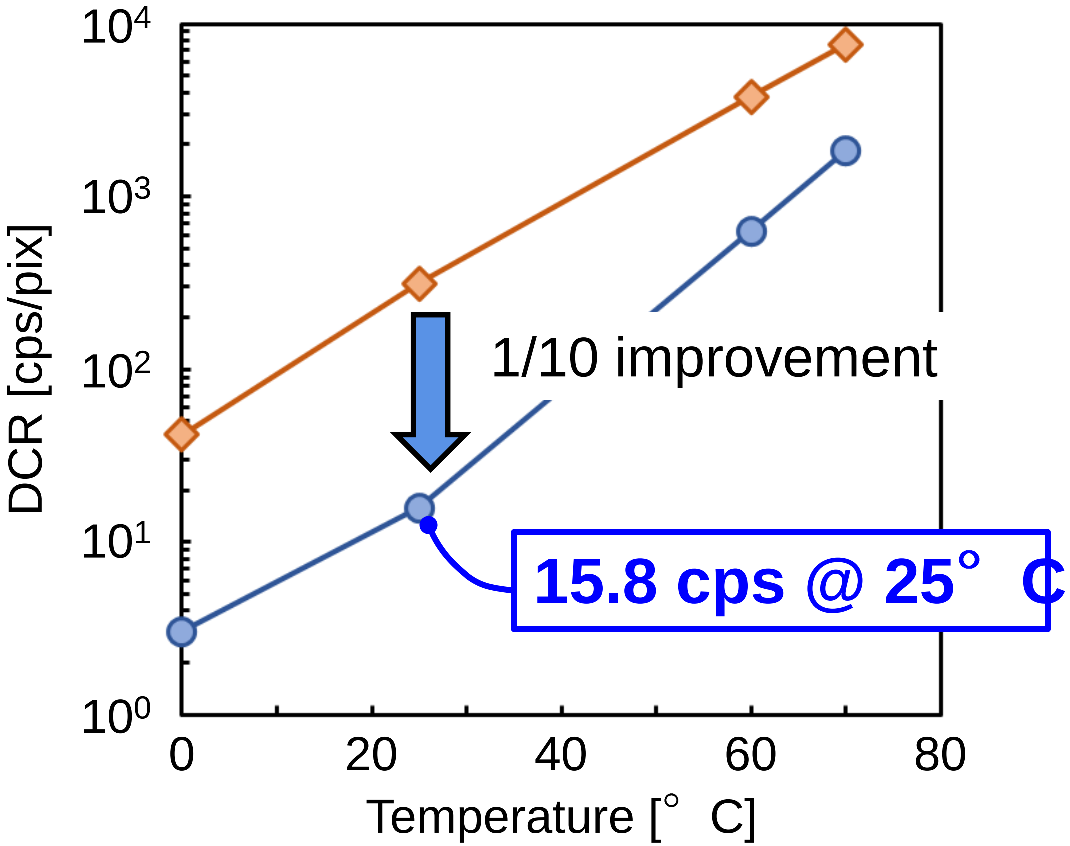




- Breakdown operation with the 3.06-μm-pitch pixels is demonstrated.
- V_{bd} variation is less than 100 mV.

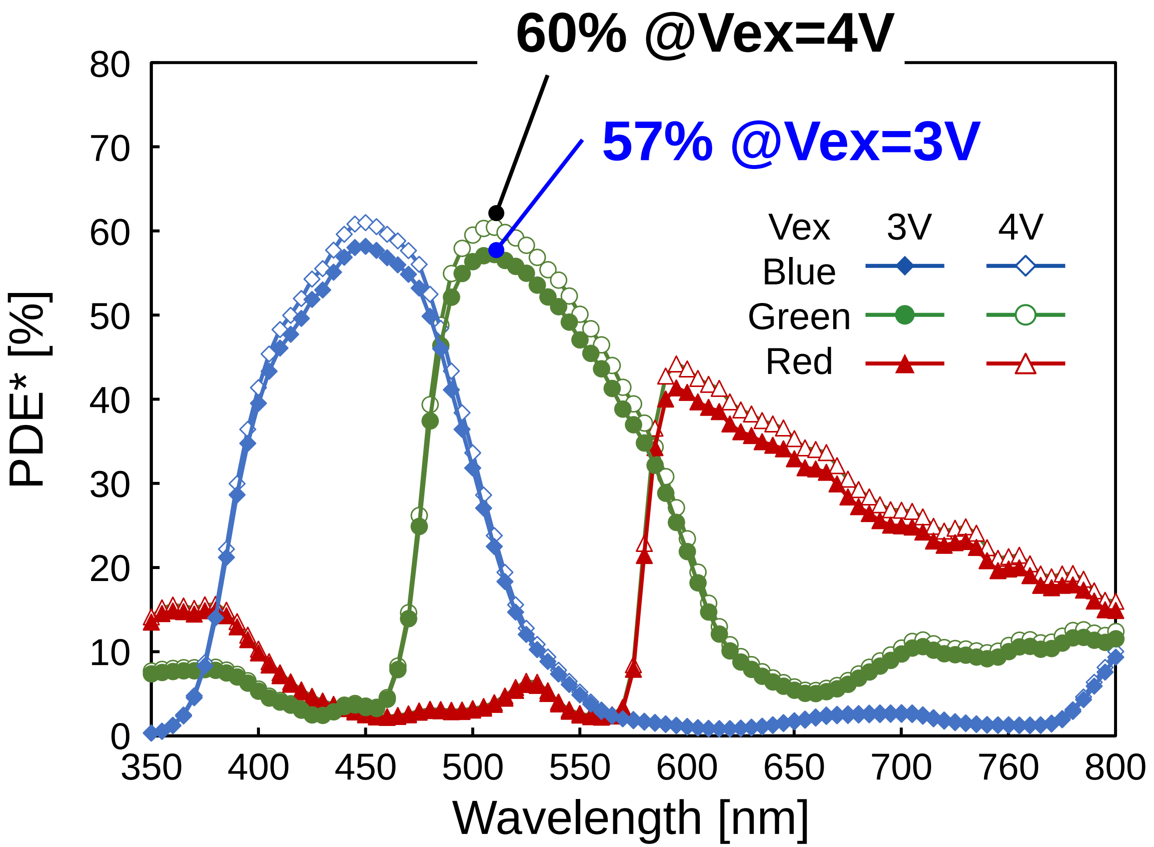
Improvement of the dark count rate





- DCR is successfully reduced with the optimized potential design to decrease the electric field around the pixel surface.

Photon detection efficiency



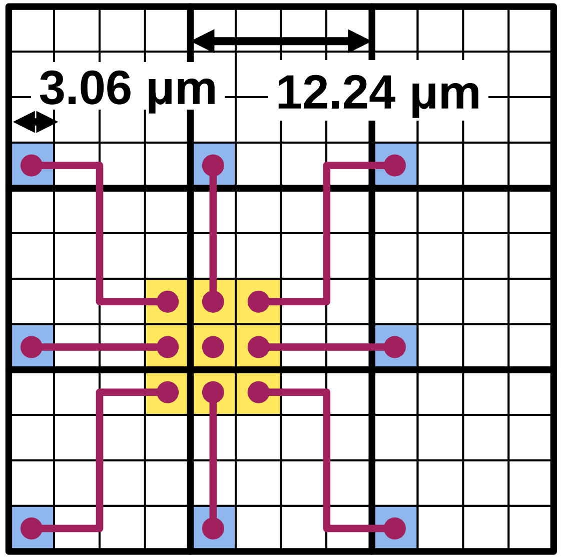
Measured at 25 ° C

*Photon detection rate to incident photons on the whole pixel area (3.06 μm□)

- The photon detection efficiency is 57% even with the small pixel size because of the optimized potential slope for the electron transfer.

Cross-talk (CT) probability

Pixel connection
for CT measurement

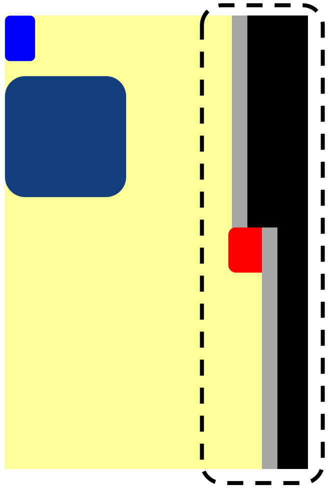


For normal measurement
For cross talk measurement
Connection wiring

Two-step full trench isolation

0.00	0.31	0.00
0.20	100	0.25
0.00	0.17	0.00

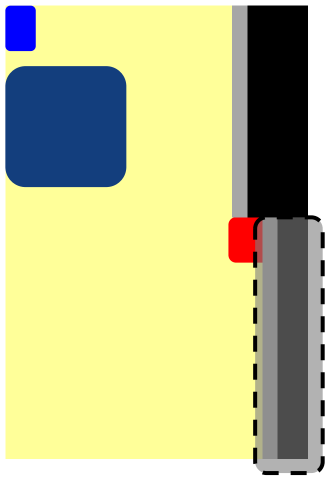
Cross talk probability [%]



Without the full trench structure

15.0	23.5	23.8
23.8	100	24.7
15.0	24.1	14.9

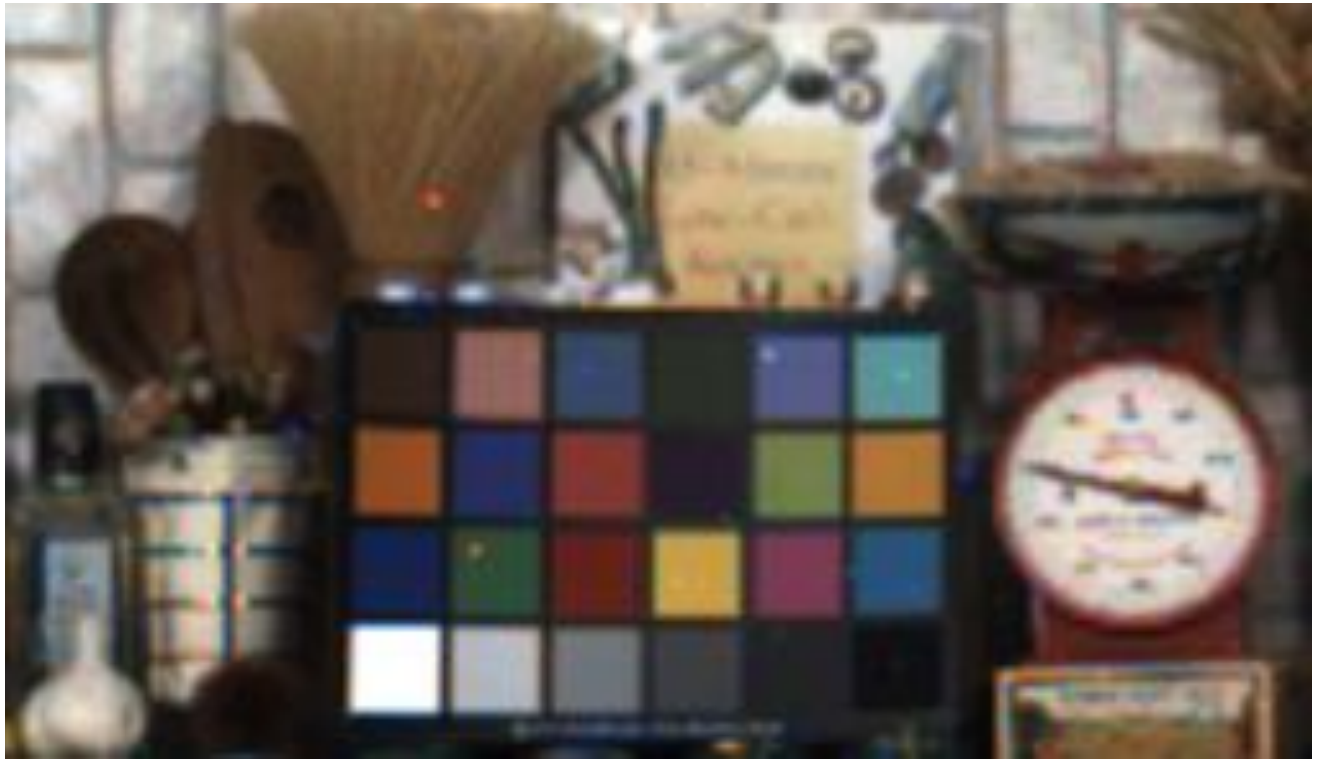
Cross talk probability [%]



Measured at 25 ° C

- The cross-talk probability is less than 0.4 % owing to the full trench isolation with the two-step full trench isolation.

Captured image with the 3 µm pixel array



- ✓ 160 x 264 pixels readout with on-chip color filter
- ✓ 1/60 sec exposure
- ✓ Room temperature

- The color image has been obtained with the 3.06 µm SPAD pixel array and photon counting circuit of the 14-bit pixel parallel counter

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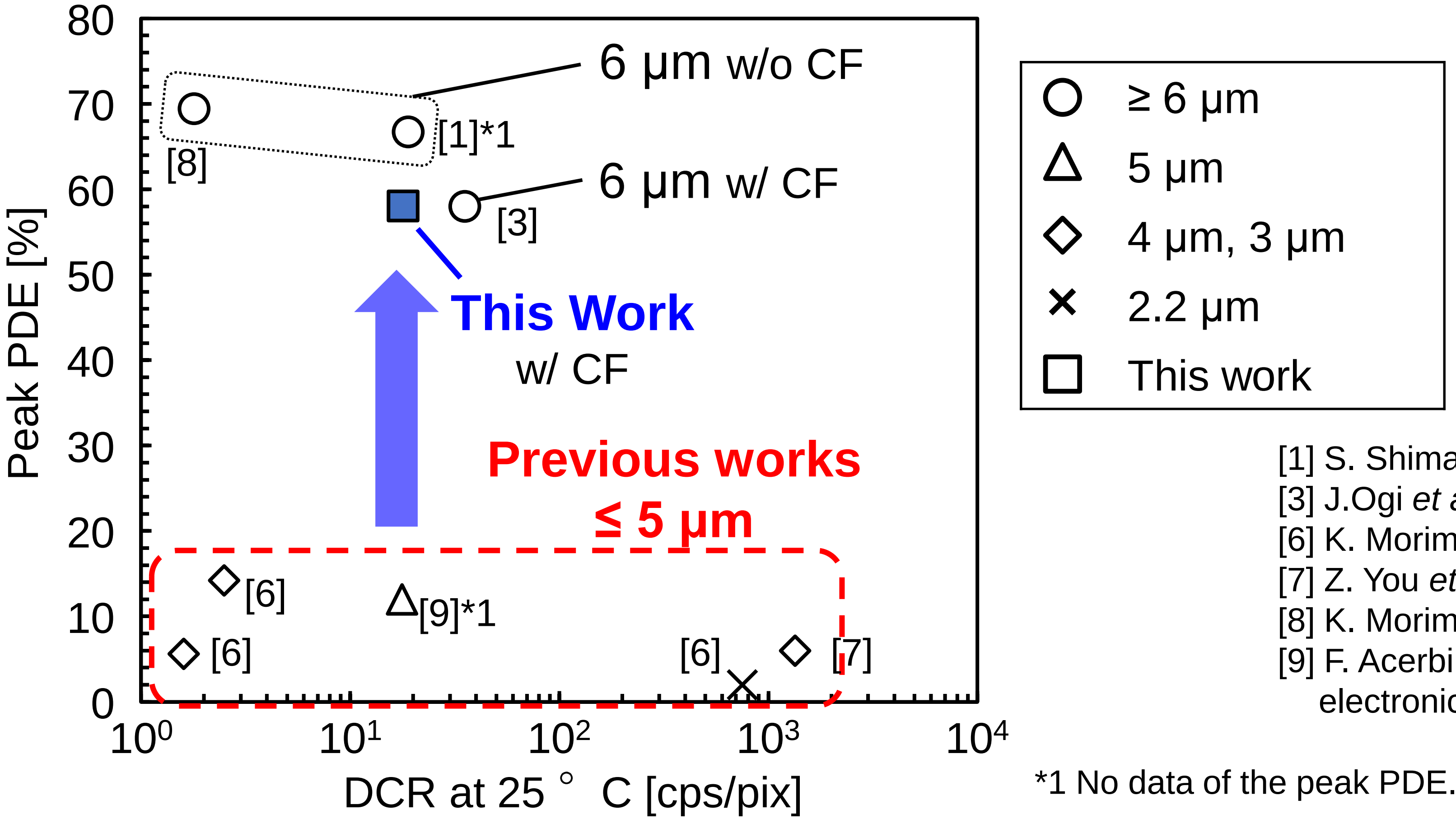
PDE and DCR comparison



[1] S. Shimada *et al*., IEDM2021
[3] J.Ogi *et al.*, ISSW 2021
[6] K. Morimoto *et al* Optic Express, April 2020
[7] Z. You *et al*., ISSW2017
[8] K. Morimoto *et al*., IEDM 2021
[9] F. Acerbi et al., J. Selected Topics in Quantum electronics, March 2018

*1 No data of the peak PDE. The largest value in the article is used.

- PDE is significantly increased compared with the previous works for pixels smaller than or equal to 5 µm.
- DCR and PDE are comparable to those with 6 µm pixels.

Characteristics comparison

	Unit	[3]	[1]	[8]	[9]	[7]	[6]			This work
Pixel pitch	μm	6.12	6	6.39	5	3	4	3	2.2	3.06
Array size		160x 264	N/D	2072x 1548	N/D	4x4	4x4			160x264
Technology		BI-3D 90nm	BI-3D 90nm	BI-3D 90nm	FI	FI 130nm	FI 180nm			BI-3D 90nm
V_{bd}	V	N/D	22	30	N/D	15.8	22.1	23.6	32.35	20.9
V_{ex}	V	3	3	2.5	5.8[*2]	1.2	6	6	6	3
Peak PDE	%	58	66.7[*1]	69.4	12[*1*2]	6[*2]	14.2	5.6	2	57
DCR@25°C	cps	35.4	19	1.8	17.3[*2]	1343	2.5	1.6	751	15.8
Cross talk	%	N/D	0.5	N/D	4.9[*2]	<0.2[*3]	3.57	2.75	2.97	<0.2

*1 No data of the peak PDE. The largest value in the article is used.
*2 No numerical value is expressed in the articles. Author calculated the value from the graphs in the articles.
*3 Vex = 1V.

- The 3 μm SPAD pixel has been demonstrated.
- We aim to improve the pixel characteristics further, in order to utilize such small pixel in a high-resolution photon counting image sensor.

Conclusions

- Sony has developed advanced SPAD sensors combining the relatively high-PDE pixels and advanced circuit designs.
- The SPAD pixel size is shrunk to 3 μm by introducing embedded metal contact on deep trench pixel isolation.
- The peak PDE using a green color filter is 57 % and cross talk probability is less than 0.4 %, while the DCR is 15.8 cps with 20.9 V of V_{bd} and 3 V of V_{ex}.
- DCR and PDE are comparable to those with 6 μm pixels. This is achieved with the embedded contact and optimized potential design for the multiplication.
- We are now trying to improve the pixel characteristics further.