The Latest on SPAD Imaging in Japan

- Event Detection and Quick Readout Schemes -

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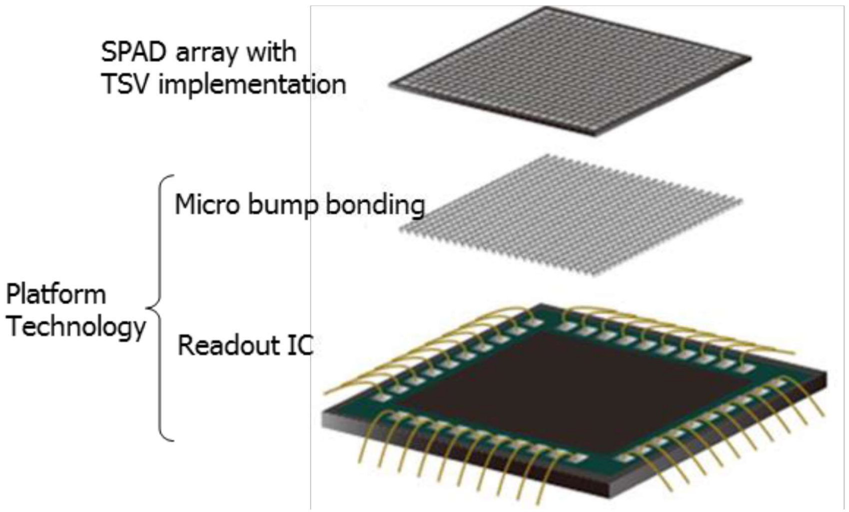
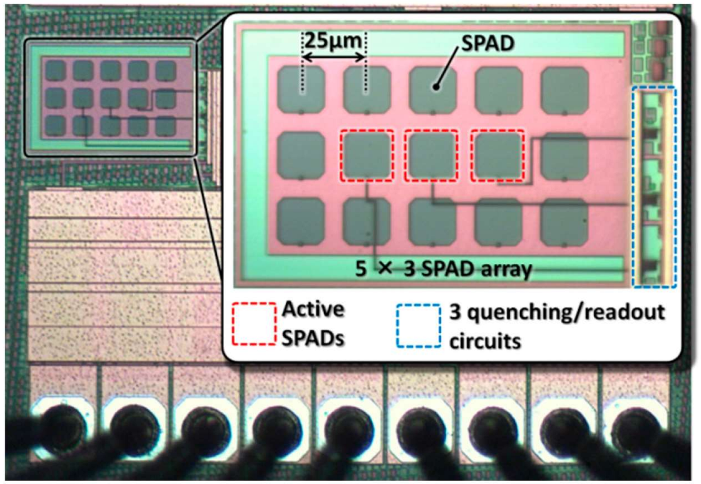
ISSW 2018＠Les Diablerets

Recent Trend of SPAD Studies in Japan

High Fill Factor & Near Infra-Red

- Hamamatsu Photonics/SPIE 2018
  - 3D Hybrid SPAD imager with SiPM
- Toyota Central R&D Lab/Sensor 2016

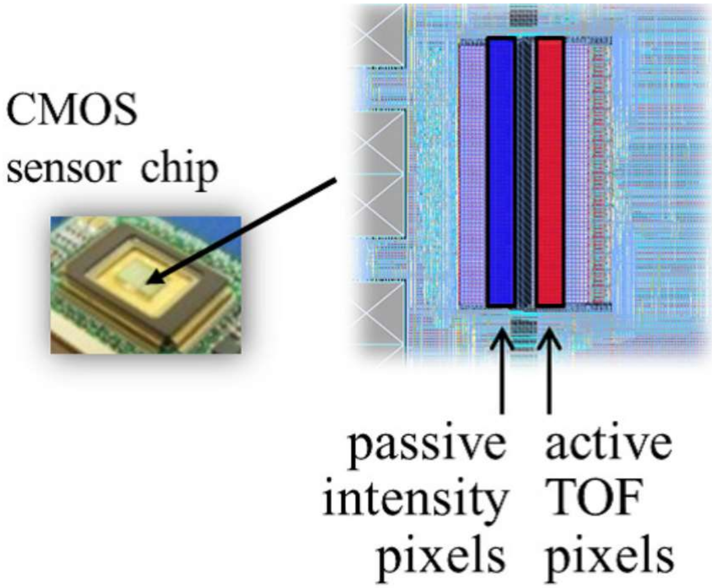


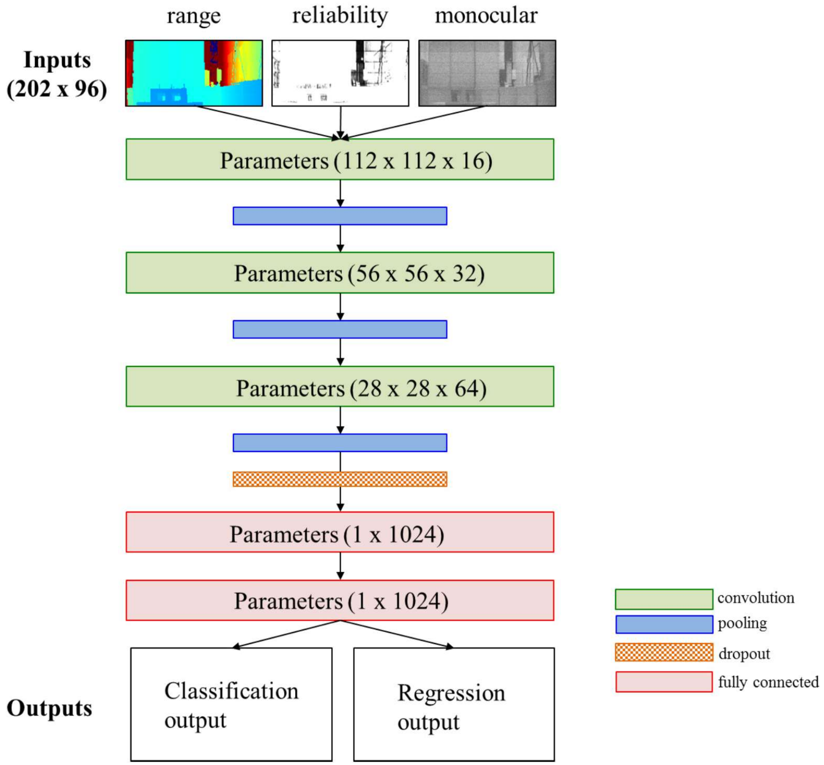


Recent Trend of SPAD Studies in Japan (2)

Information Processing:SPAD + DCNN

- Toyota Central R&D Lab/Sensor 2017
  - Depth、Image, →Neural Net →Classification + Regression

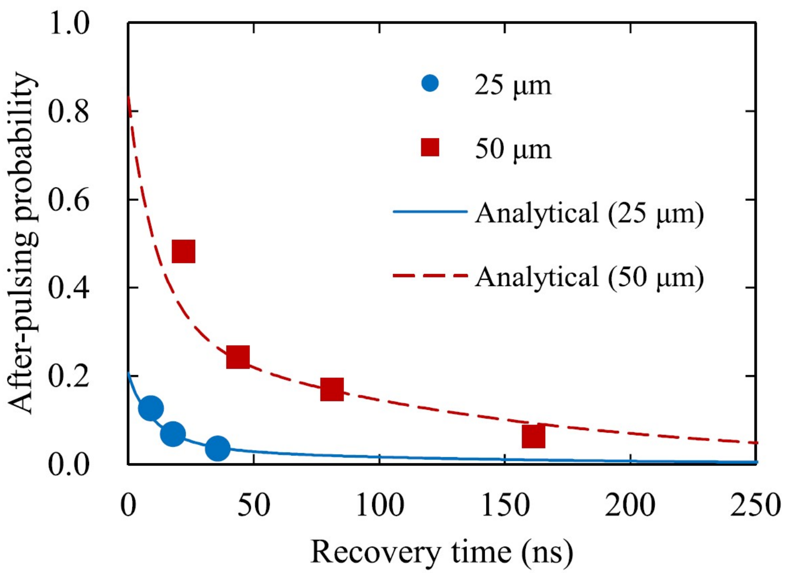


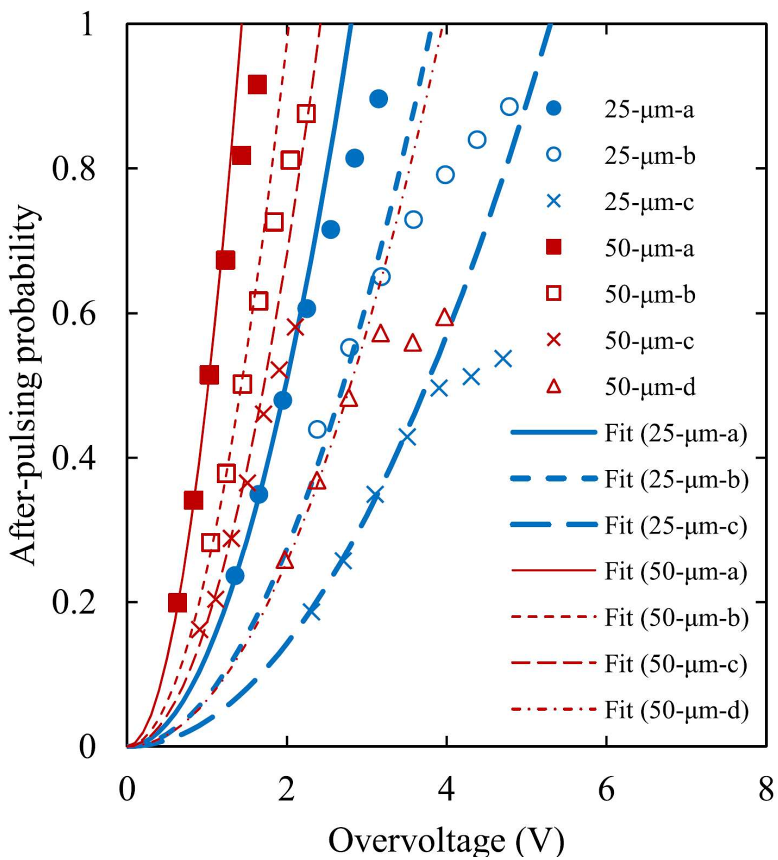


Recent Trend of SPAD Studies in Japan (3)

Basic Study on After-Pulse

- Toshiba R&D Center/IEEE Trans 2017
  - Overdrive Voltage, Structure, Recovery Time →After-Pulse





Recent Trend of SPAD Studies in Japan (4)

Quick access to pixels in ROI

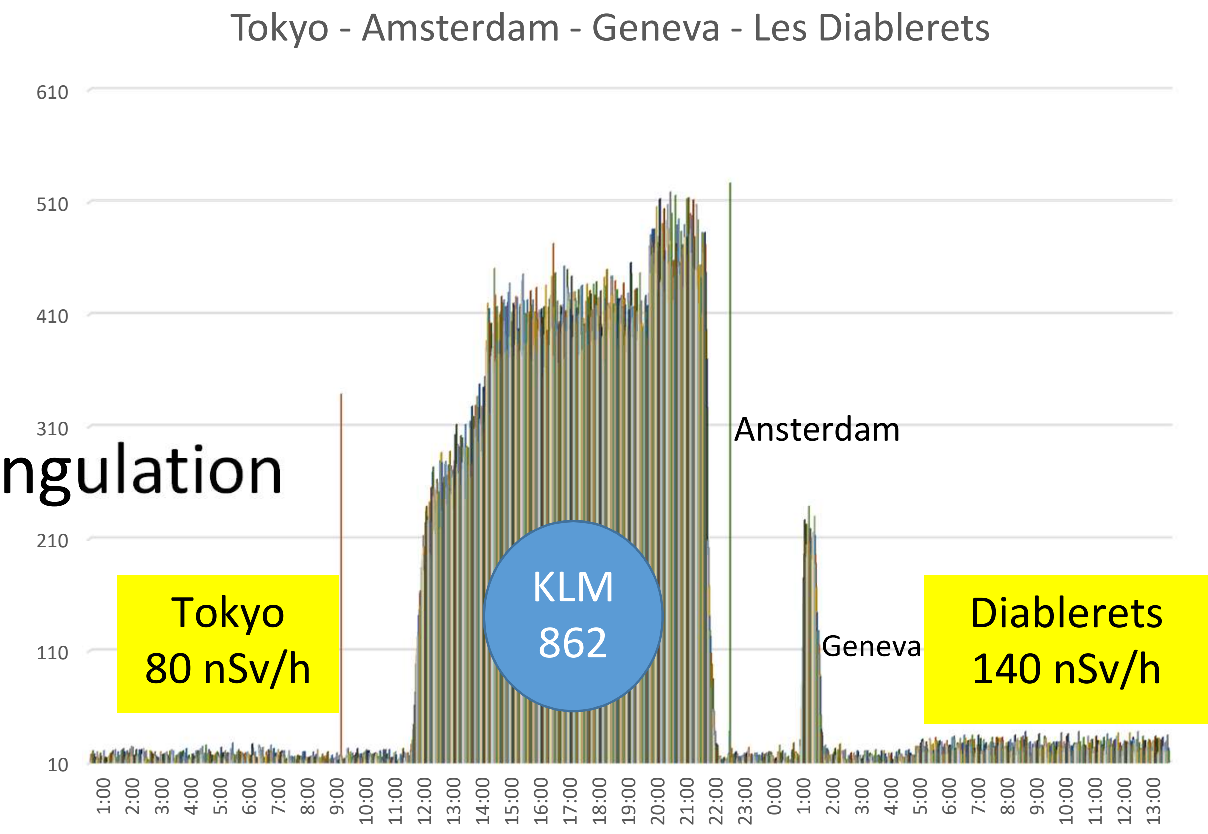
- University of Tokyo, VDEC/Sensor 2017
  - Selective quick access to breakdown-pixels
  - Background readout during photon detection
  - Filtering method of noise

Background of our Laboratory

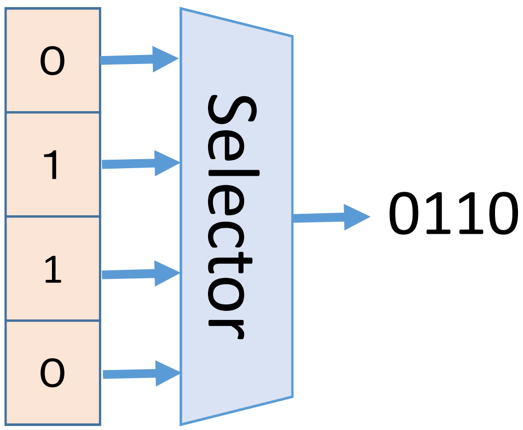
History of Imagers

- ➢ CMOS APS 3D imagers
  1995 – now
  - Combination of APS & Selective quick readout
  - 3D image sensing by triangulation

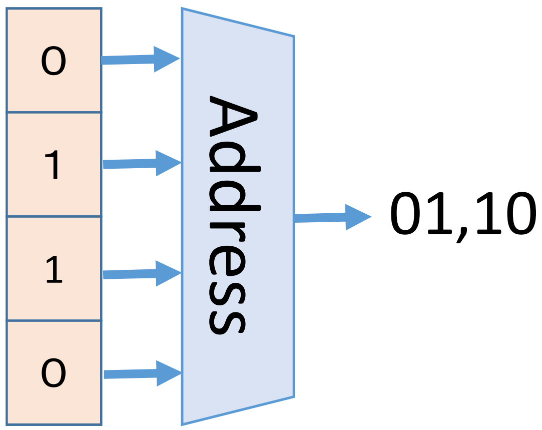
- ➢ CMOS SPAD imagers
  2011 – now
  (after Fukushima disaster)



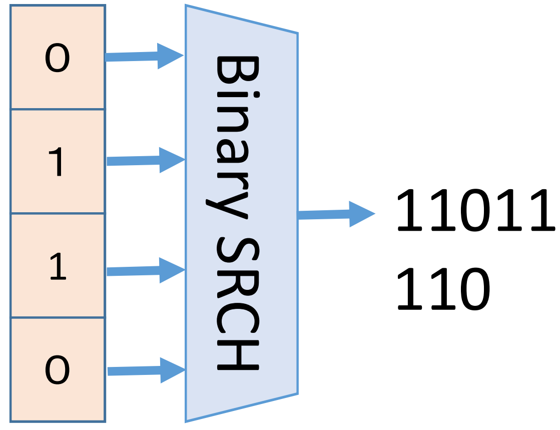
Comparison of 3 access methods



(1) Address Scan
N bits



(2) Data Scan
0 .. $N \cdot \log_2 N$ bits
(Priority Encode)
(This study)



(3) Binary Scan
1 .. 2N bits

Example: Binary/Quarter Scan method

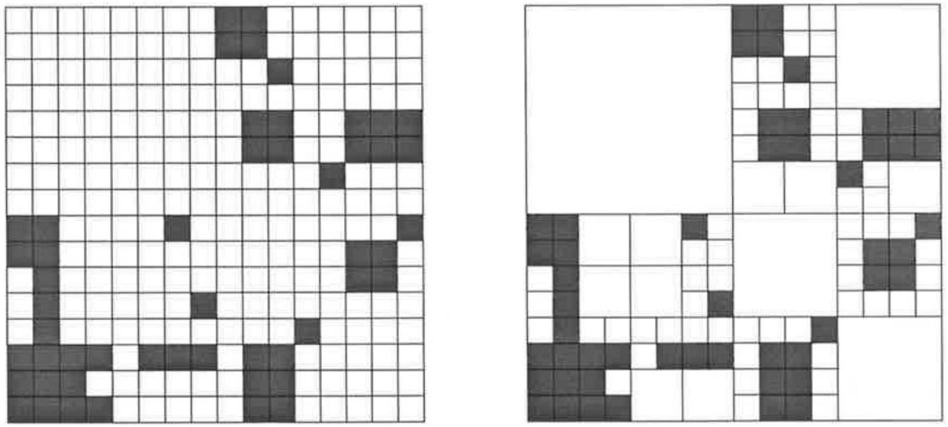
L : Mean Code Length

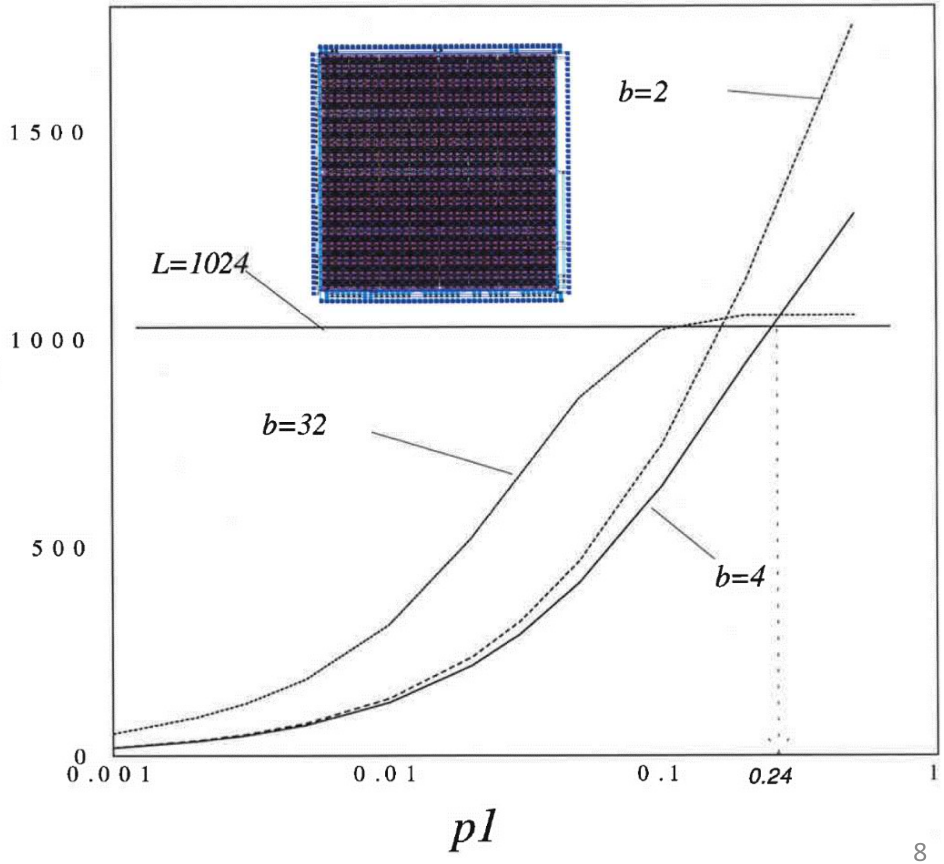
b : # of Branch

N : # of Depth

p_1 : Active Probability of Sensor

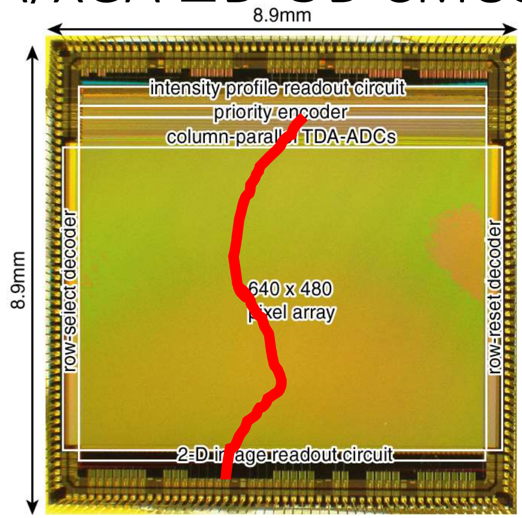
➢ Quad-Tree Search
  - Sequential priority encoder
  - Suitable for spot light detection



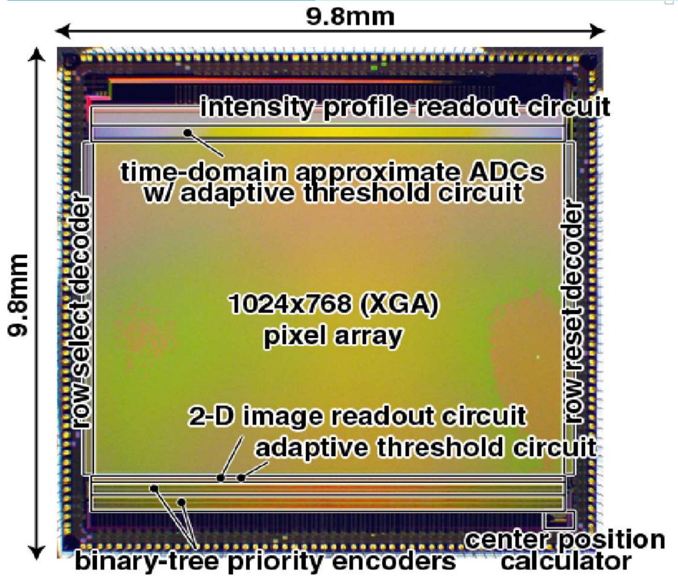


Example: Data Scan Method suitable for sheet light detection

VGA/XGA 2D-3D CMOS imager

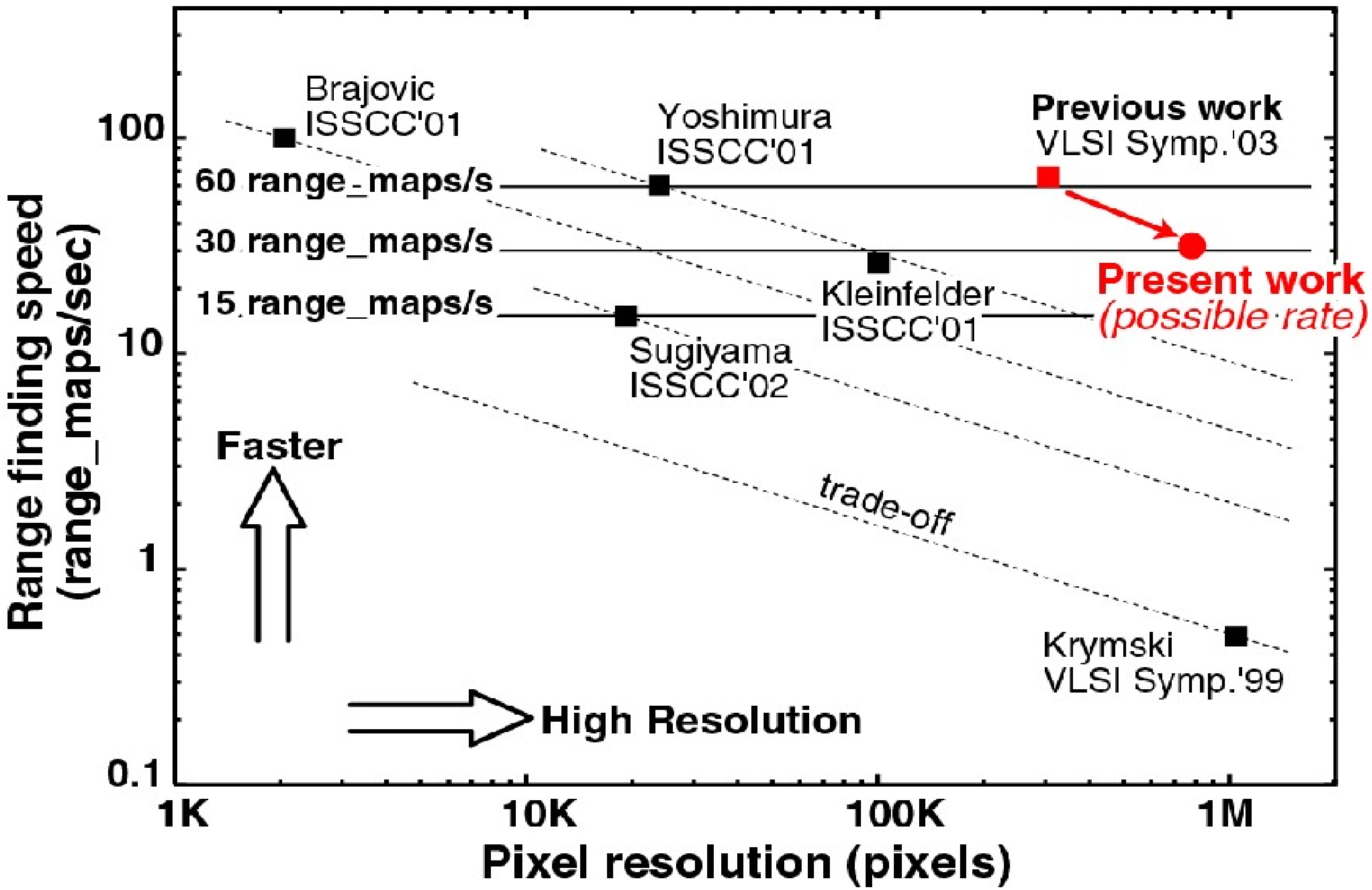


Specifications	
Process	0.6μm CMOS process
Die Size	8.9mm × 8.9mm
# Pixels	640 × 480 pixels
Pixel Size	12.0mm × 12.0mm
Fill Factor	29.54%
# Trans. / Pixel	3 trans./pixel



Process	**0.35μm 2P3M CMOS**
Die size	**9.8 mm x 9.8 mm**
# pixels	**1024 x 768 pixels (XGA)**
# FETs	**3.2M FETs**
Pixel size	**8.4 μm x 8.4 μm**
Photo diode	**pn junction**
# FETs/pixel	**3 FETs**
Fill factor	**29.0 %**

Comparison of Speed v.s. Resolution at 2004



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1. SPAD structures and characteristics
   PAP: Probability of After-Pulse
2. Quick readout circuits for short time-window
3. High resolution method of scintillation light position

SPAD design for Standard CMOS 0.18 with Deep Nwell

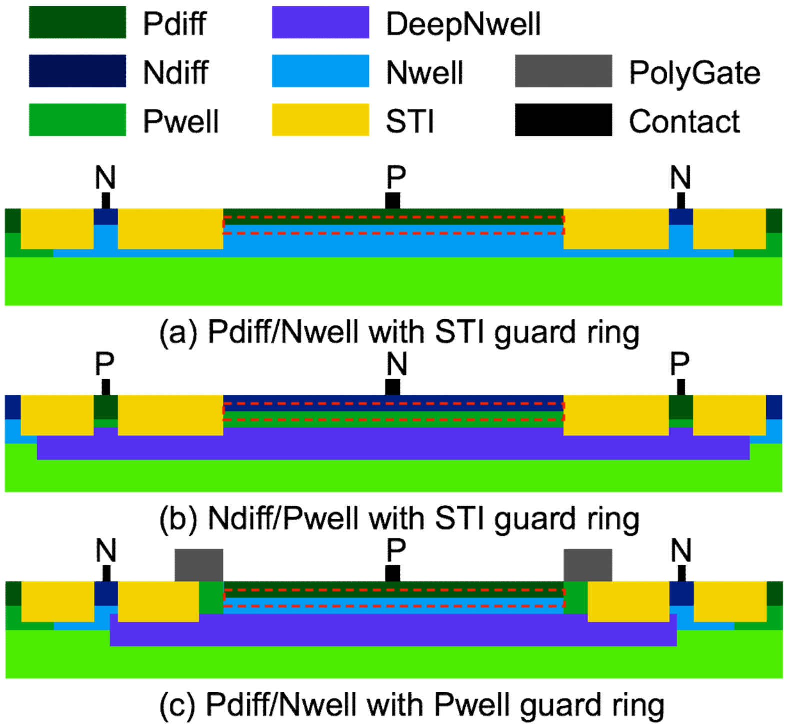
Unsuccessful trials:

(a) Pdiff/Nwell with STI guard

(b) Ndiff/Pwell eith STI guard

(c) Pdiff/Nwell with Pwell guard

SPAD	V_{BR} [V]	DCR [Hz]
(a)	7.9	>2 MHz@ V_{EX} = 0.1V
(b)	8.0	>2 MHz@ V_{EX} = 0.1V
(c)	7.9	>1 MHz@ V_{EX} = 0.1V



Dark counts rate is very large due to the low breakdown voltage (mainly tunneling)

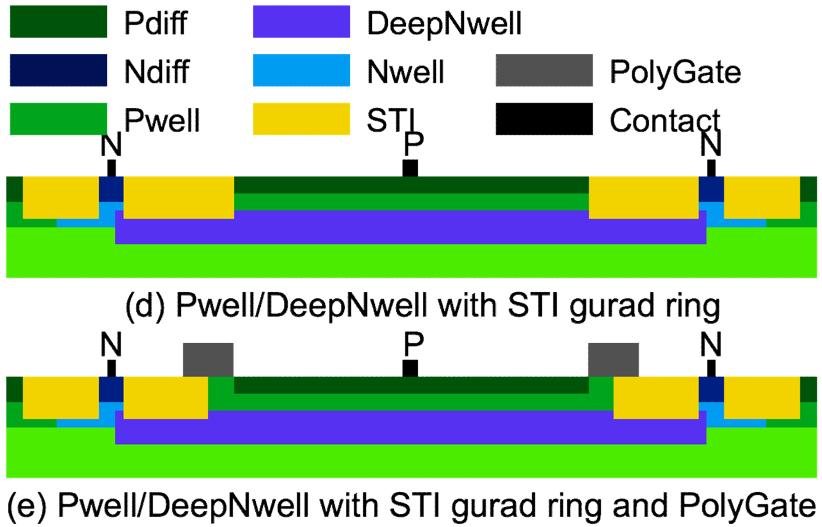
Final tolerable SPAD structure for Standard CMOS

Not yet tolerable

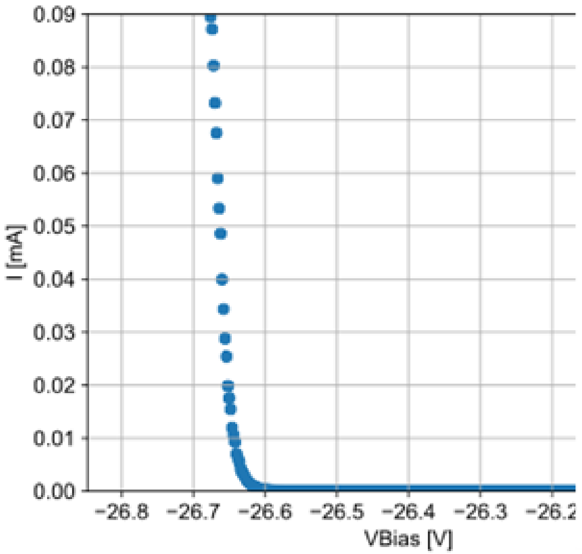
(d) Pwell/Deep_Nwell with STI guard

Tolerable:

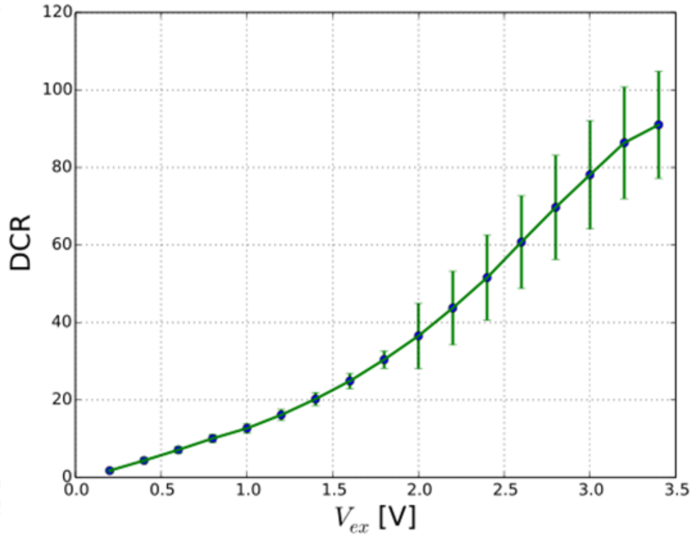
(e) Pwell/Deep_Nwell with STI & Poly guard



I-V characteristic



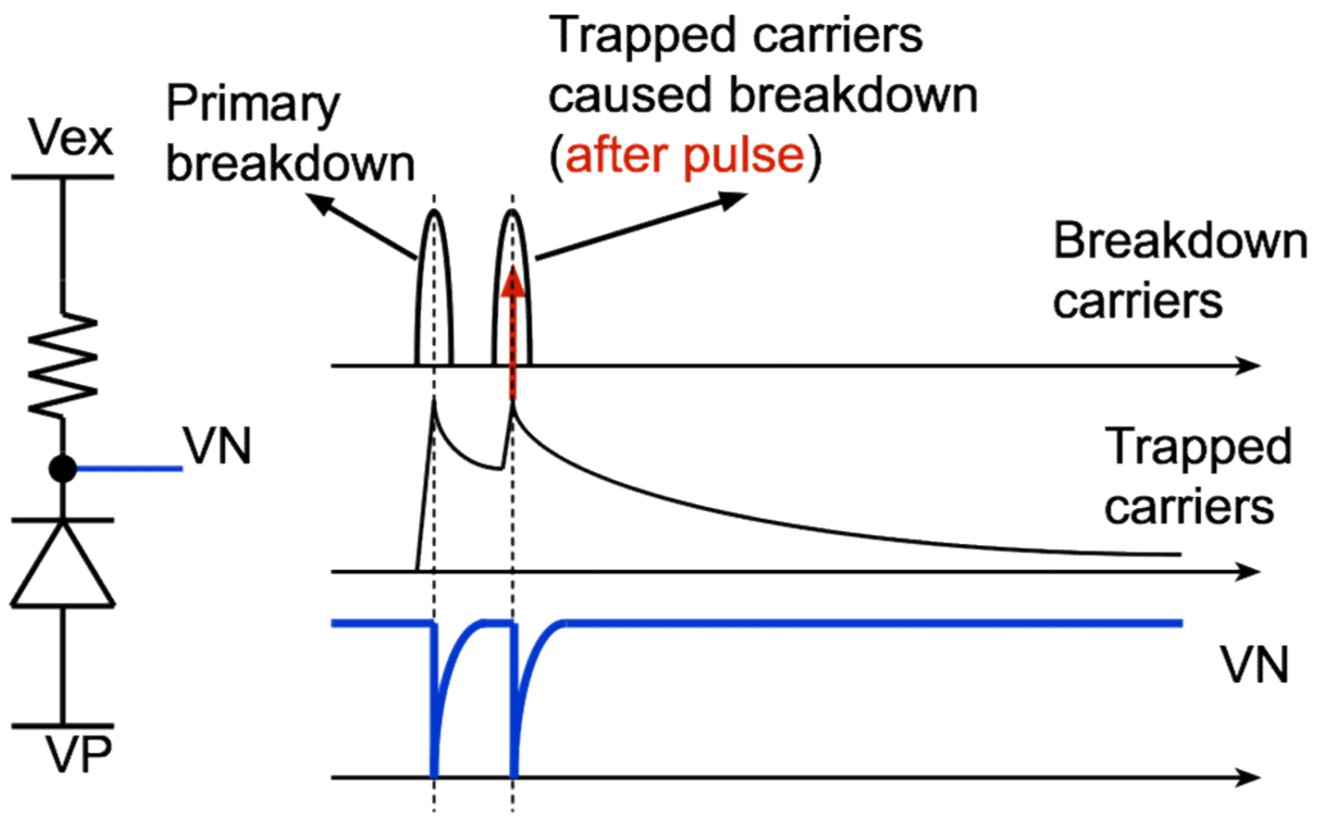
DCR kHz



SPAD	V_{BR} [V]	DCR [Hz]
(d)	26.6	5.4 kHz@ V_{EX} = 0.1V
		331 kHz@ V_{EX} = 0.3V
(e)	26.6	<1 kHz@ V_{EX} = 0.3V
		7.3 kHz@ V_{EX} = 1.0V
		26.8 kHz@ V_{EX} = 2.0V

SPAD: After-pulse (AP) phenomenon

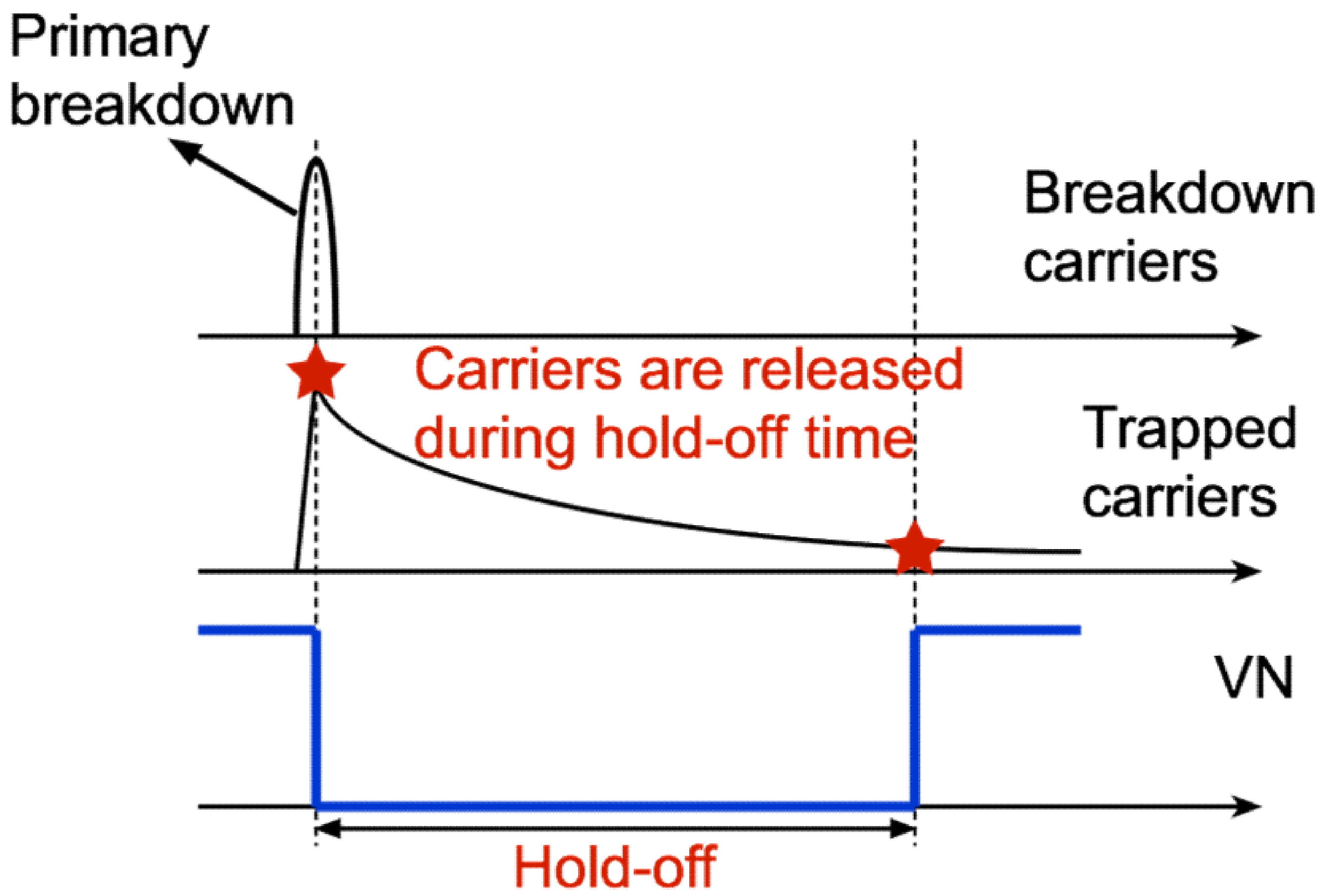
After pulse: dark counts caused by deep traps in depletion region.



S. Cova et al., IEEE Electron Device Letters, 1991.

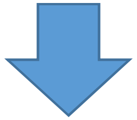
After-pulse characterization on hold-off time

The probability of AP can be reduced by hold-off time

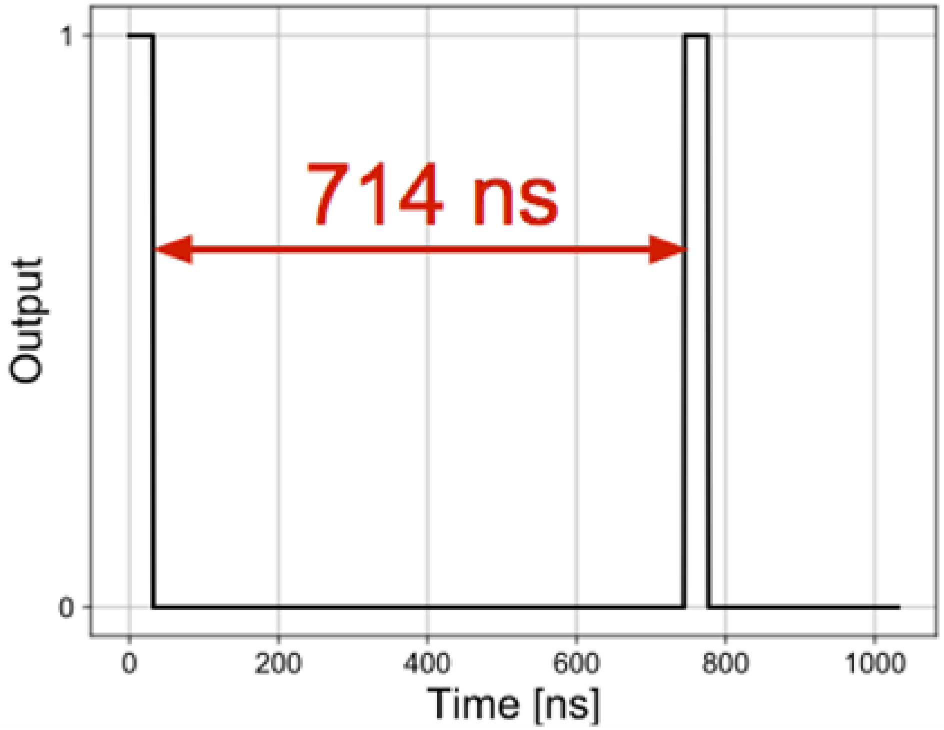


Breakdown Pulse interval measurement

- Measure time differences between the falling edge of a pulse and the rising edge of next pulse.
- Repeat the measurements many times (>100,000).
- Normalization.

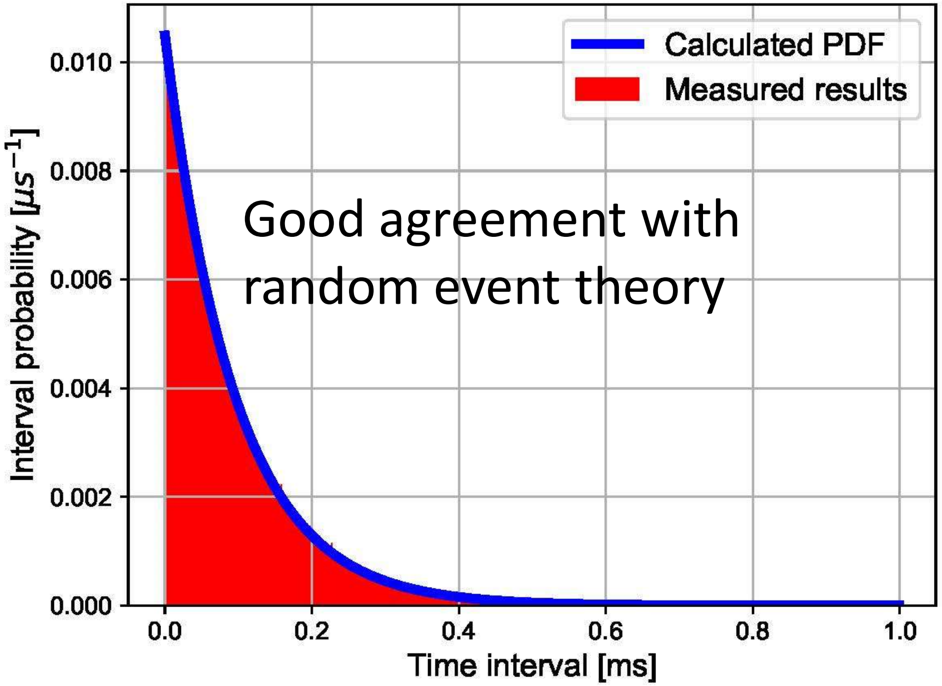


Time interval distribution analysis.



Pulse interval probability for Long hold-off time

- Hold-off time is 1 ms set by the external ‘Force_off’
- Free of after-pulsing
- Time interval: Exponential distribution
- 250,000 measurements, bin=100 ns



Measured :

Mean : $95.32\,\mu s$

Var : $8.986 \times 10^9\, ns^2$

Std : $94.8\,\mu s$

Median : $66.36\,\mu s$

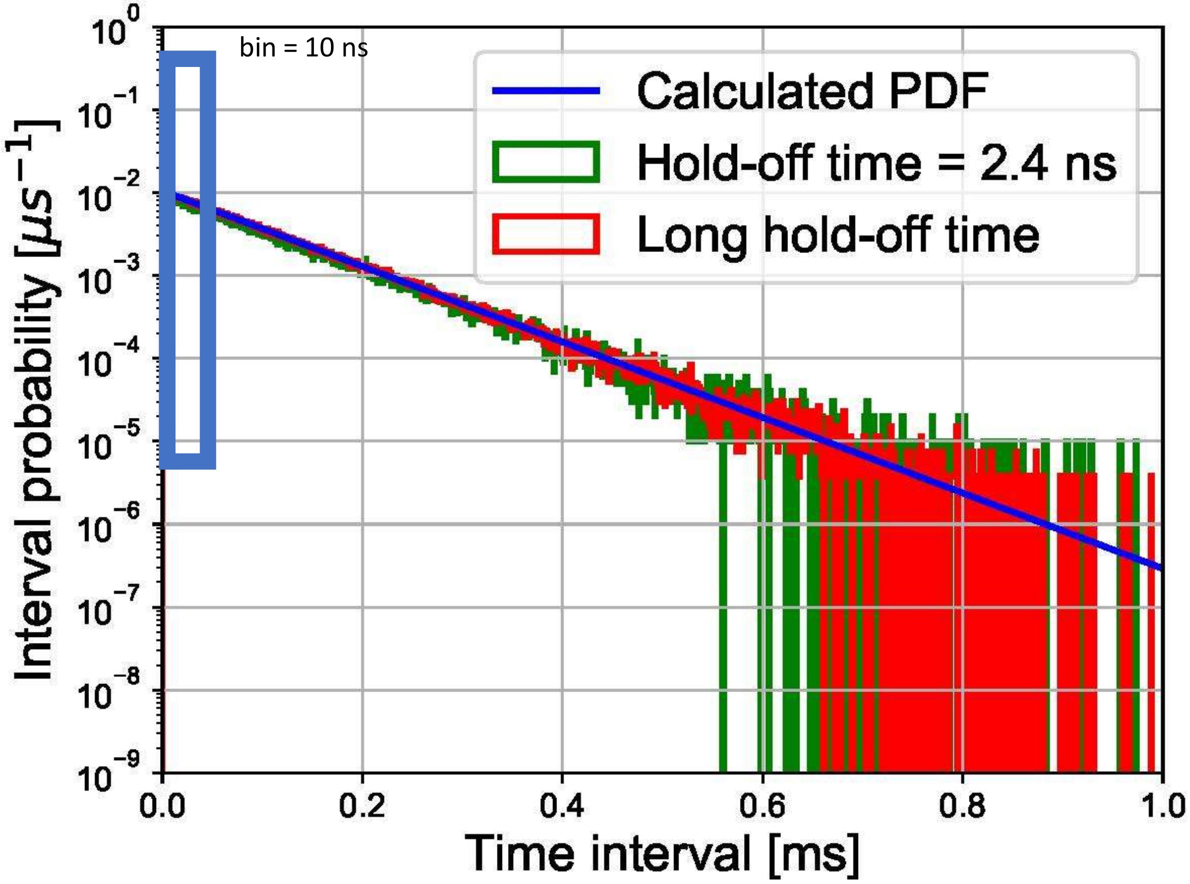
Exp distribution

$$p(t) = \lambda e^{-\lambda t}, \lambda = \frac{1}{\text{Mean}}$$

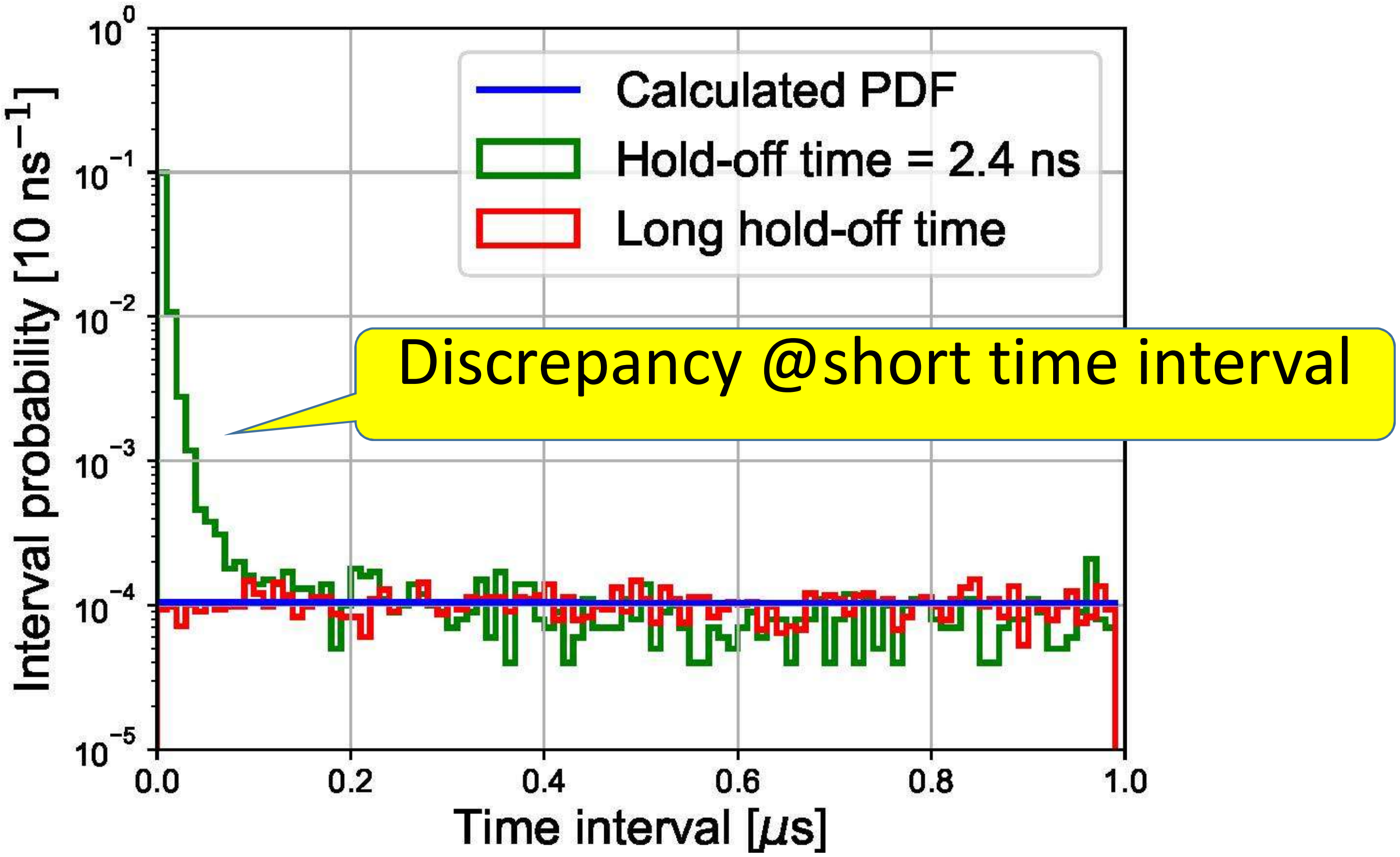
Var : $\frac{1}{\lambda^2} = 9.085 \times 10^9\, ns^2$

Median : $\frac{\ln(2)}{\lambda} = 66.08\,\mu s$

Pulse interval probability with short & long hold-off



Discrepancy for short & long hold-off time → After-pulse



Calculation of After-Pulse probability

For a certain time period ’Δt’ （ =1 us) :

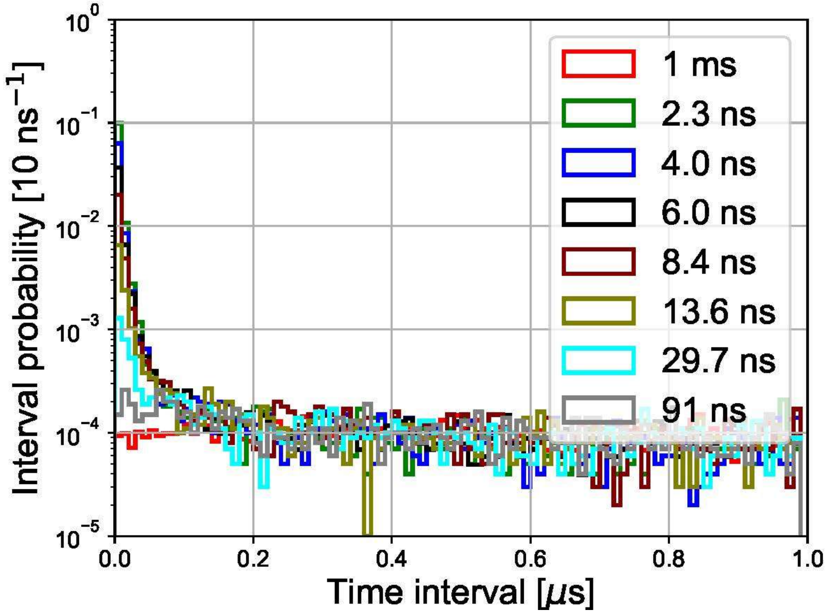
$P_{BD}(t)$: measured breakdown probability

$P_{DC}(t)$: measured breakdown probability at long hold-off time

$P_{AP}(t)$: After-pulsing probability

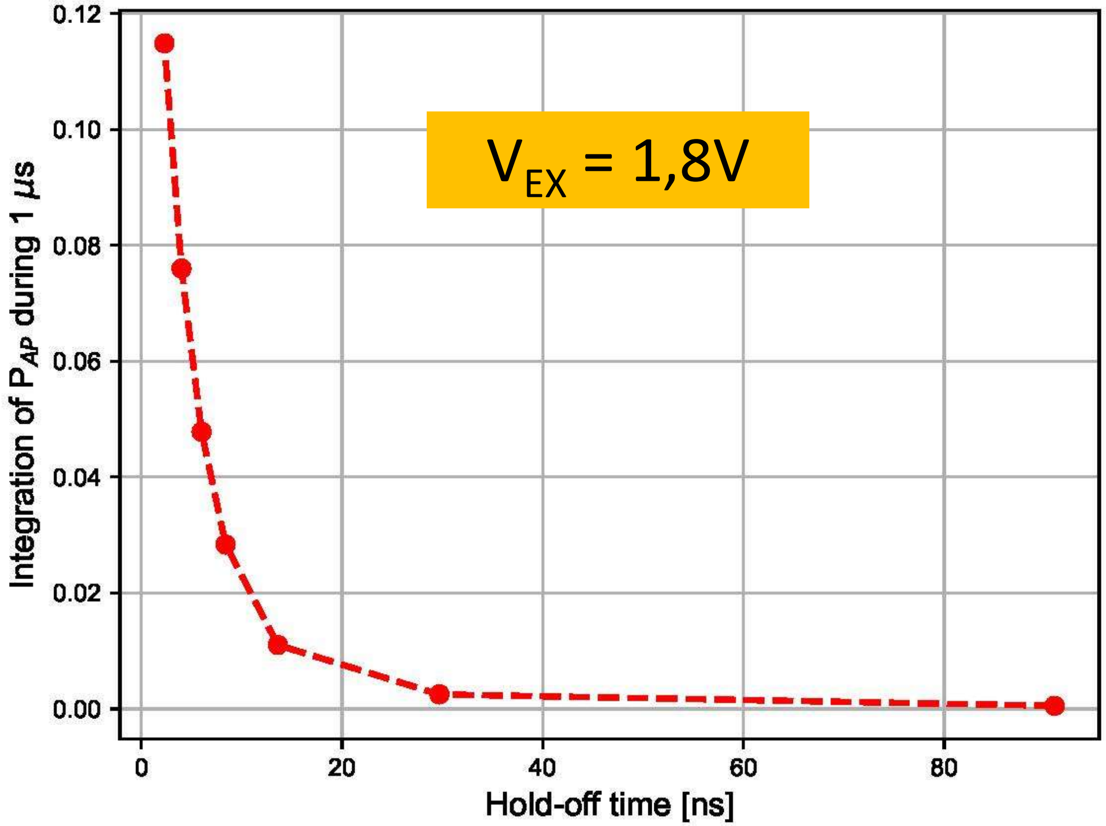
$$P_{BD}(t) = 1 - (1 - P_{DC}(t))(1 - P_{AP}(t))$$

$$P_{AP}(t) = 1 - \frac{1 - P_{BD}(t)}{1 - P_{DC}(t)}$$



Hold-off time vs. After Pulse Probability

P_{AP} can be reduced to 1 % @ 20 ns hold-off



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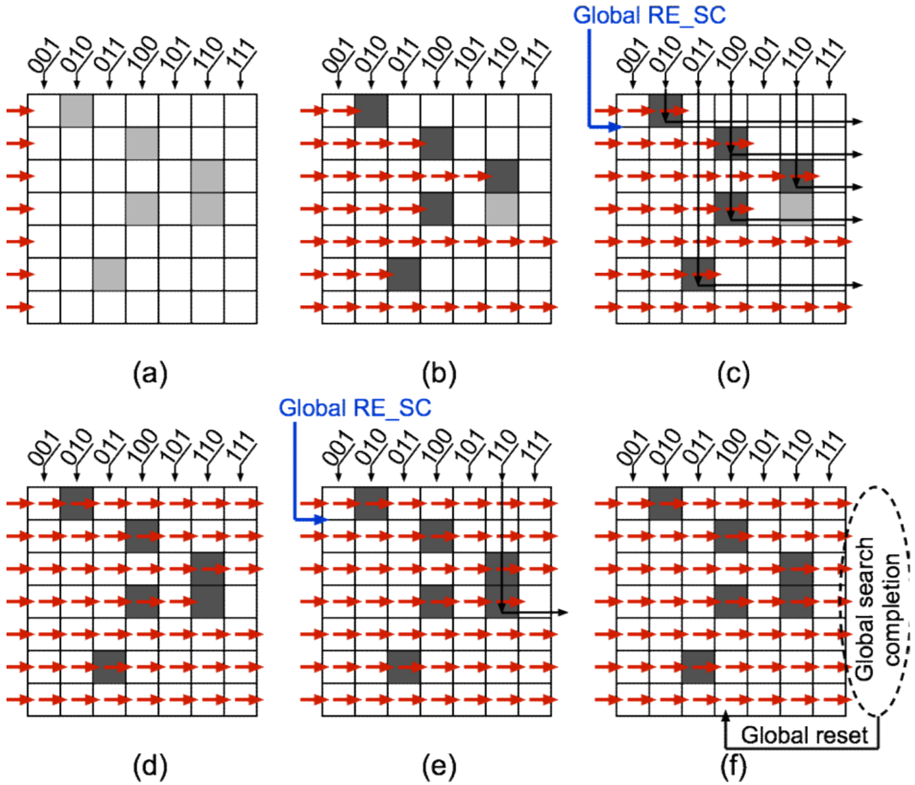
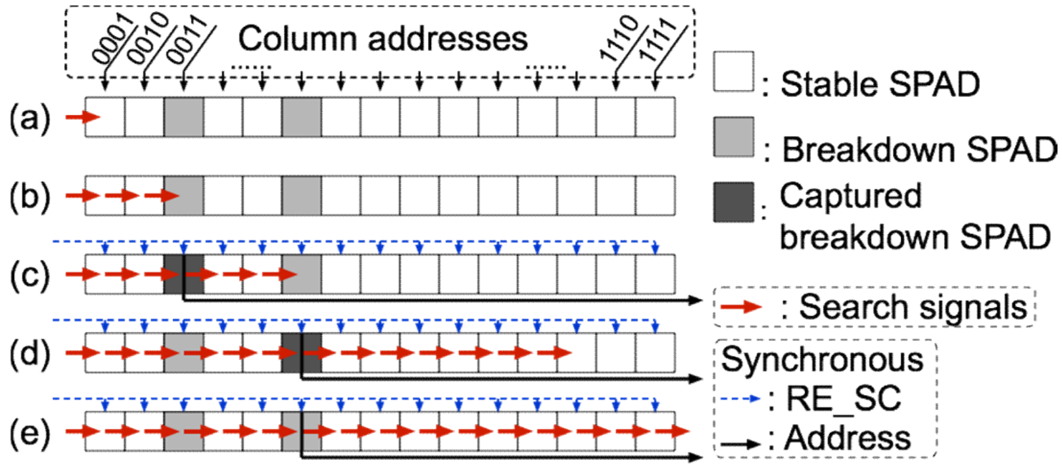
Row-parallel: Breakdown-pixels-extraction (BPE)

- Row parallel scan of breakdown pixels
- Readout cycles: $1+\mathrm{Max}(N_{BD,i})$ X (4+1) for 15 x 15 SPAD array

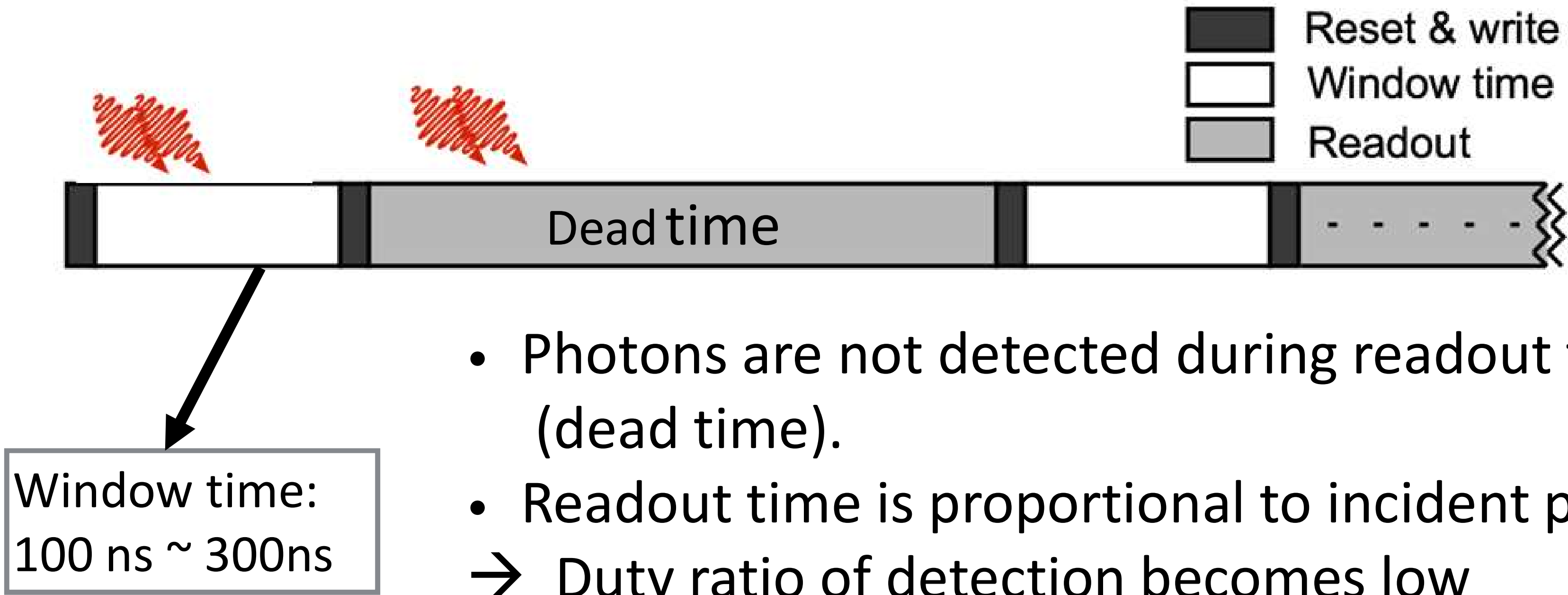




N_{BD}: the # of breakdown pixels in the whole chip
$N_{BD,i}$: the # of breakdown pixels in the i-th row

Readout after photon detection (Non-pipeline)

- Typical pulse light (20 ns~100 ns)
- Short window time for low dark counts & high frame rate

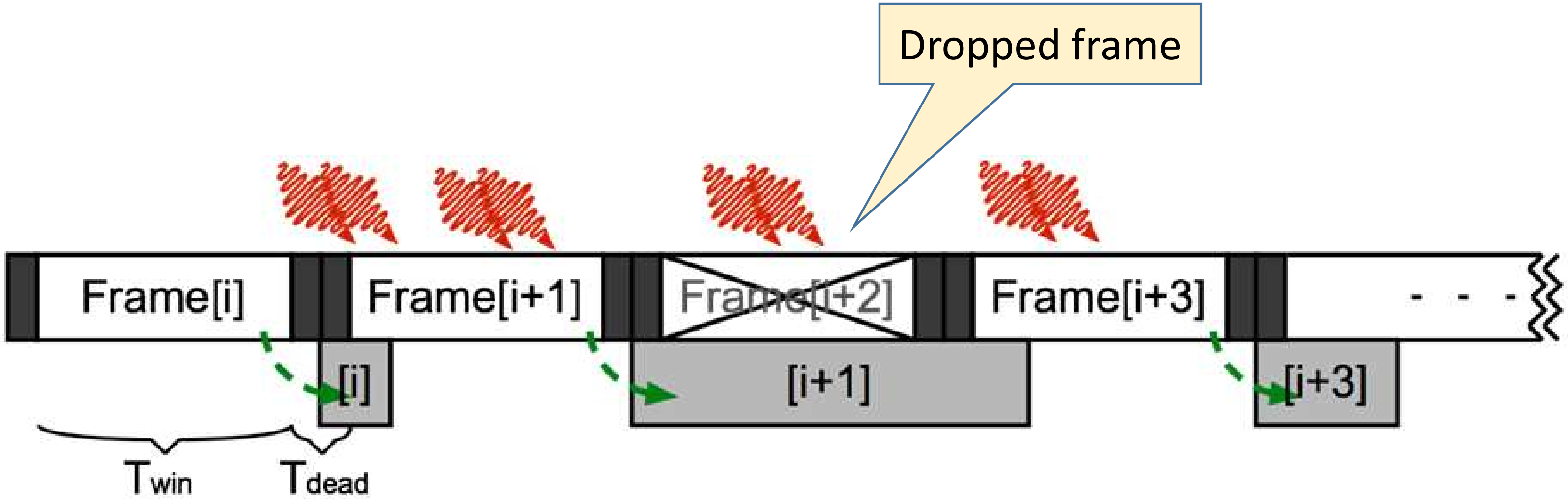


- Photons are not detected during readout time (dead time).
- Readout time is proportional to incident photons.

→ Duty ratio of detection becomes low

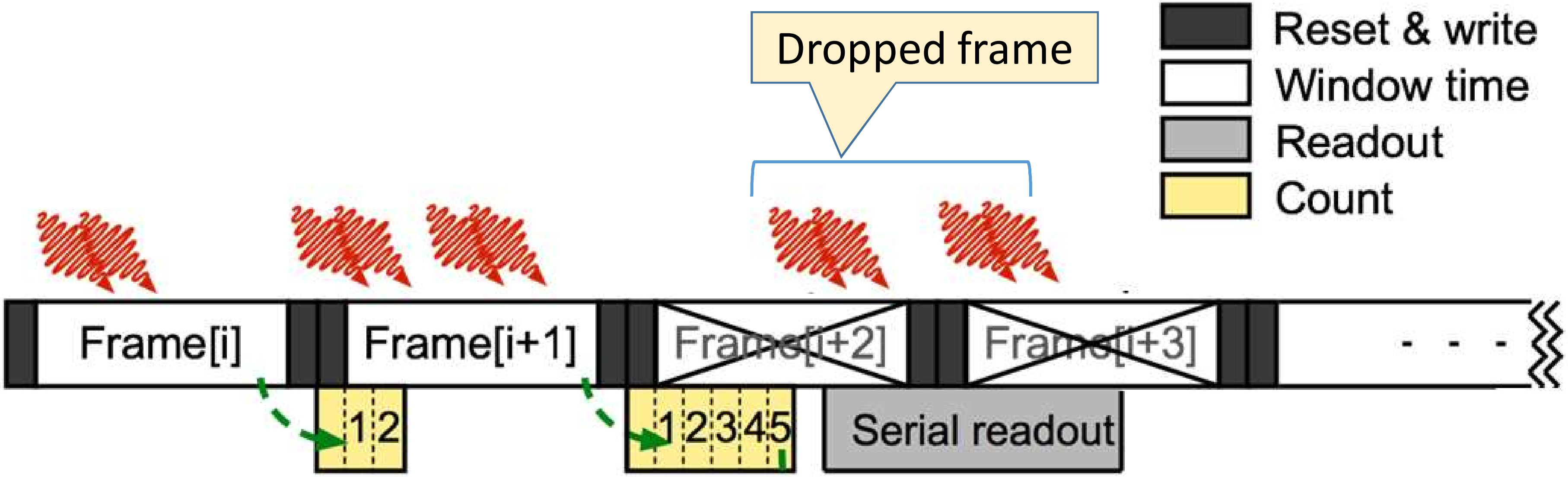
Photon detection & background readout (Pipeline)

- One more bit memory to each pixel
- Pipelined photon detection & readout
- Minimized dead time
- Drop a frame if readout is longer than window time

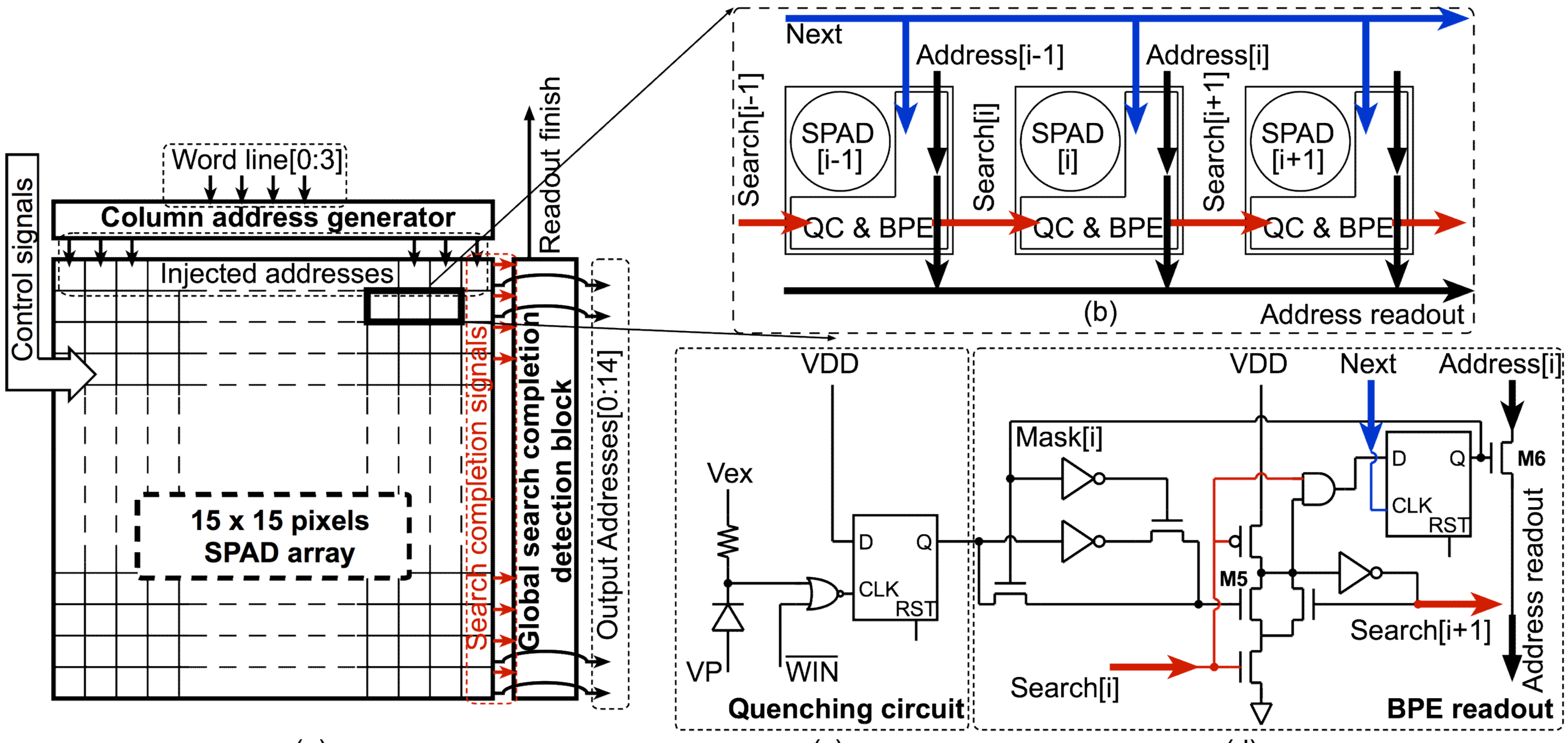


Readout with event discriminator (pre-screening)

- # of breakdown pixels is counted before readout
- Total counting cycles are proportional to max($N_{BD,i}$)
- Noise discrimination based on cycle count

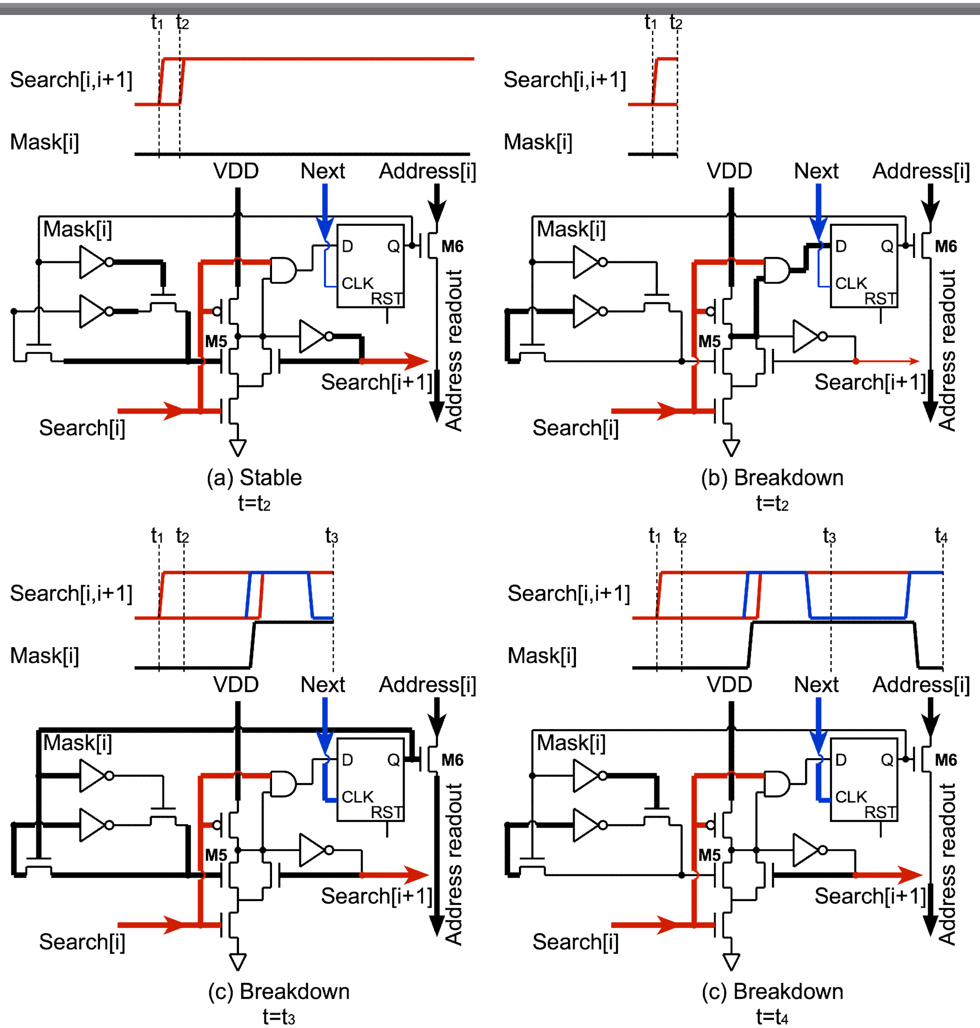


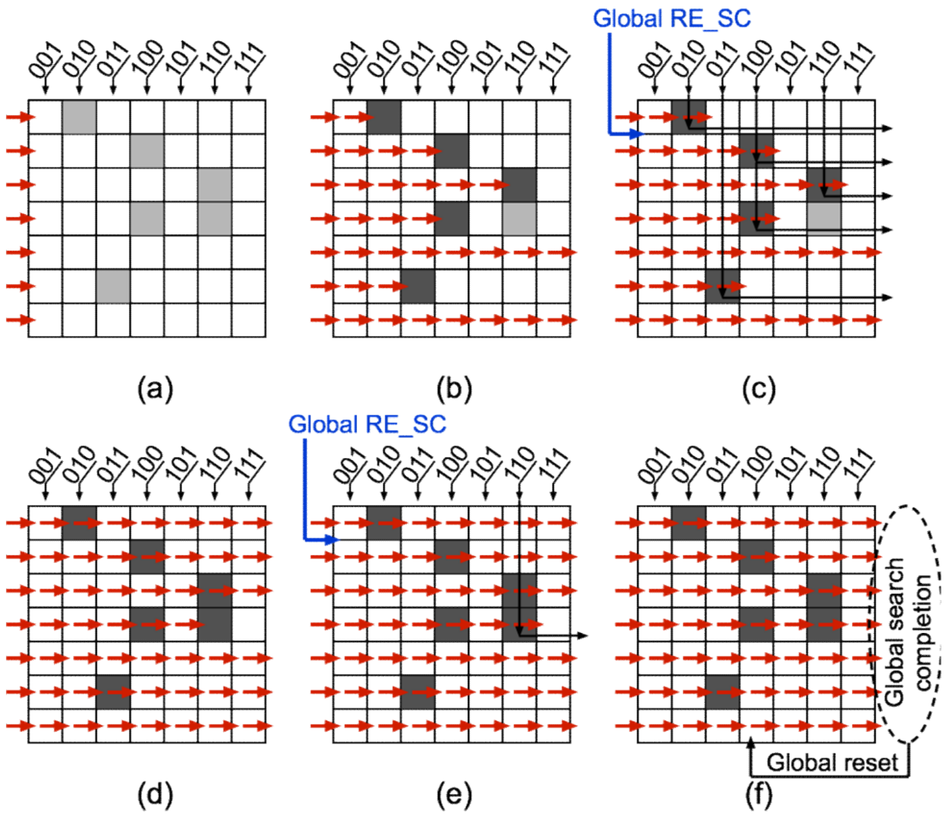
Circuit details: non-pipeline architecture



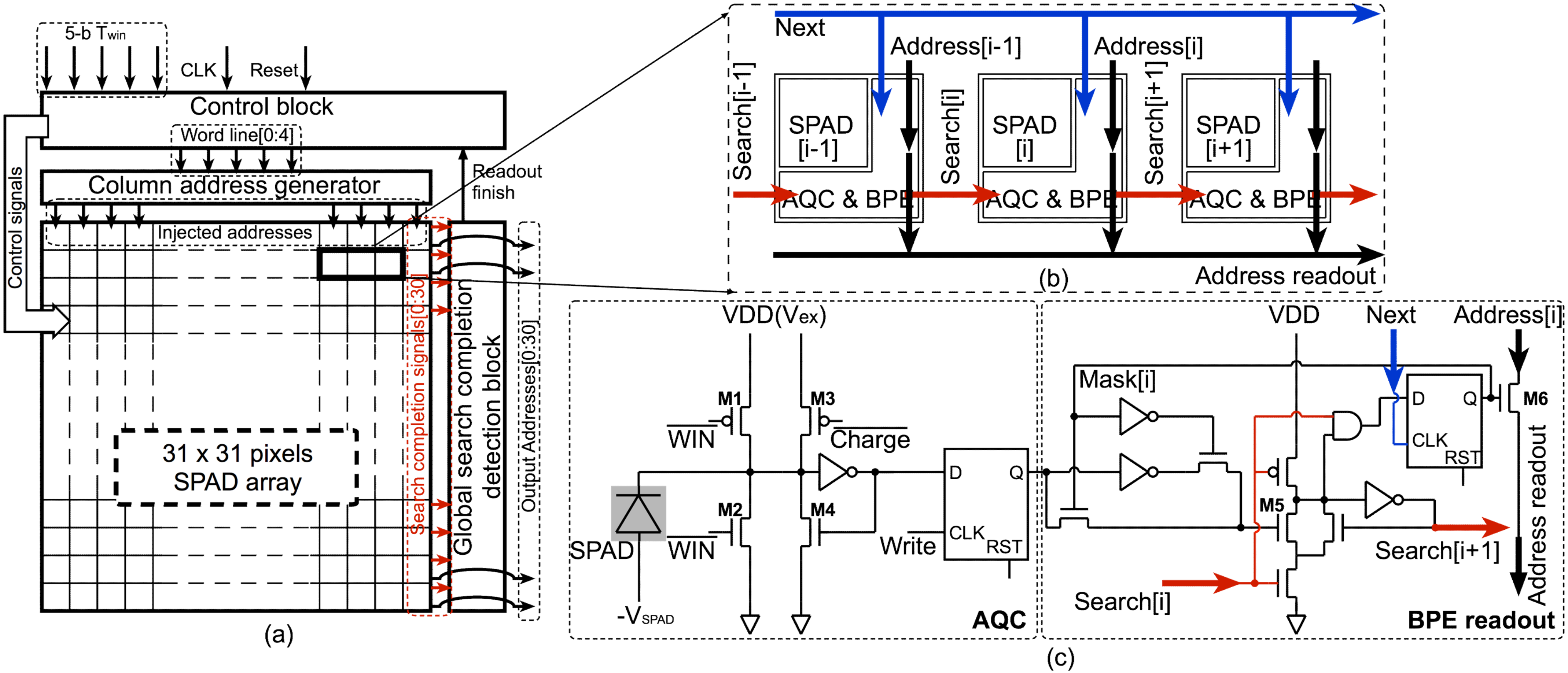
(a) (b) (c) (d)

Detailed sequence of readout operation

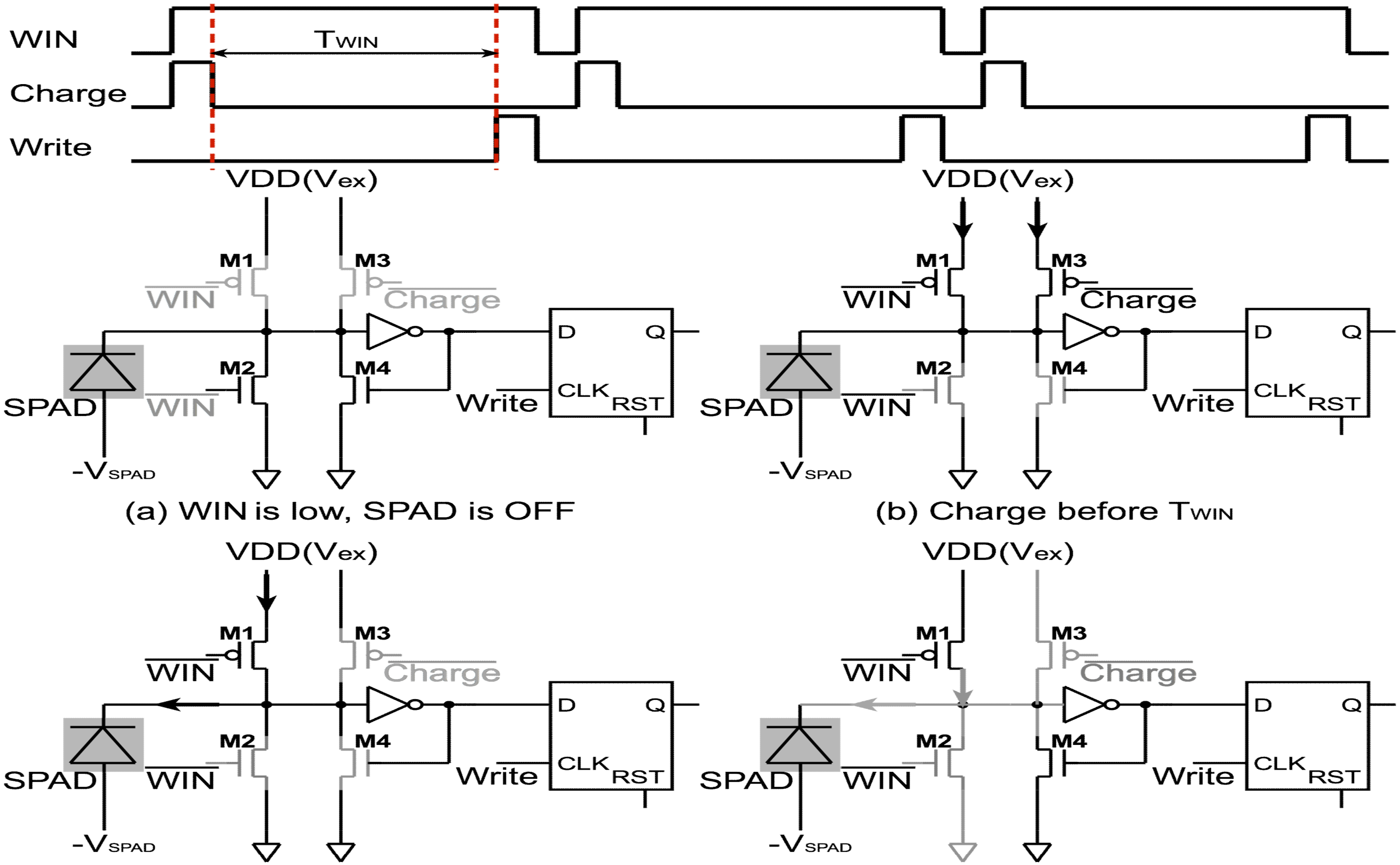




Circuits details: Pipeline architecture



Circuits details: Active quenching circuit for pipeline



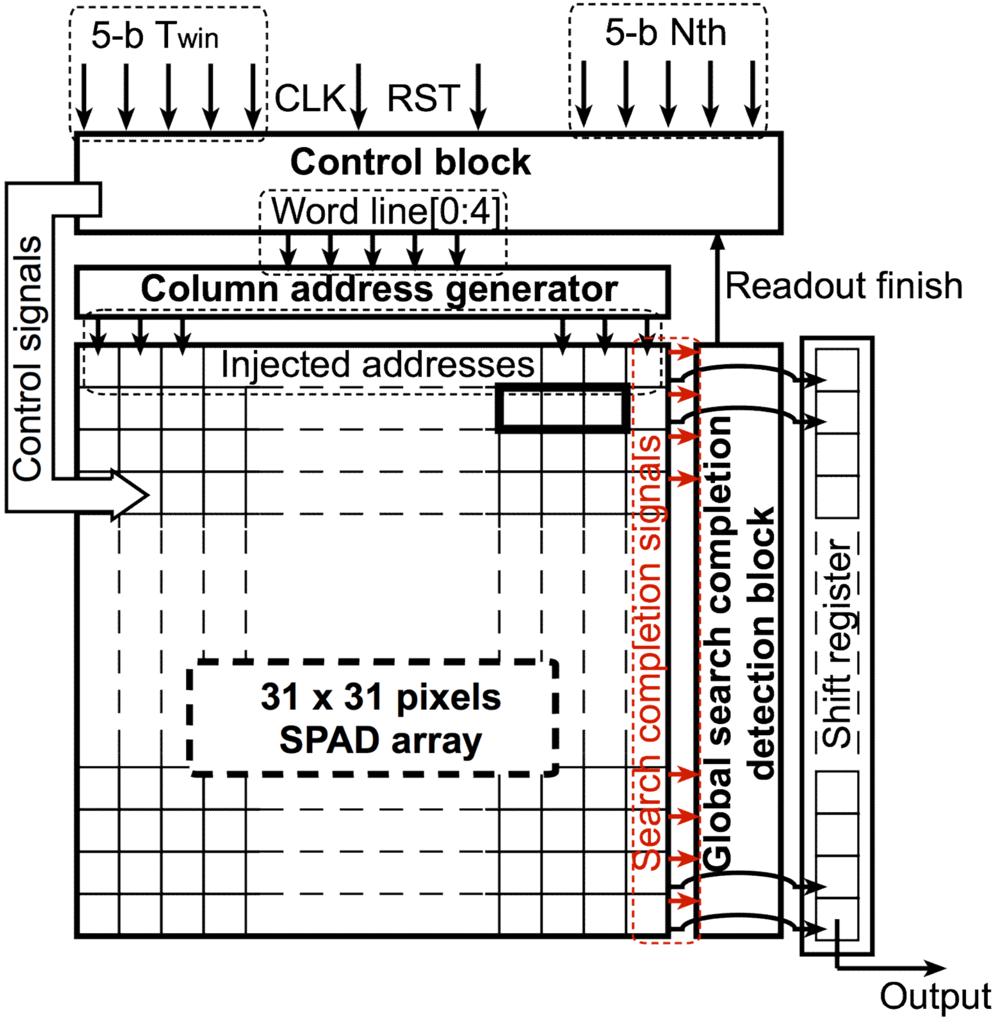
(a) WIN is low, SPAD is OFF

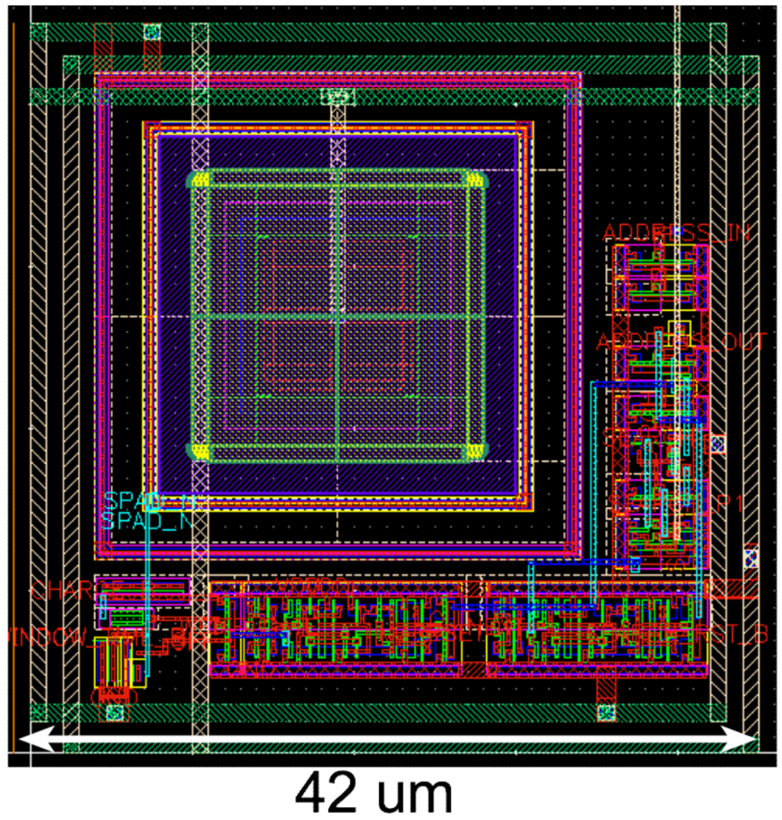
(b) Charge before TWIN

(c) SPAD is stable @ TWIN

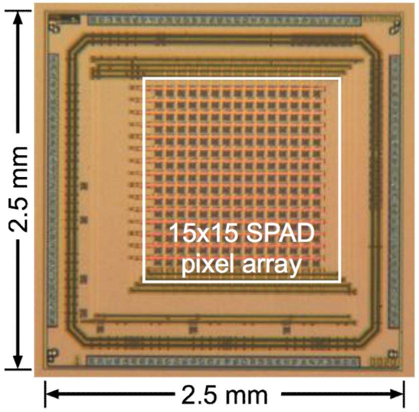
(d) SPAD is breakdown @ TWIN

Chip outline: Pre-screening architecture

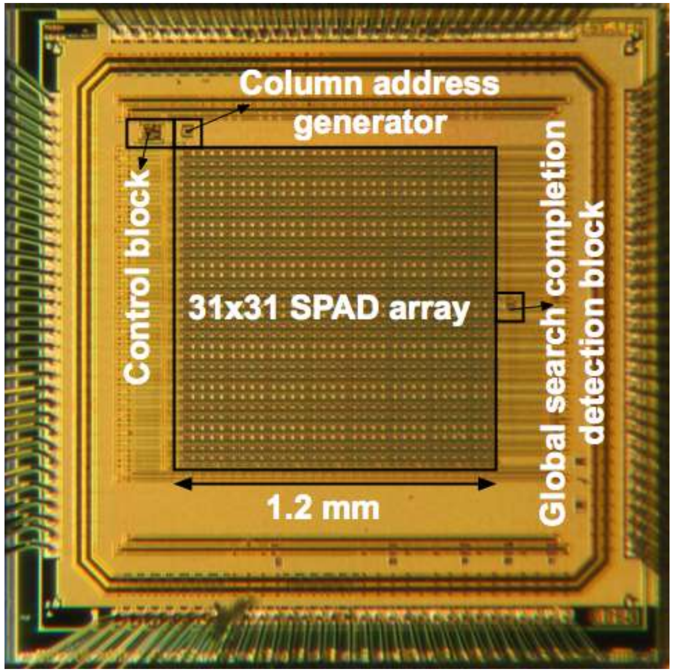




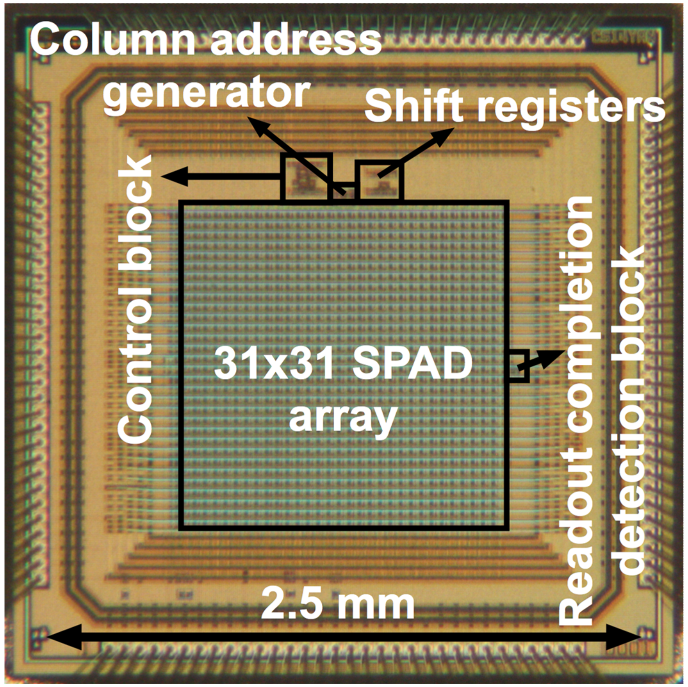
Chip micro-photographs (CMOS 0.18um)



Type A:
Non-pipeline



Type B: Pipelilne

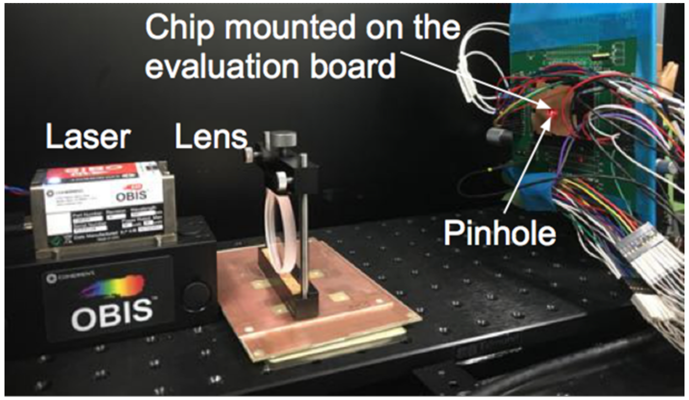


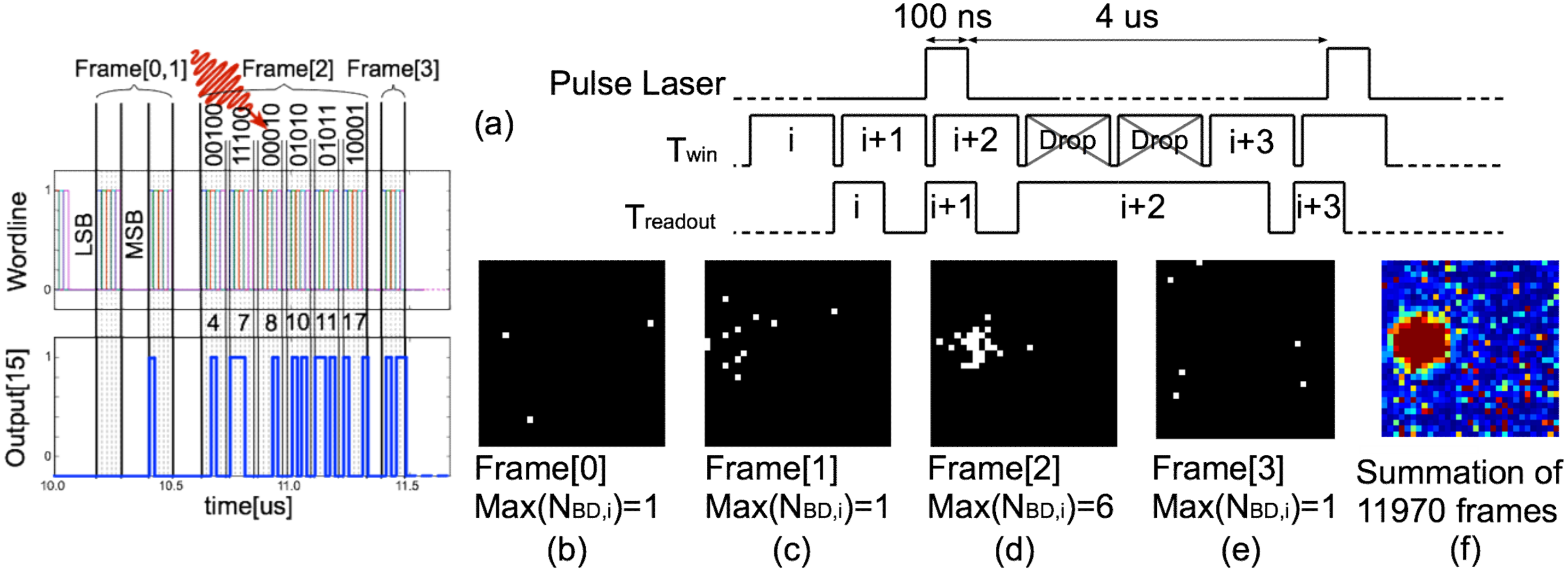
Type C: Pre-screening

Measurement setup: Pulse-laser pinhole imaging

Laser
- Pulse width: 100ns

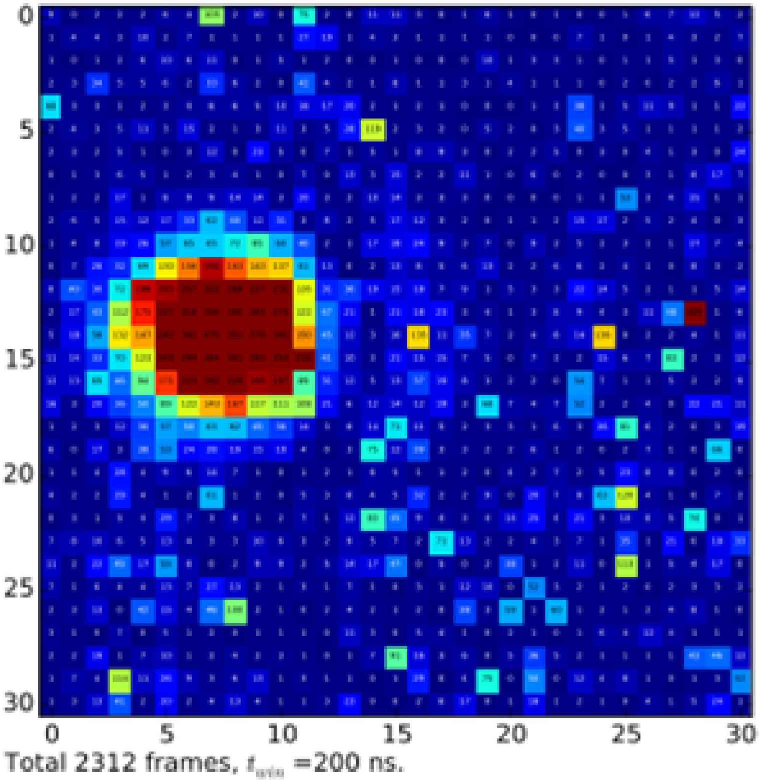
Chip
- Window time: 200 ns
- Frequency: 50 MHz
- Vex: 1.8 V





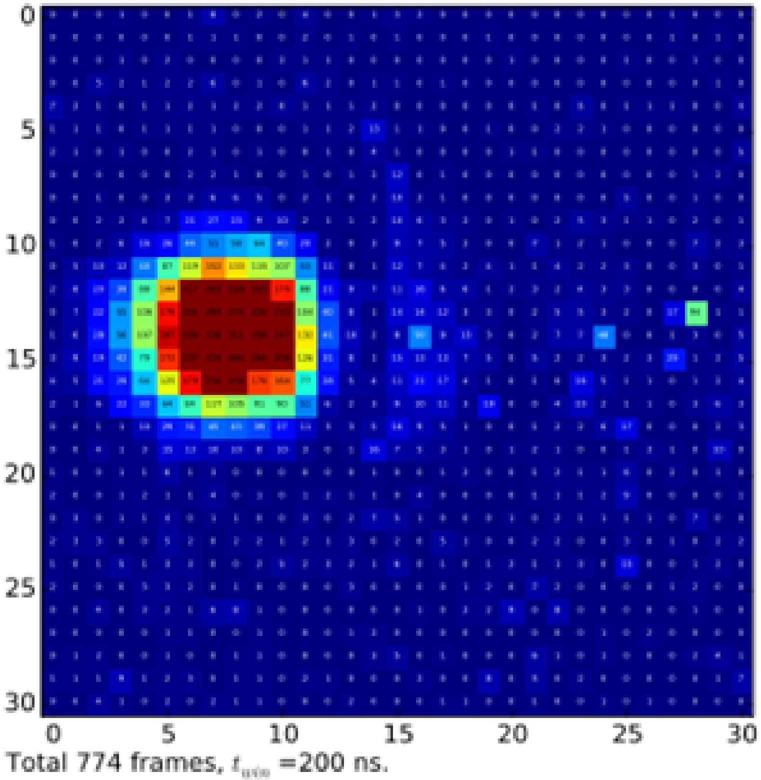
Integrated Images: Effect of event discrimination

$Max(N_{BD,i})>1$



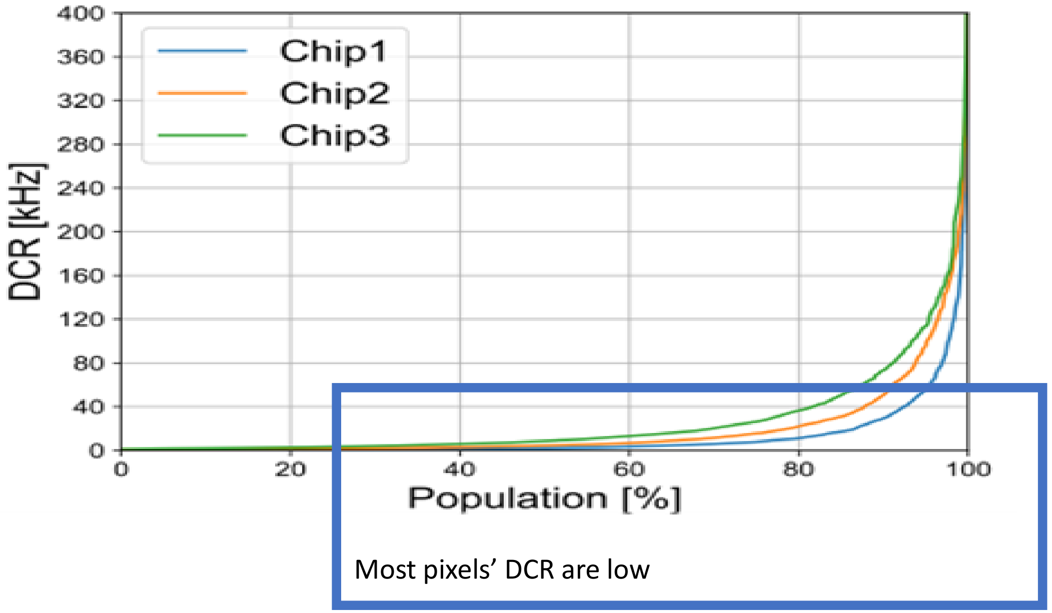
(a)

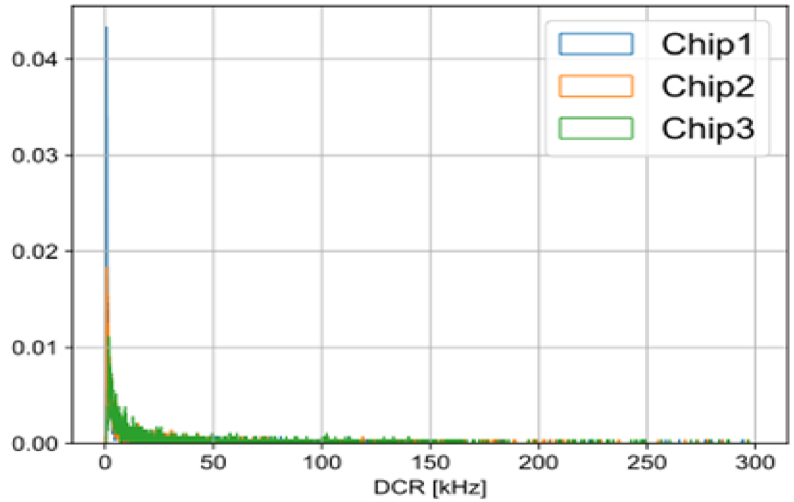
$Max(N_{BD,i})>2$

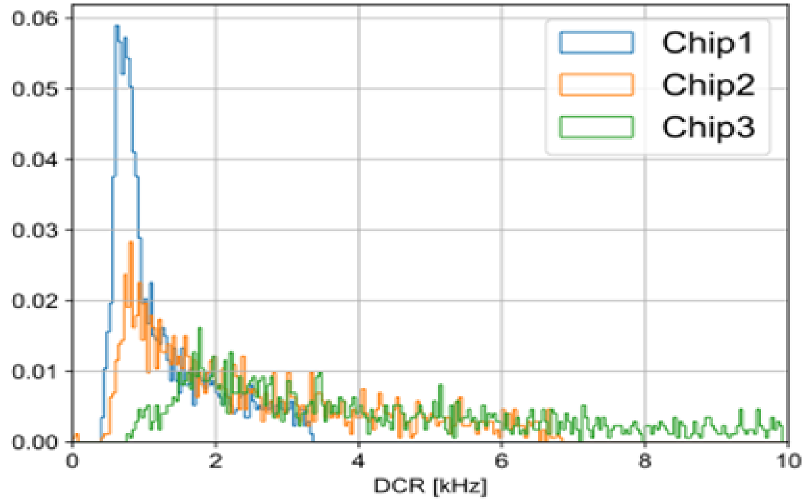


(b)

Measurement of Dark Count Rate (DCR) distribution







	Chip1	Chip2	Chip3
Area [um^2]	144	196	256
Perimeter[um]	24	28	32
Mean[kHz]	12	19	27
Median[kHz]	2	4	9
Max[kHz]	444	591	966

Measurement of photon detection probability (PDP)

Photon detection probability (PDP):

Probability that one single incident photon triggers breakdown.

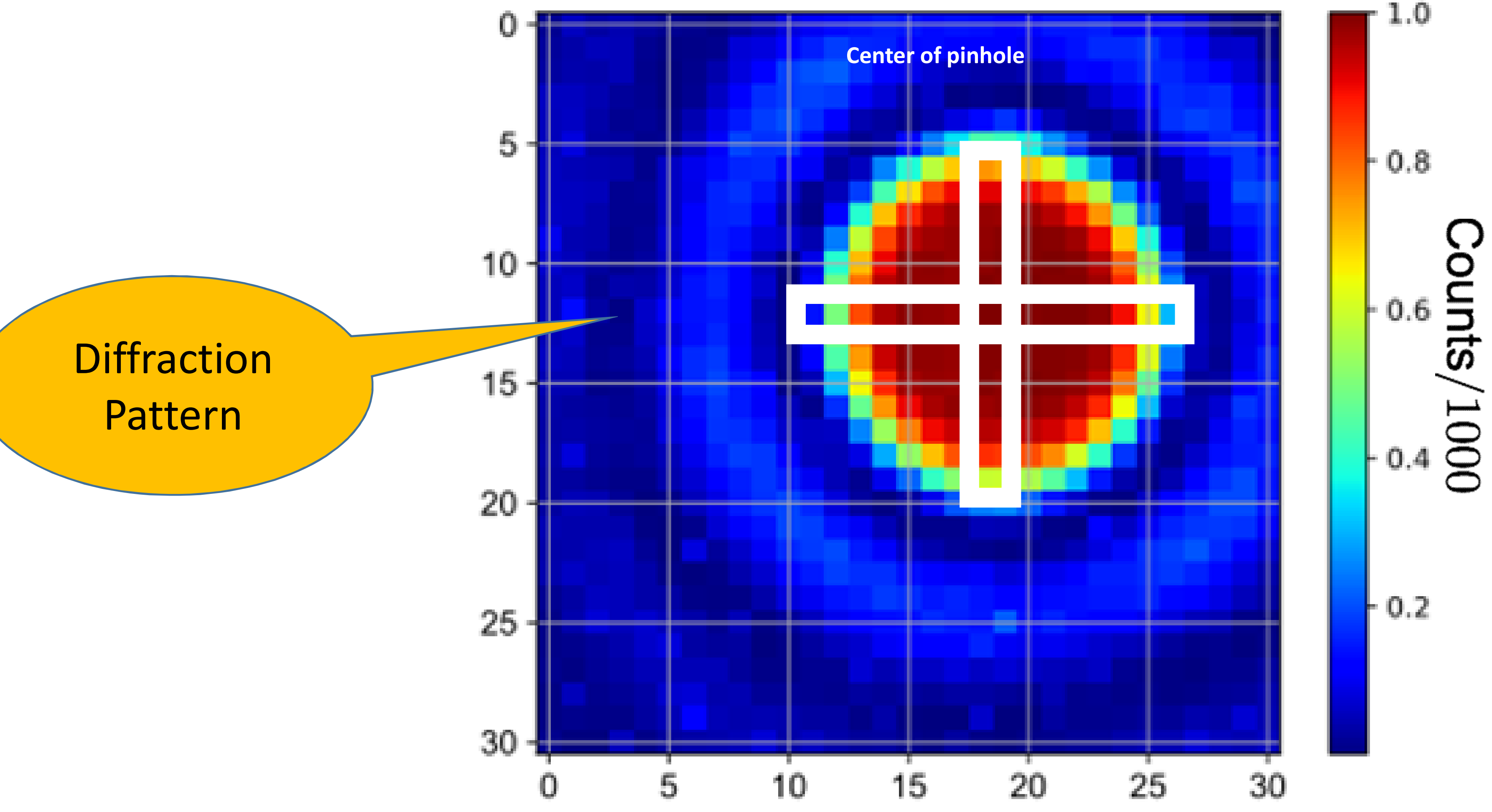
Measurement procedure:

- Put a 25 um pinhole in front of SPAD imager socket.
- Activate a pulsed laser after the global reset.
- Record the first frame after the laser pulse.
- Repeat the measurement 1000 times → **Counts**
- Calculate the # of incident photos/pixels → **N**
- Take into account the probability of the dark counts → $\mathbf{P_{DC}}$

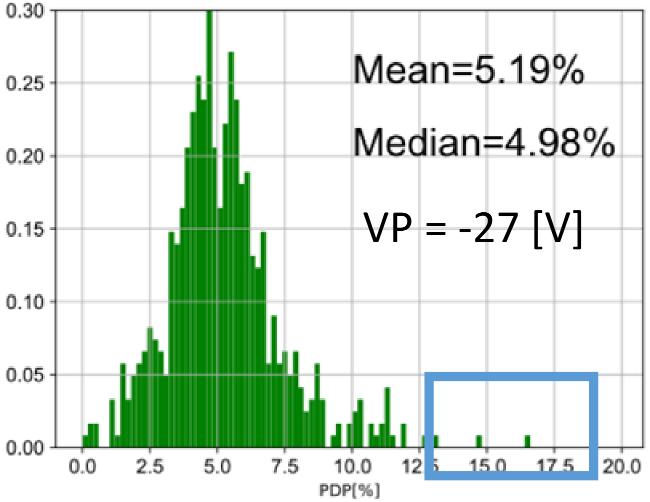
$$\frac{\text{Counts}}{1000} = 1 - (1 - PDP)^N (1 - P_{DC})$$

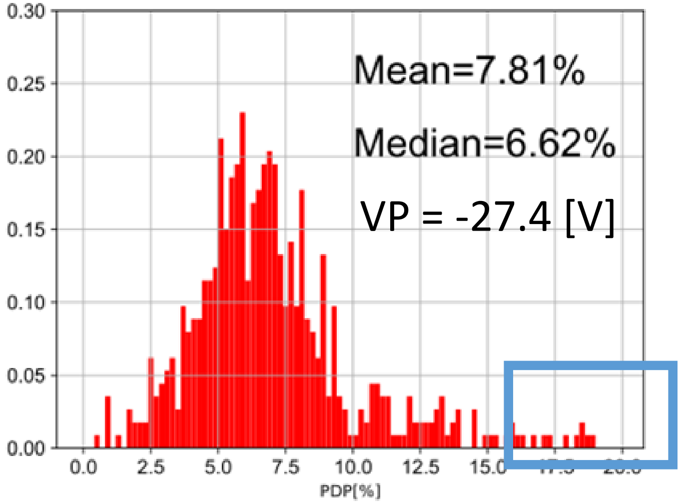
$$PDP = 1 - \left(\frac{1 - P_{BR}}{1 - P_{DC}}\right)^{\frac{1}{N}}$$

Pinhole matching for calculating detracted photon map



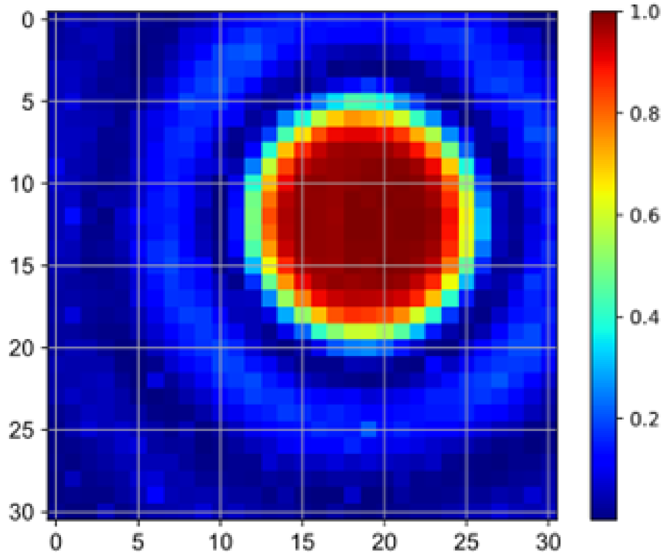
PDP distribution calculated from measurement results



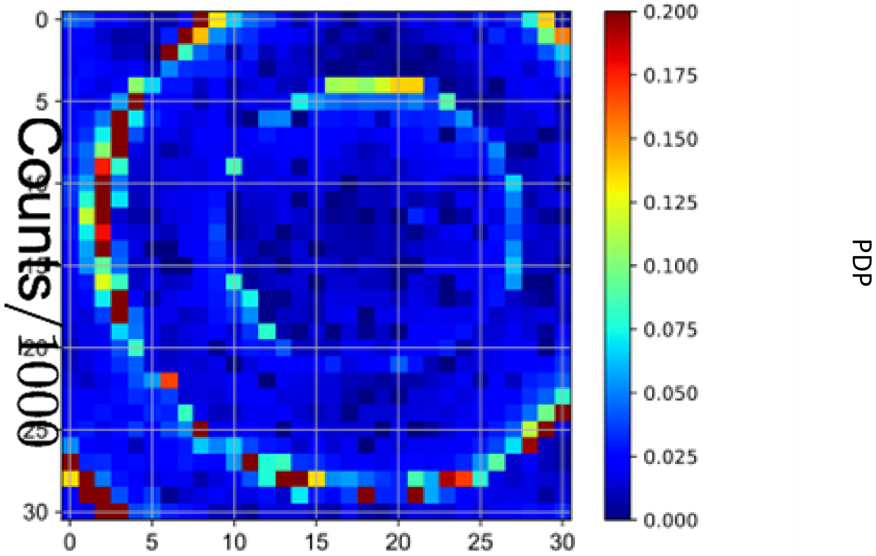


- PDP= (Quantum efficiency) x (Breakdown probability)
- Higher over-bias voltage → higher PDP
- There are afew
- False pixels with very high PDP

PDP distribution



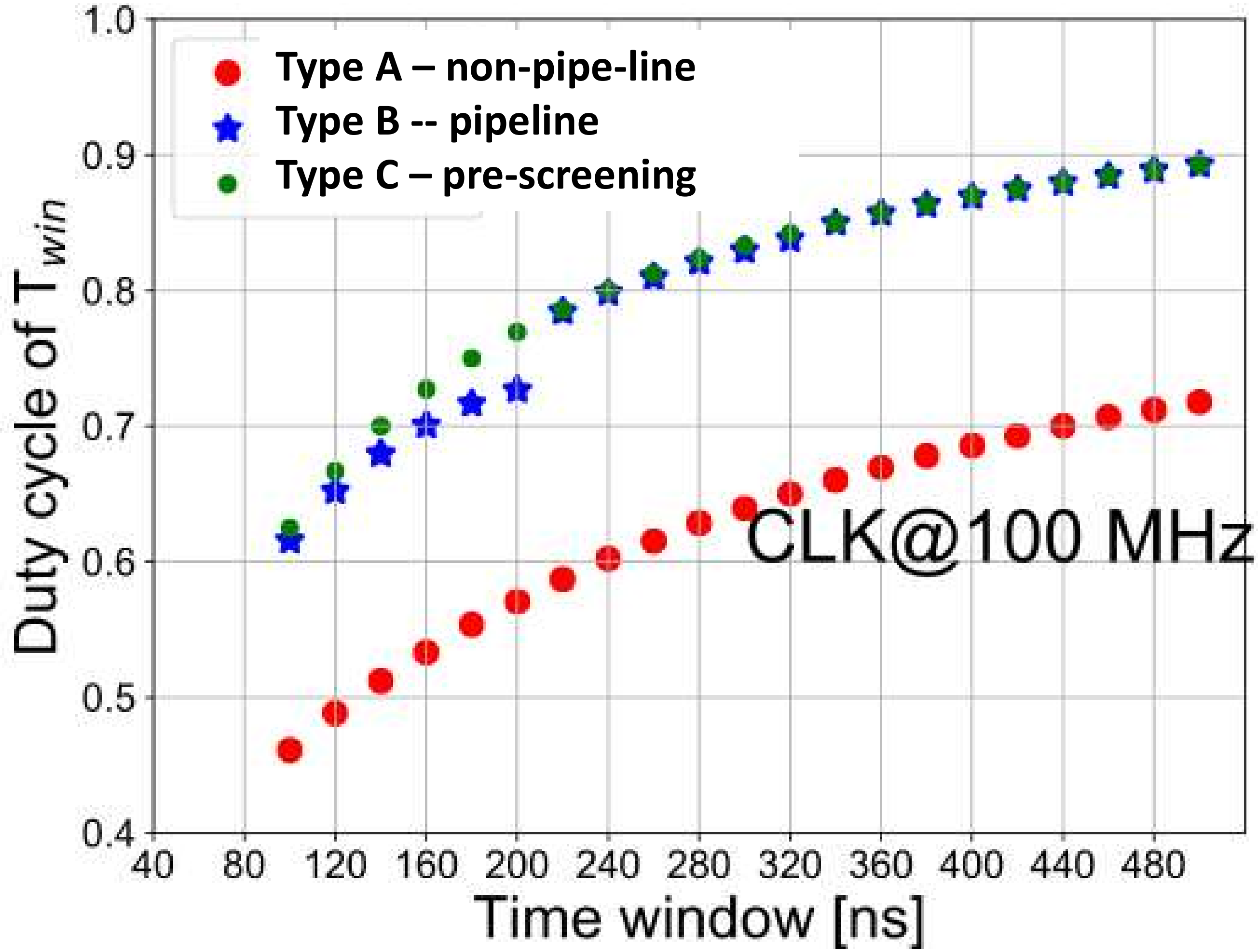
Captured image



Calculated PDP mapping

False pixels with very high PDP;
located at the ring zones of low defracted photons

Duty ratio: photon-sensitive-time/total-time



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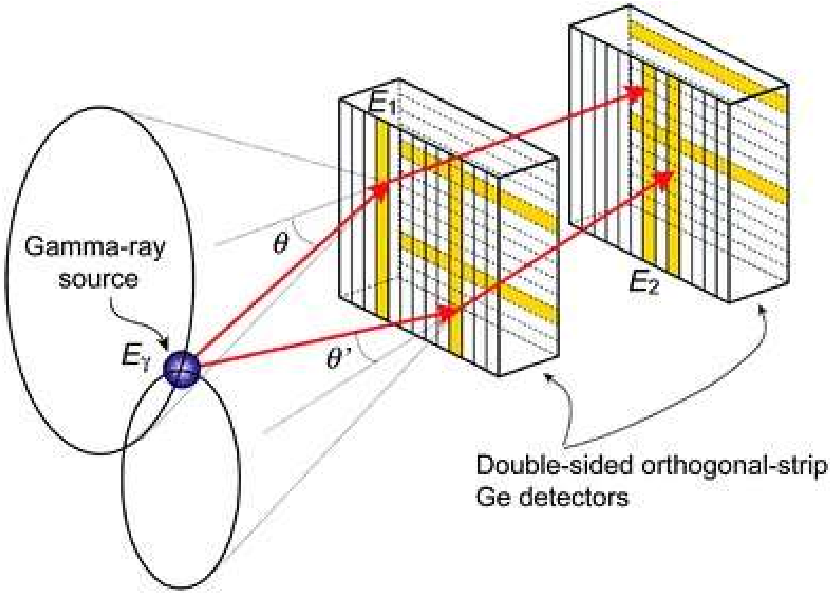
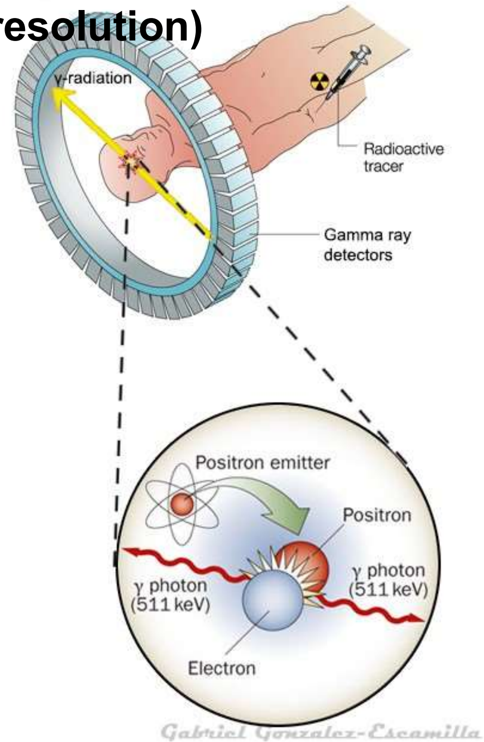
Requirements for Scintillation Detector

Principles of Compton Camera and PET are different. However both need precise estimation for scintillation point (spatial resolution)



Principle for Compton Camera[4]

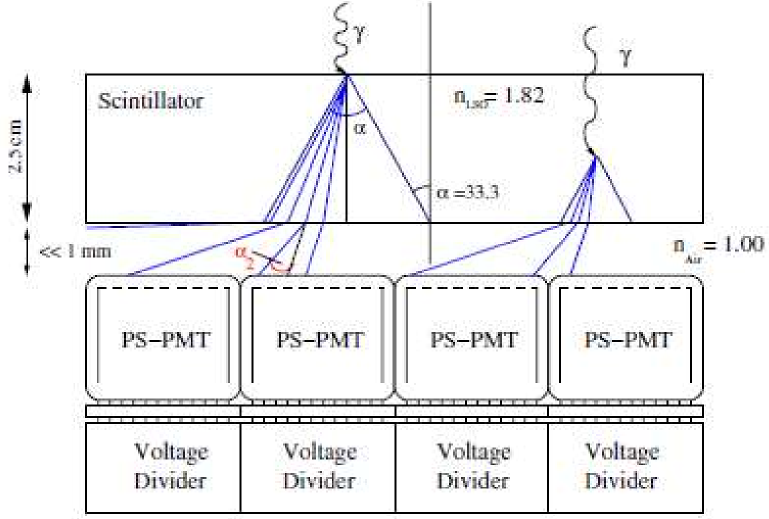


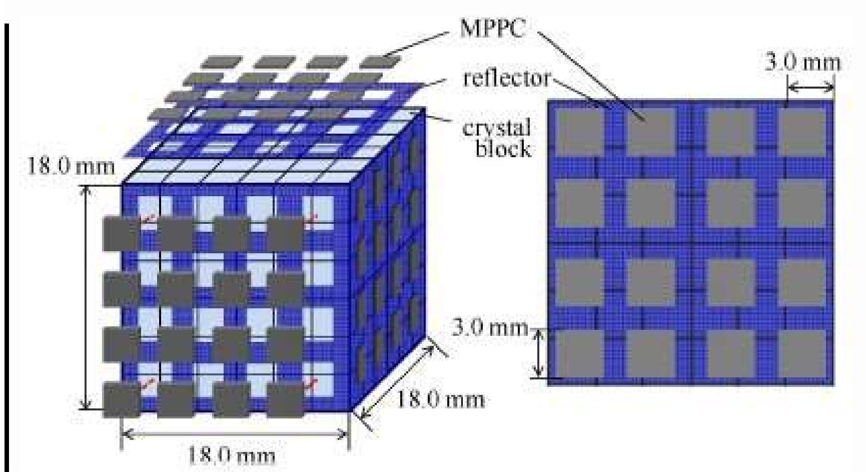
Principle for PET[5]

[4] : [Online] URL: http://pubs.rsc.org/is/content/articlehtml/2008/ja/b802964d
[5] : [Online] URL: https://multimodalneuroimaging.wordpress.com/2015/04/28/c-positron-emission-tomography/

Known methods

Two methods for raising the spatial resolution of scintillation detector





(1) Space resolution : ~ 1mm[6]

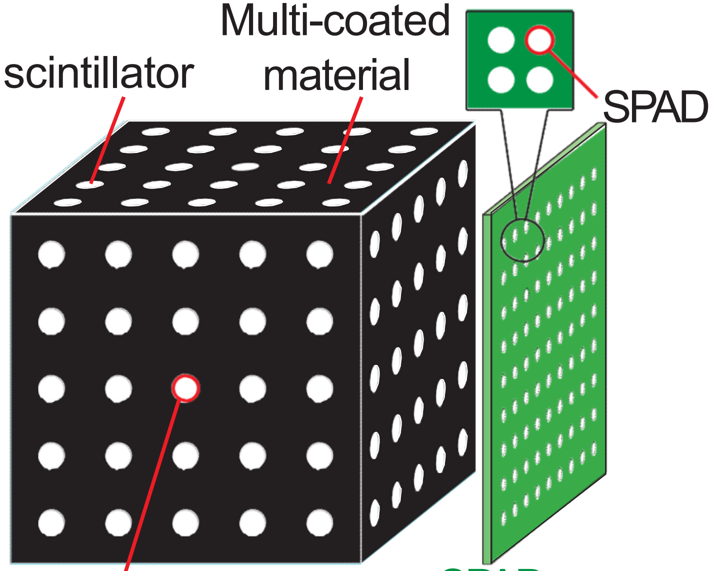
(2) Space resolution : ~ 300um[7]

Space resolution requirement for medical application → 10 ~ 100 um

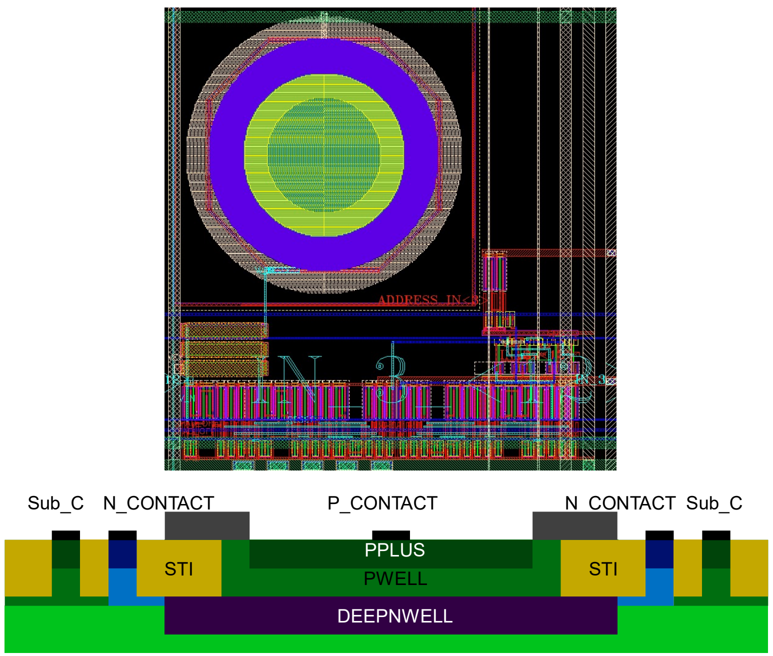
[6] : N. Uhlmann et al. , "3D-Posi9on-Sensi9ve Compact Scin9lla9on Detector as Absorber for a Compton-Camera," *IEEE Trans. Nucl. Sci.* , Vol. 52, No.3, Jun.2005.
[7] : T. Matsumoto et al. , "Simula9on Study to Op9mize the Number of Photo-detec9on Faces and Inter-crystal Materials for the X'tal Cube PET Detector," 2012 *IEEE Nuclear Science Symposium and Medical Imaging Conference* Record (NSS/MIC).

Our proposal for Scintillation Detector

Scintillation detector of SPAD & scintillator covered by multi-pinholes



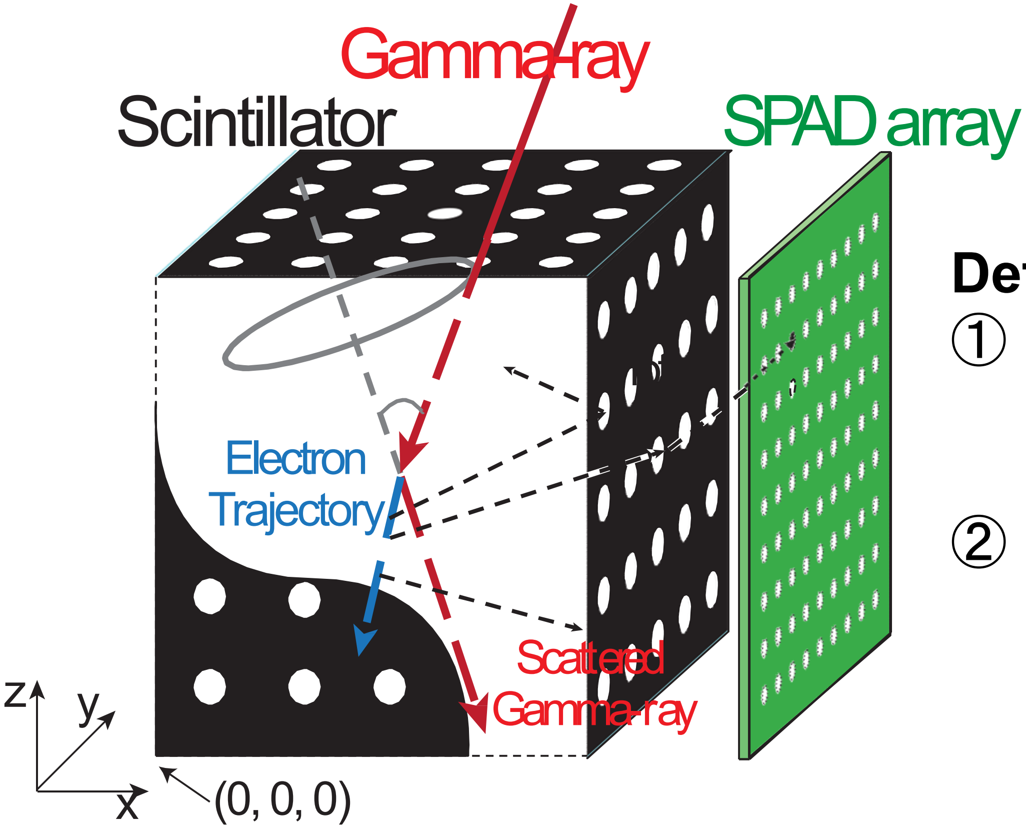
Structure of proposed scintillation detector



Structure of SPAD[8]

X.Yang et al., "A 15×15 single photon avalanche diode sensor featuring breakdown pixels extrac9on architecture for efficient data readout," Japanese Journal of Applied Physics, Volume 55, Number 4S

Principle of Light source position detection



Detection method by proposed scintillation detector

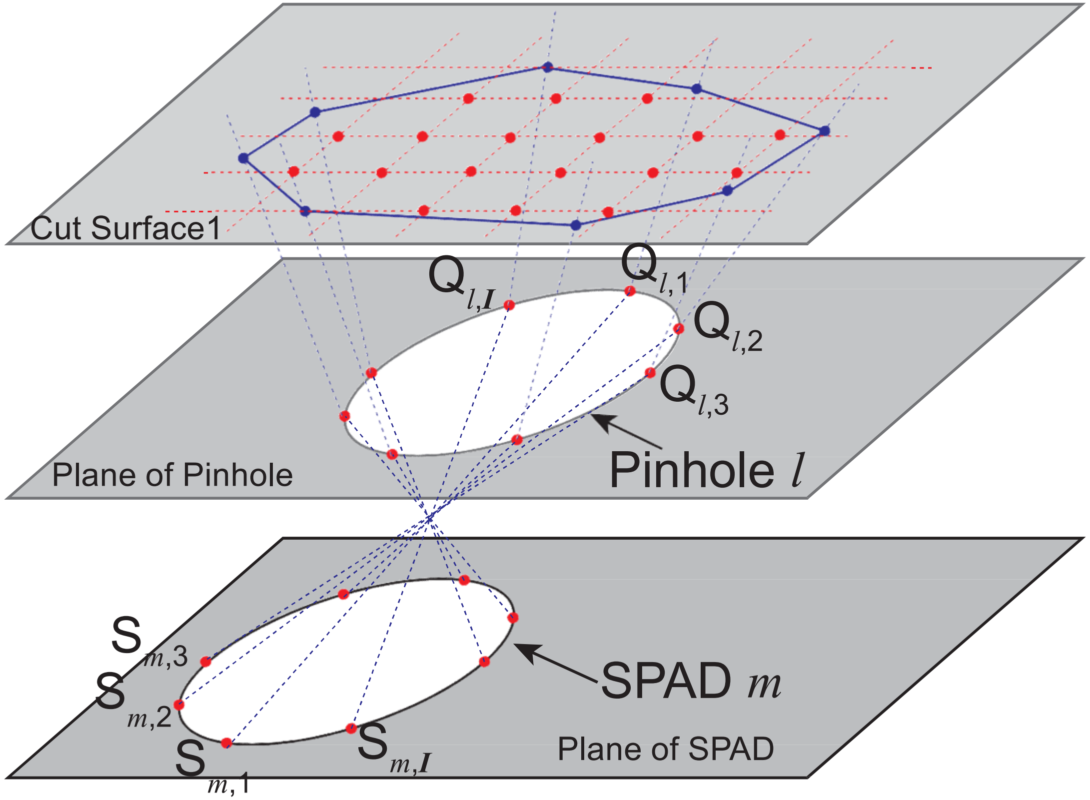
Detection Method

① Calculating area probability of light source for each SPAD (store it in table)

② Calculating the total probability of light source for all the active SPADs

Step1: Calculating area probability for each SPAD

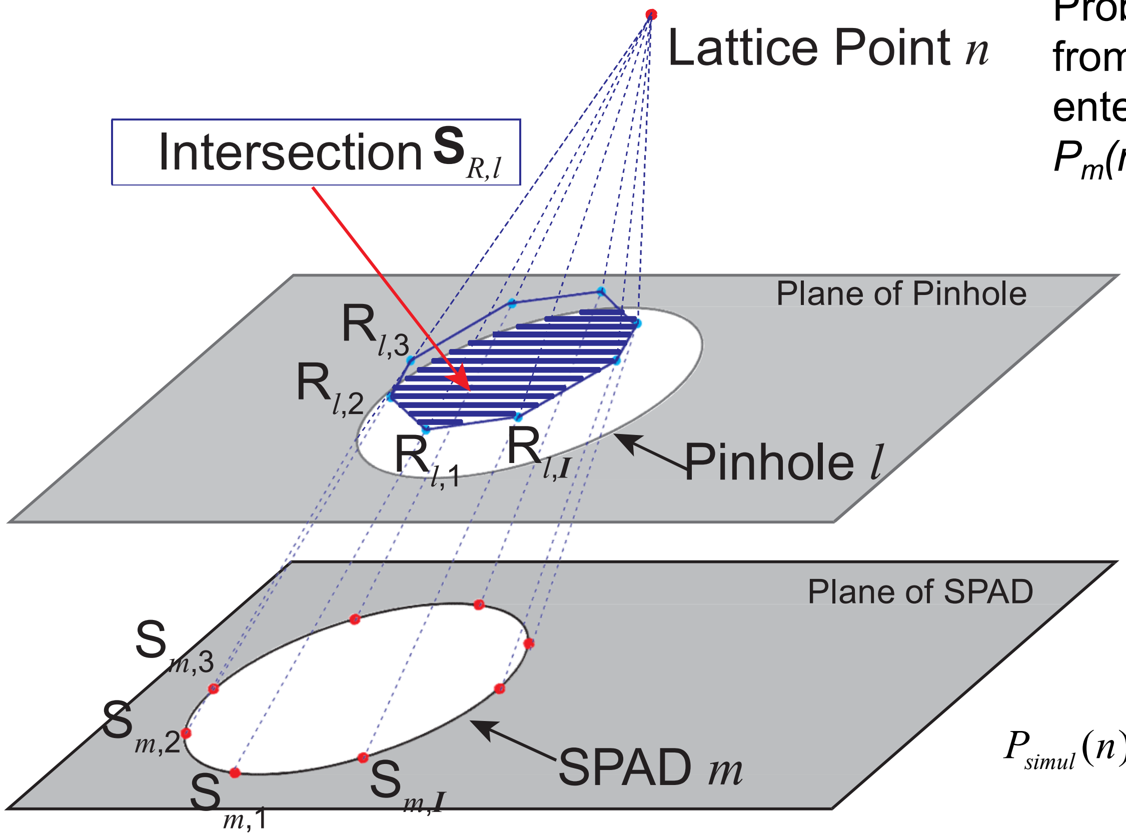
When a SPAD breakdowns, the area inside scintillator can be divided into 2 parts: ① the light source can exist ② the light source can not exist



Pattern diagram of calculating the possible light source area

Step2: Calculating the total probability

Position of light source can be estimated based on the breakdown information of SPADs



Pattern diagram of light source estimation method

Probability that photon from n-th lattice point enter m-th SPAD
$P_m(n) \propto$ solid angle

Probability that multiple SPADs m'=1,2,……, M' simultaneously breakdown due to the photon from the *n*-th lattice point $P_{simul}(n)$ is calculated as

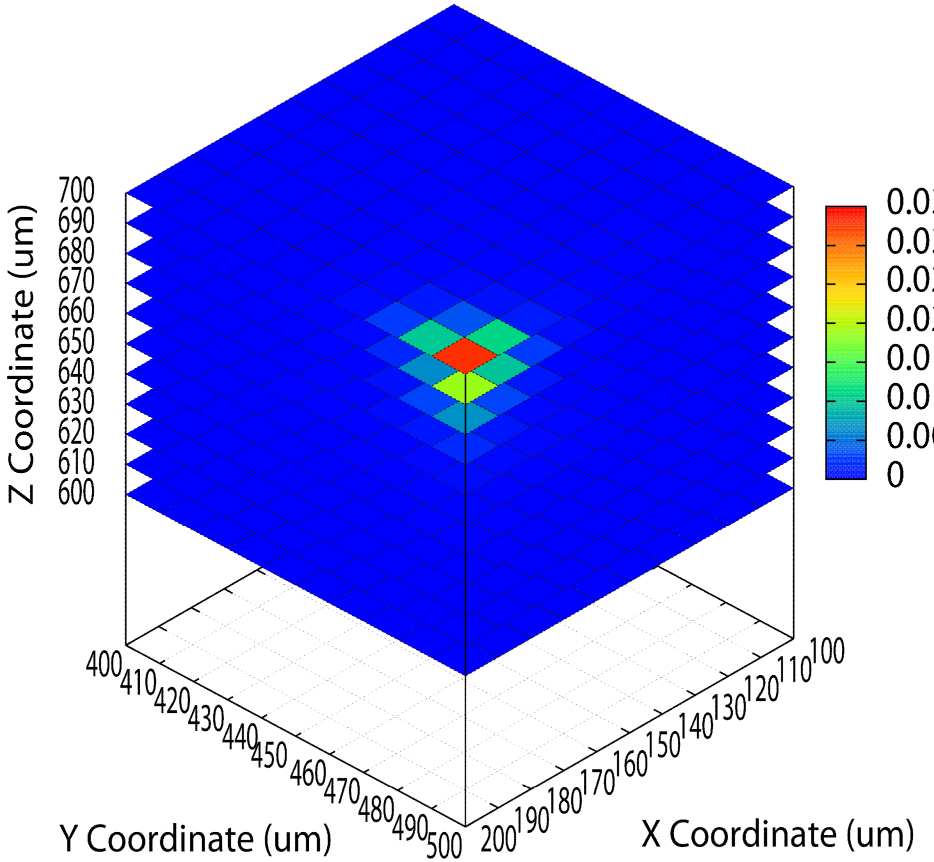
$$P_{simul}(n) = \frac{\prod_{m'=1}^{M'} P_{m'}(n)}{\sum_{n=1}^{N}\left(\prod_{m'=1}^{M'} P_{m'}(n)\right)}$$

Simulation parameters

① Simulate point light source using Monte Carlo Method at particular position
② Estimate light source position based on proposed methodology
③ Evaluate the methodology from the result

No	Parameter Name	Value
1	Diameter of Pinhole	40 um
2	Interval between pinholes	100 um
3	Diameter of SPAD	10 um
4	Interval between SPADs	40 um
5	Interval between SPAD array and Pinhole array	500 um
6	Size of scintillator cube	1 mm
7	Number of generated photons	20000
8	SPAD detection efficiency	20%
9	Error rate of SPAD by dark count	0.2%
10	Position of simulated light source	(200um, 500um, 700um)

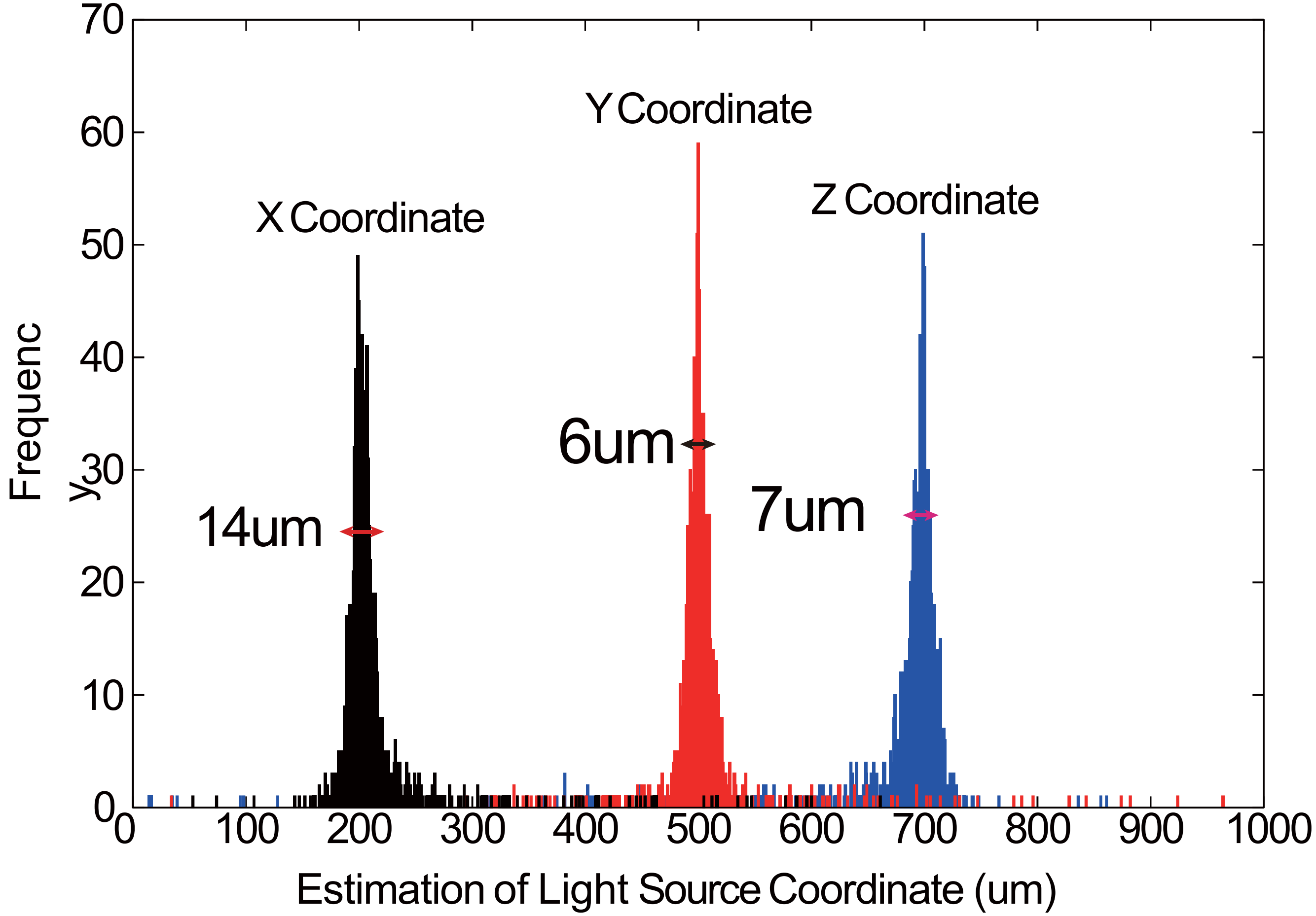
Simulation Results ①



Probability of lattice point around light sources

Estimated light source coordinate = Expected value of probabilities in each position

Simulation Results ②



Frequency of 1000 times simulations

Spacial resolution

1. This research proposed a novel type of scintillation detector and use photon reverse ray tracing method
2. Proposed scintillation detector has a spatial resolution than prior arts

Reference	[6]	[9]	[10]	**Proposed**
Type of Scintillation Detector	Conventional scintillation detector	PET Crystal Cube	Si/CdTe Compton Camera	**Scintillator cube with pinholes**
Type of Sensors	PSBPMTs	MPPCs	Double-sided Si strip detectors (DSSDs)	**SPADs**
Spatial resolution	1mm	300um	250um - 500um	**10 - 20 um**

[9] Y. Yazaki *et al*., "Development of the X'tal Cube: A 3D Posi9on-Sensi9ve Radia9on Detector With All-Surface MPPC Readout," *IEEE Trans. Nucl. Sci.*, Vol.59, No.2, Apr. 2012.
[10] S.Watanabe *et al*., "High Energy Resolu9on Hard X-Ray and Gamma-Ray Imagers Using CdTe Diode Devices," *IEEE Trans. Nucl. Sci.*, Vol.56, No.3, Jun. 2009.

Conclusions & Co-workers

- **A quick readout method of 100-200ns/frame SPAD was demonstrated**
- **Characteristics of standard 0.18um CMOS SPAD imagers was reported**
- **A concept of single event fast SPAD imager was proposed**
- **A possible application of SPAD imagers for scintillation with pin-hole matrix was presented**

- **Xiao Yang (PhD student)**
- **Kai Xu (Master student)**
- **Hongbo Zhu (Assistant professor/Sony)**
- **Toru Nakura (Associate professor)**
- **Tetsuya Iizuka (Associate professor)**

Than you