A 1.1 mega-pixels vertical avalanche photodiode (VAPD) CMOS image sensor for a long range time-of-flight (TOF) system

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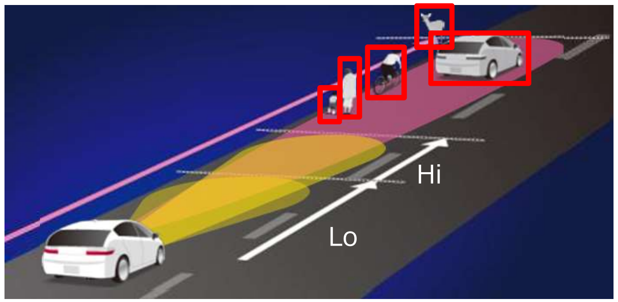
Outline

1. Motivation: Targeting a long range/high resolution TOF system
2. Device
   - Vertical Avalanche Photodiode (VAPD) CMOS image sensor
   - Capacitive Quenching
3. System
   - Direct Time-of-Flight by Sub-ranges Synthesis (SRS)
   - System/Circuit architecture
   - In-pixel photon counting
4. Demonstration
   - Long range
   - Day-time
   - Improvements in depth-resolution
5. Summary

Motivation : Lots of opportunities

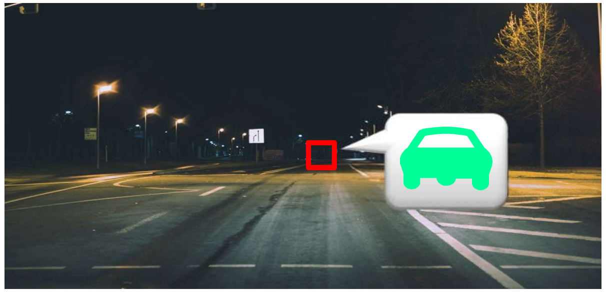
A long range/high resolution direct Time-of-flight (DTOF) systems

AD* sensing

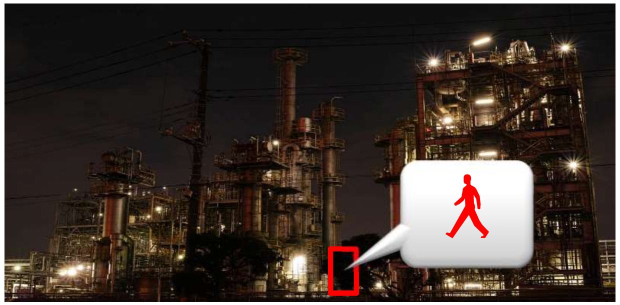


*Autonomous Driving

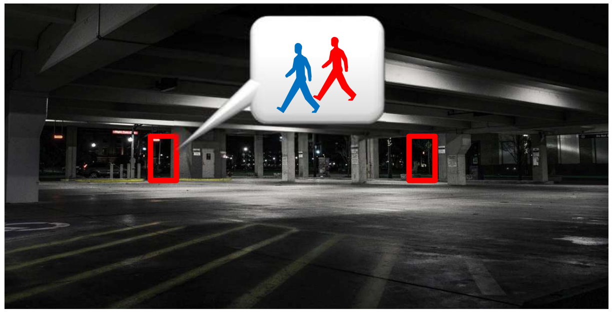
Road Monitor



Factory Surveillance



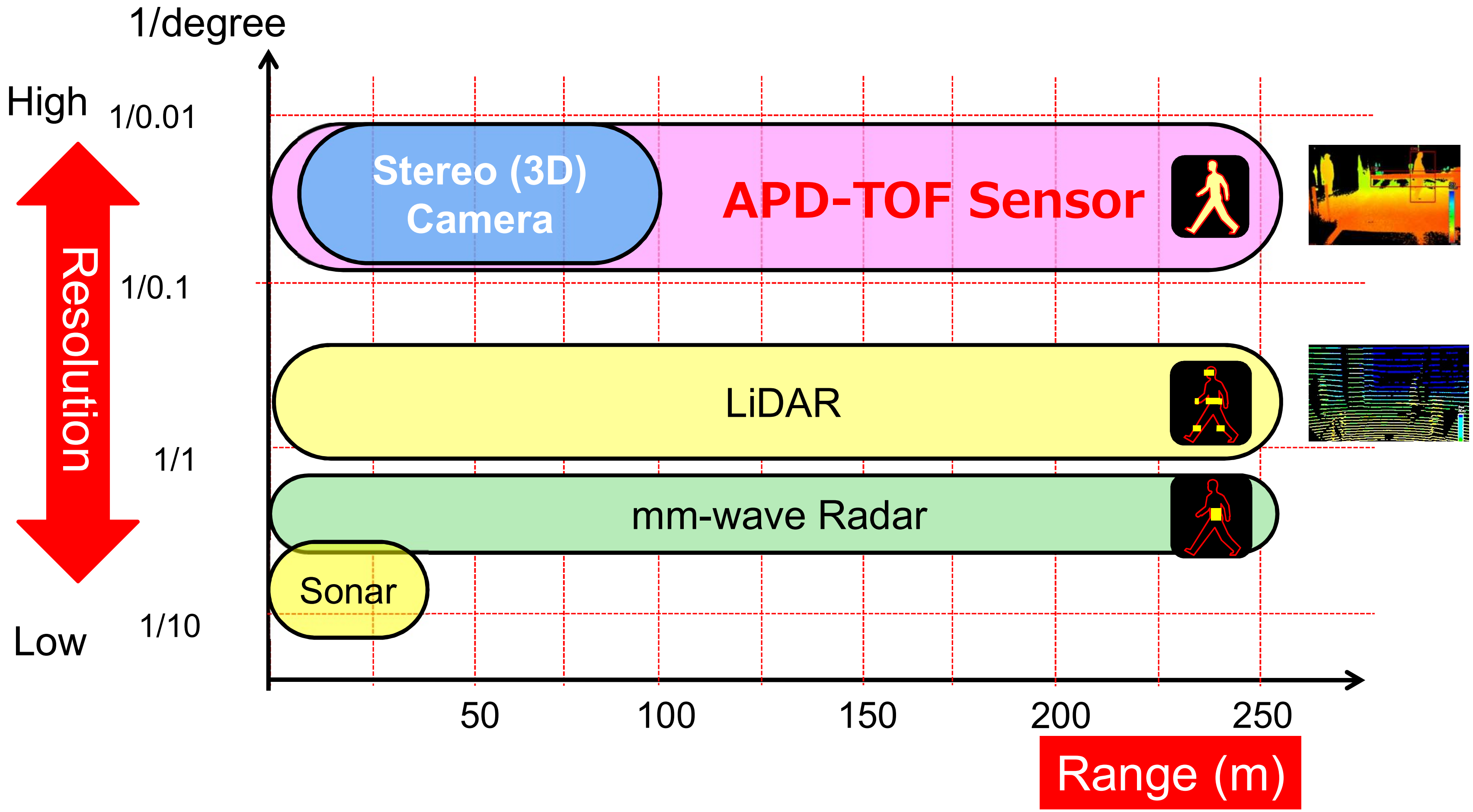
Parking Lot Monitor



Targeted performance and enabling technologies

Range : APD-TOF

Resolution : CMOS image sensor (CIS)



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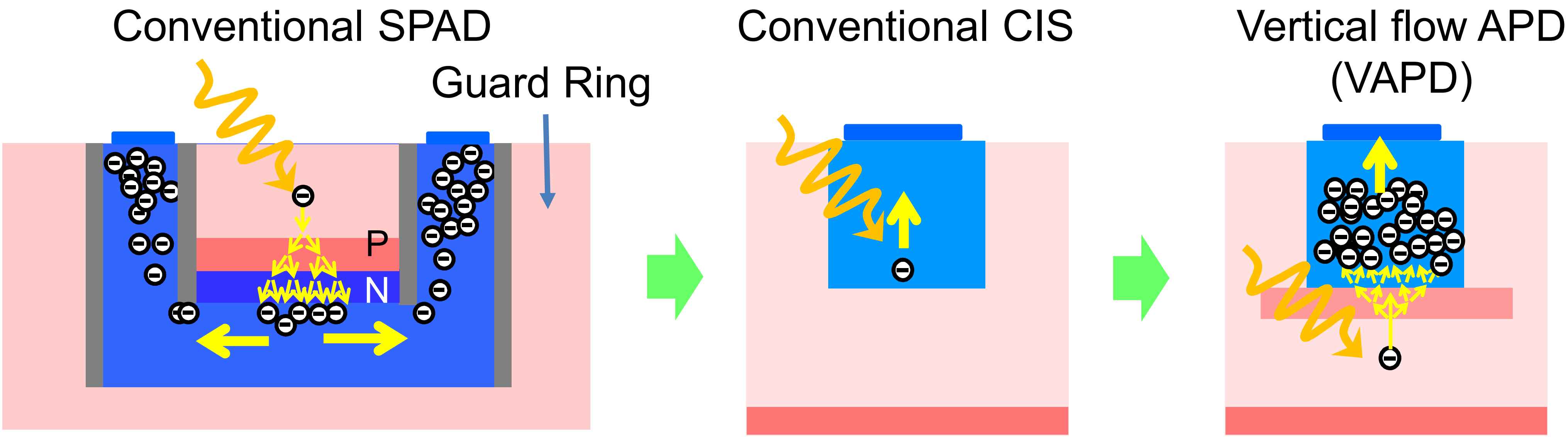
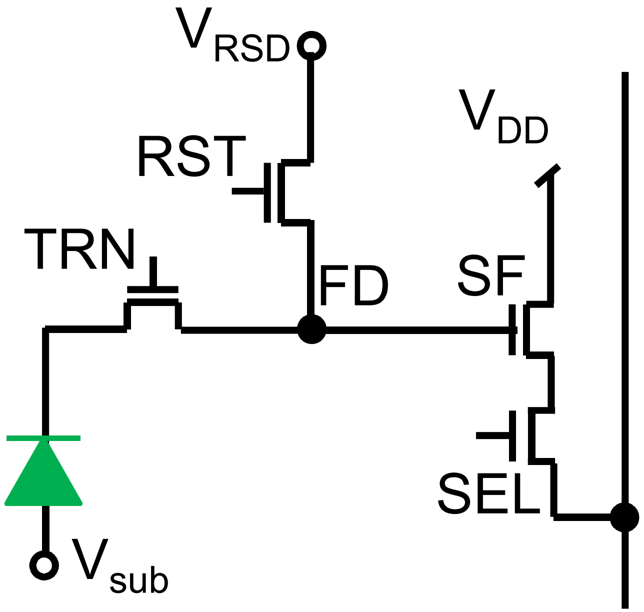
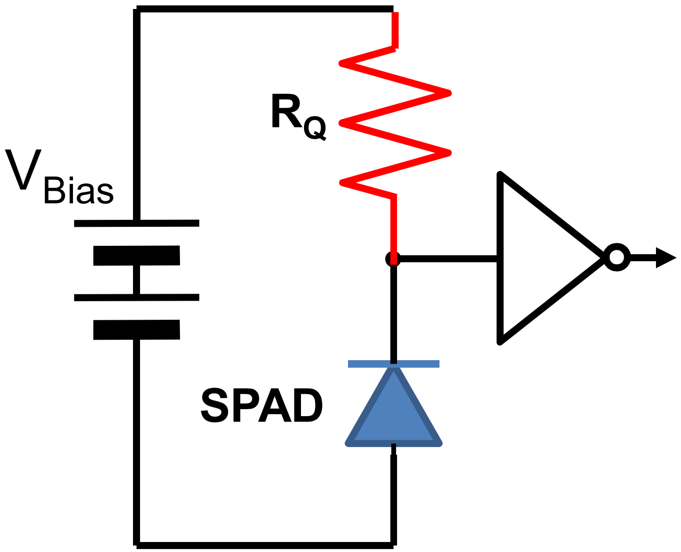
Vertical avalanche photodiode (VAPD) CMOS image sensor



Large pixel
Low fill factor

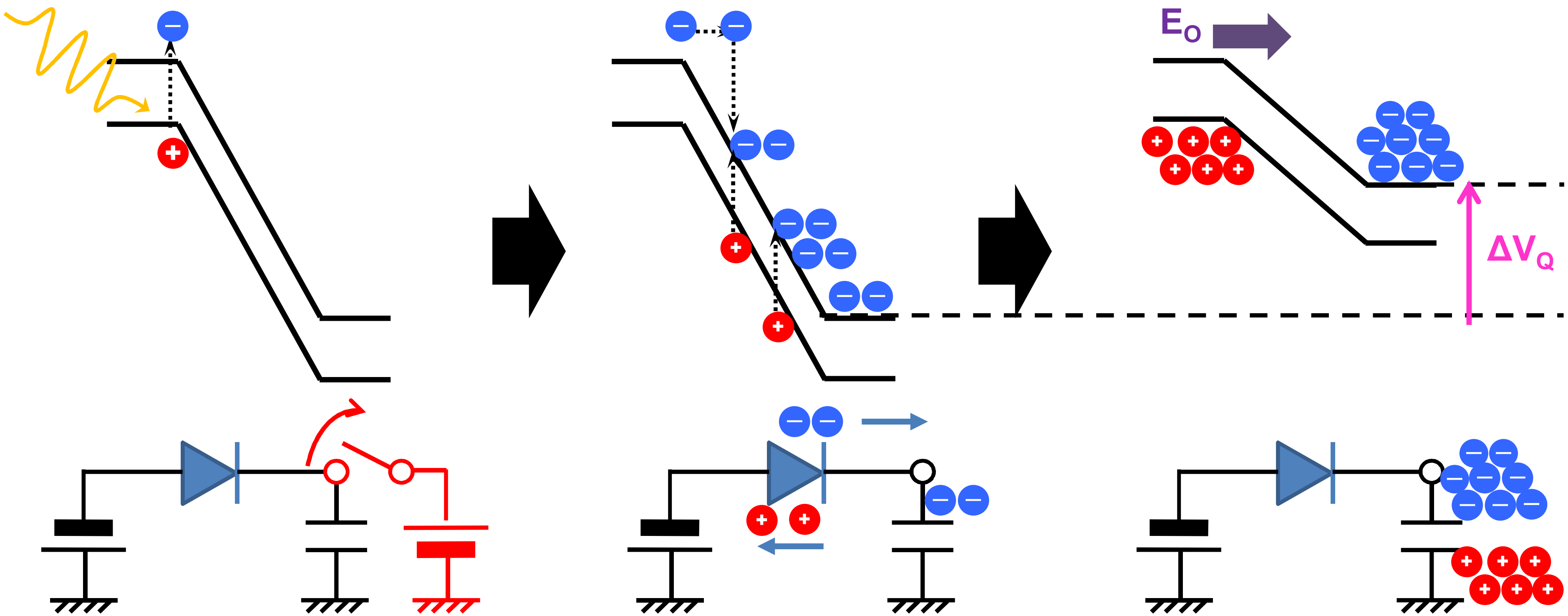
Small pixel
High fill factor

Technical issue : To guarantee quenching

Conventional CIS	SPAD
	
Reset Tr.	Quenching Circuit

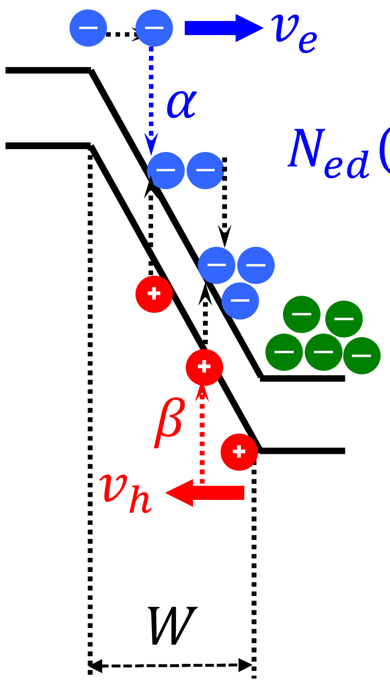
Idea of capacitive quenching

- To set R_Q ∞.
- To accommodate all carriers generated. ⇒ Need a large capacitor ?



Simulating relaxation quenching process

- Carriers run with saturation velocities.
- Fixed depletion region width (W).
- Continuity equation → Integration of space dependence. →Time dependence.



Charge in *W* | **Ionization** | **Drift-out**

$$N_{ed}(t+\Delta t) = N_{ed}(t) + \{\alpha v_e \cdot N_{ed}(t) + \beta v_h \cdot N_{hd}(t) - v_e/W \cdot N_{ed}(t)\}\Delta t$$

Charge on C

$$N_{ec}(t+\Delta t) = N_{ec}(t) + v_e/W\, N_{ed}(t)\Delta t$$

Voltage drop

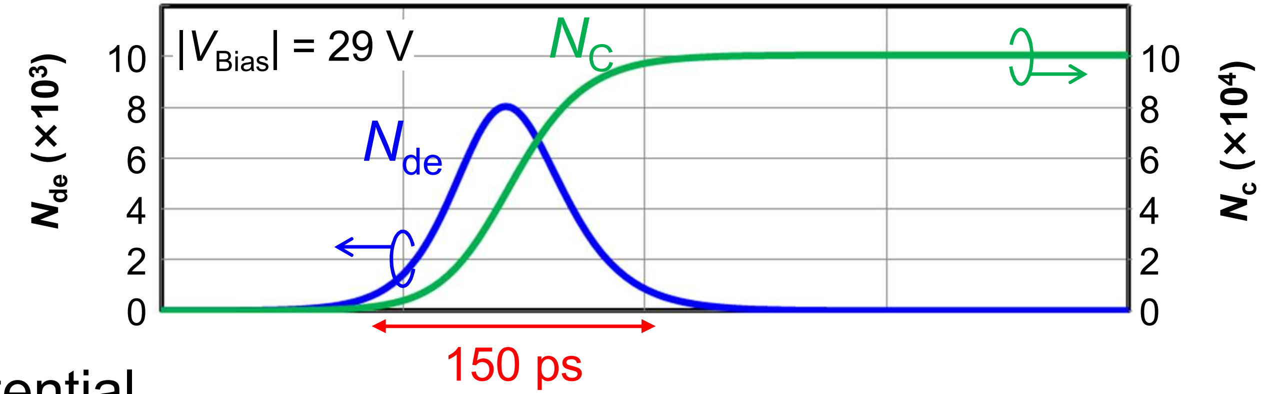
$$\Delta V_Q(t) = -\frac{qN_{ec}(t)}{C}$$

Full set of equations

Meaning	Equations
The number of electrons in a depletion region	$N_{ed}(t)$
The number of electrons in a capacitance	$N_{ec}(t)$
The number of holes in a depletion region	$N_{hd}(t)$
The average time of an electron to pass the depletion region by drift	$t_{1,e} = \frac{W}{2v_{sat,ele}}$ (electron)
	$t_{1,h} = \frac{W}{2v_{sat,hole}}$ (hole)
Mean time between avalanche multiplications for an electron and for a hole	$t_{0,e} = \frac{1}{v_{sat,ele}\alpha}$ (electron)
	$t_{0,h} = \frac{1}{v_{sat,hole}\beta}$ (hole)
The Difference equations of electrons and holes in a depletion region	$N_{ed}(t+\Delta t) = N_{ed}(t) + \left\{\frac{N_{ed}(t)}{t_{0e}} + \frac{N_{hd}(t)}{t_{0h}} - \frac{N_{ed}(t)}{t_{1e}}\right\}\Delta t$
	$N_{hd}(t+\Delta t) = N_{hd}(t) + \left\{\frac{N_{ed}(t)}{t_{0e}} + \frac{N_{hd}(t)}{t_{0h}} - \frac{N_{hd}(t)}{t_{1h}}\right\}\Delta t$
Electrons accumulated in the capacitance	$N_{ec}(t+\Delta t) = N_{ec}(t) + \left\{\frac{N_{ed}(t)}{t_{1e}}\right\}\Delta t$
Impact ionization ratio of electrons and holes	$\alpha(t) = \alpha_0 \exp\left(-\frac{a}{E(t)}\right)$
	$\beta(t) = \beta_0 \exp\left(-\frac{b}{E(t)}\right)$
Electric field in the depletion region	$E = \frac{V}{W}$
Voltage drop due to charge accumulation	$V_Q(t) = V(t=0) - \frac{qN_{ec}(t)}{C}$

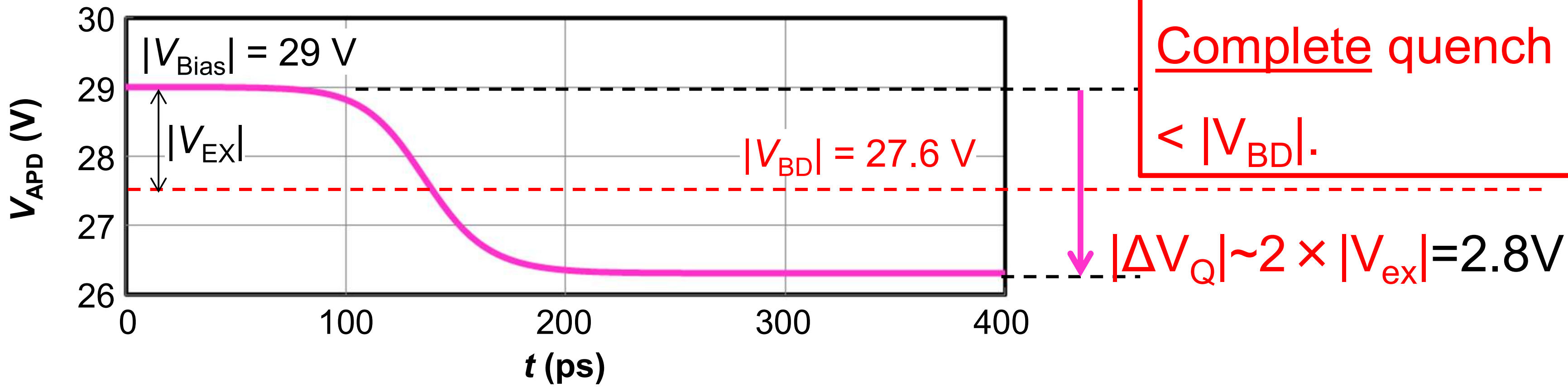
Simulation in time domain

Change of charges



Quenching as fast as 150 ps.

Change of potential

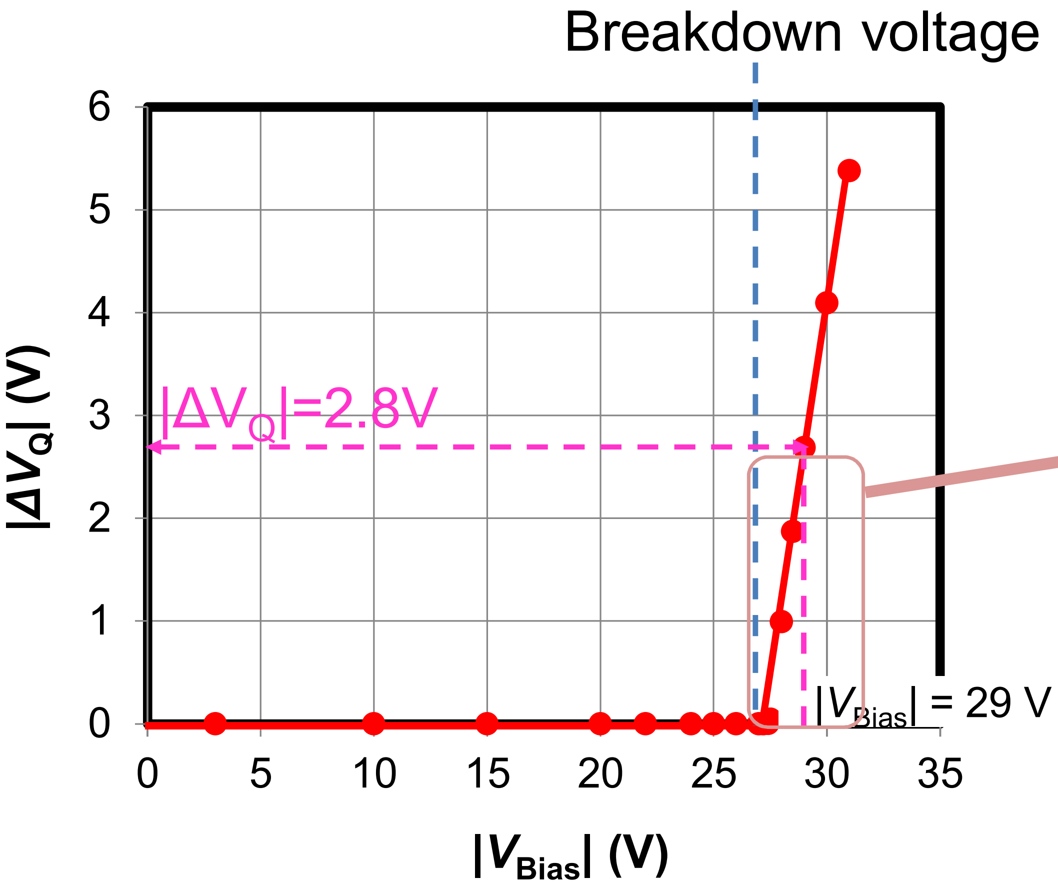


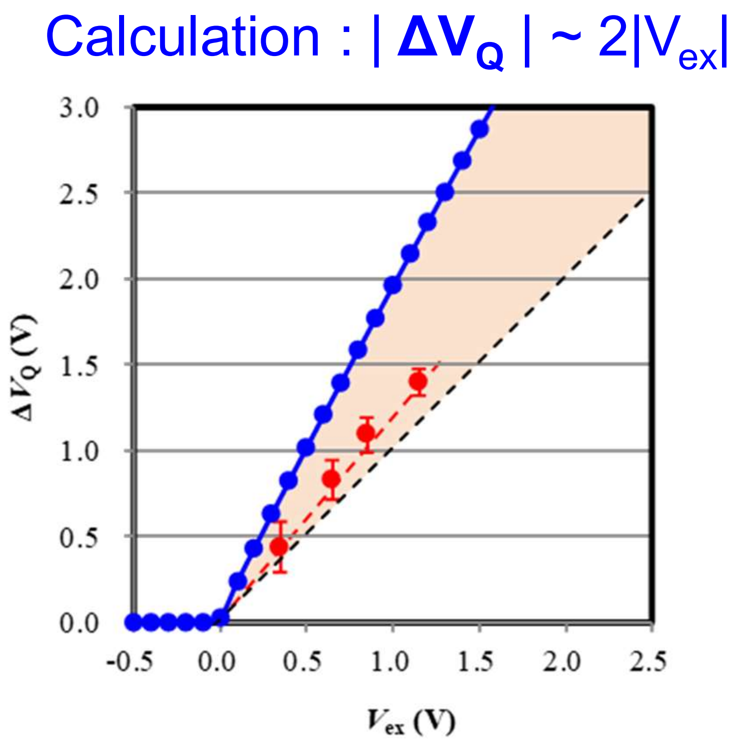
Complete quench < $|V_{BD}|$.

Quenching Voltage (ΔV_Q) depends only on V_{Bias}

- ΔV_Q proportional to $|V_{Bias}|$.

⇒Set the isolation barriers where N_C is stored.



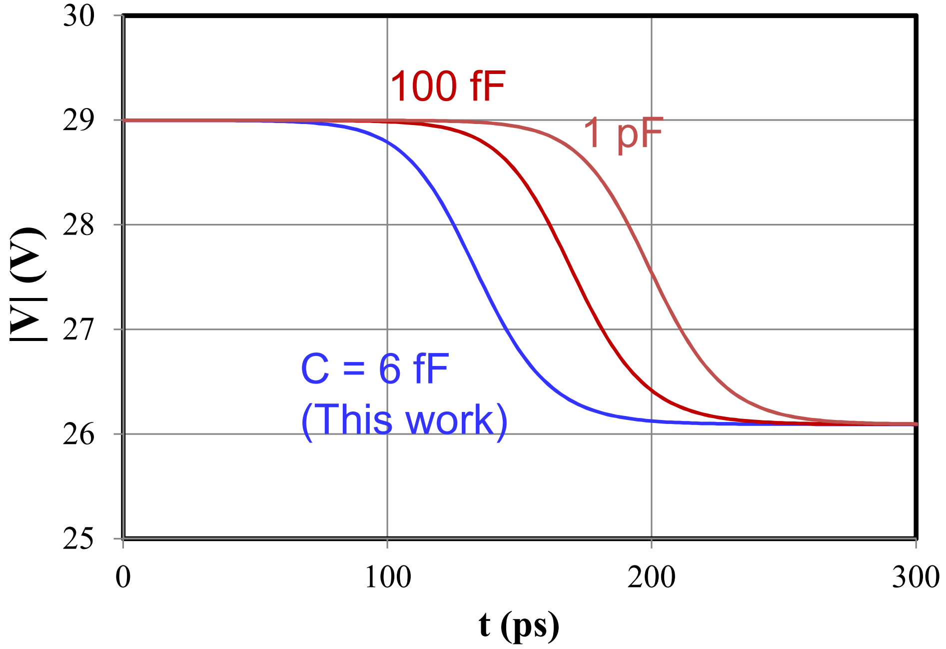


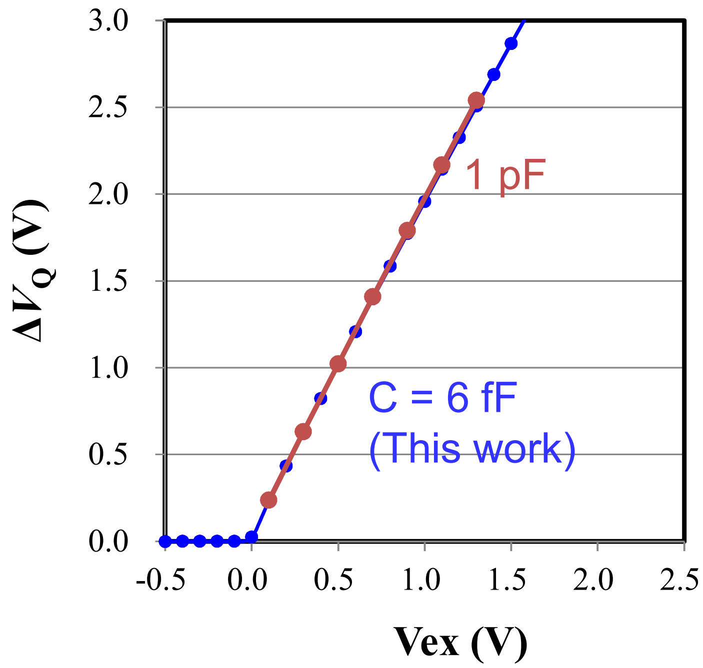
Quenching Voltage (ΔV_Q) depends only on V_{Bias}

- **ΔV_Q proportional to $|V_{Bias}|$.**

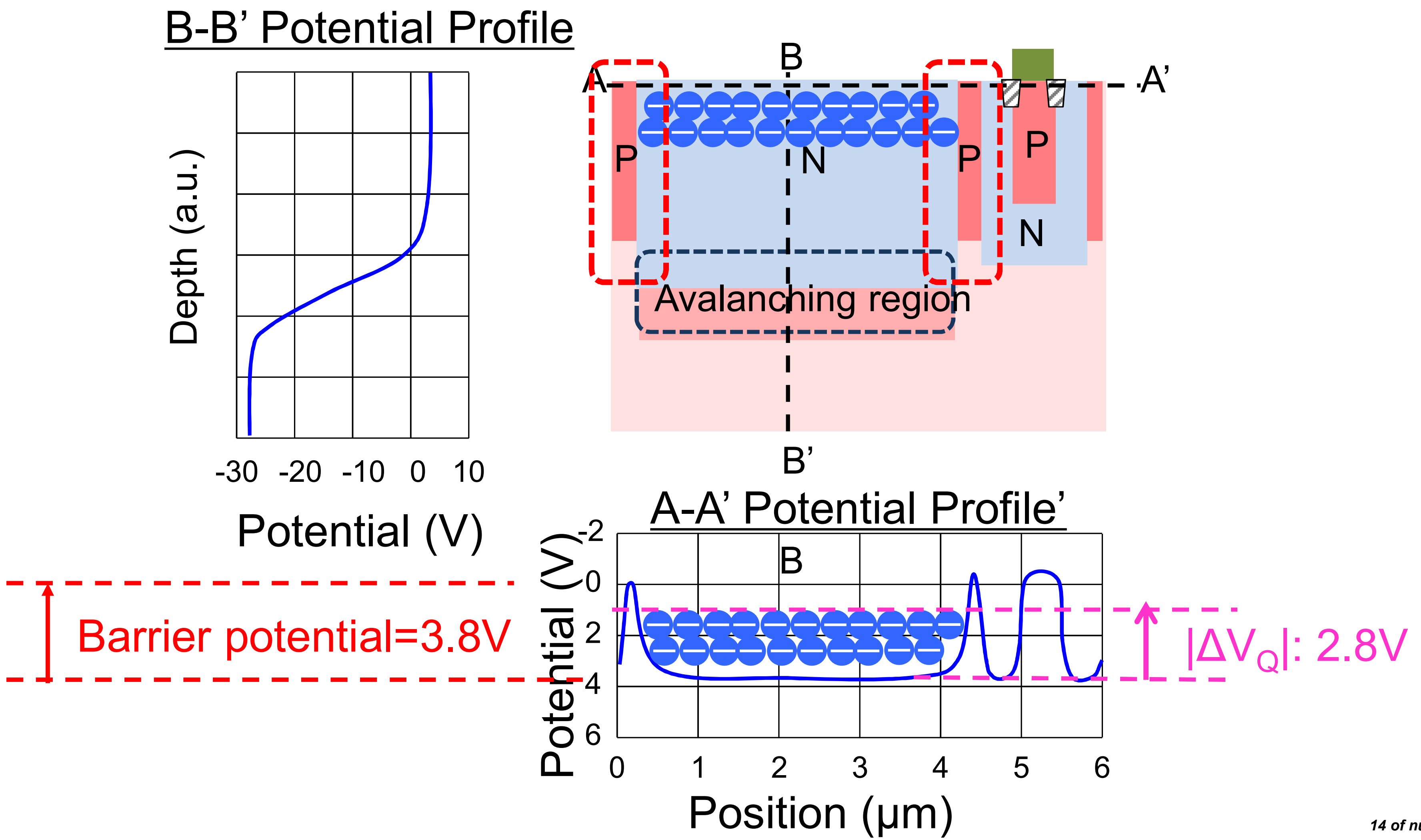
⇒Set the isolation barriers where N_C is stored.

- **When the capacitance is larger, the quenching time becomes longer.**



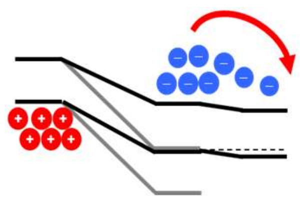
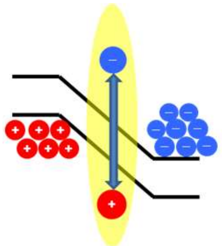
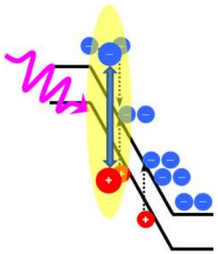


Overflow can be avoided if barrier potential > ΔV_Q

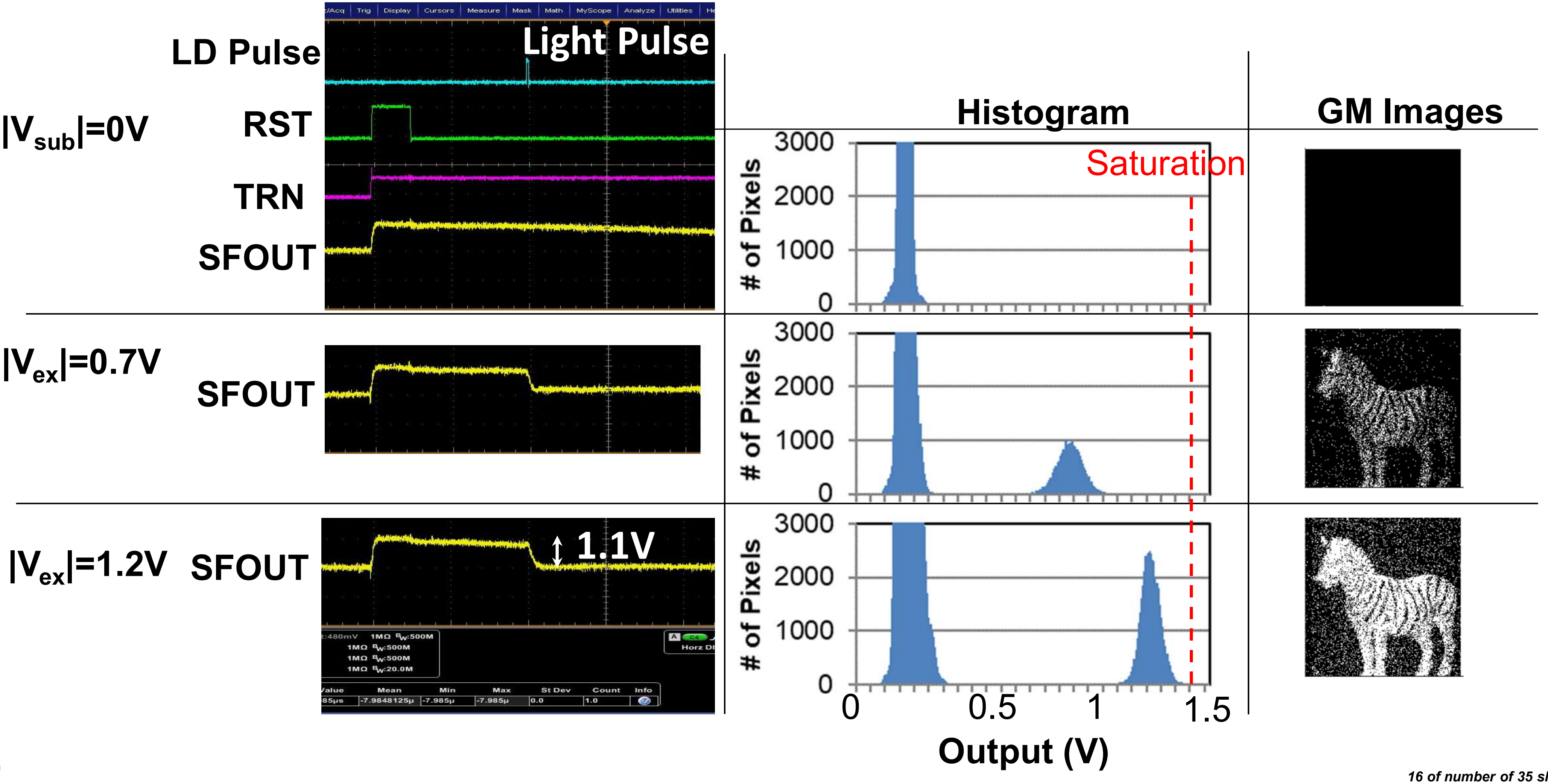


Characteristics of capacitive quenching

Three non-obvious questions are answered.

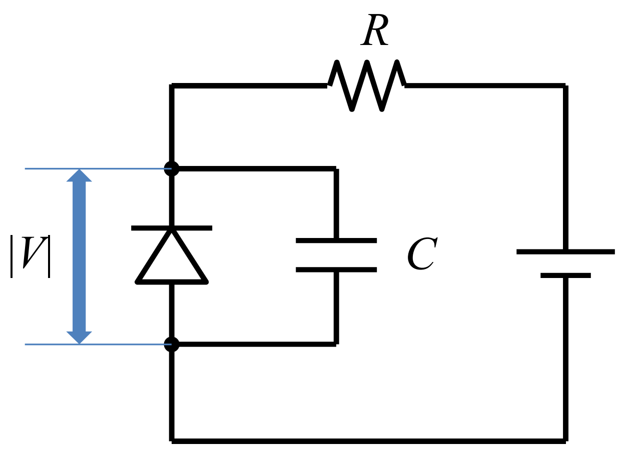
	Phenomenon	Comments
No overflow		· $\lvert V_{Barrier} \rvert > \lvert \Delta V_Q \rvert$ Generated carrier numbers are predictable.
No after-pulse		Completely "relaxed". ⇒ No Geiger mode pulse. · $\lvert \Delta V_Q \rvert \sim 2 \times \lvert \Delta V_{ex} \rvert$
No double counting		Not important during avalanche. Good for synchronous detection ⇒ Direct Time-of-Flight

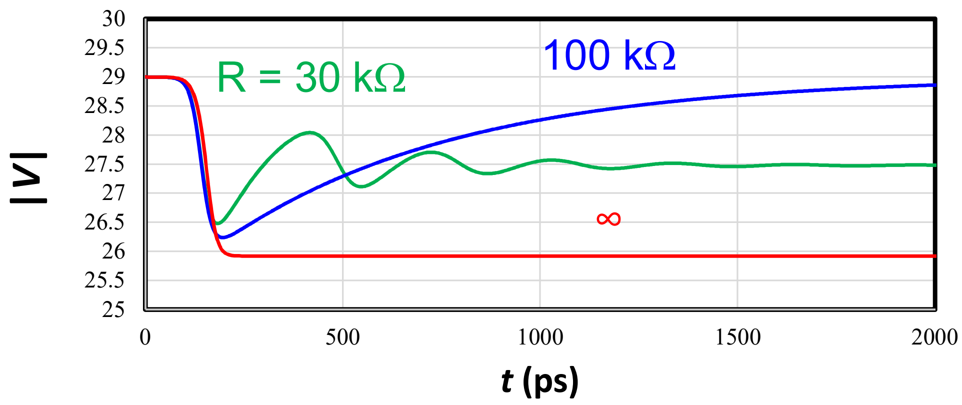
Verification of capacitive quenching

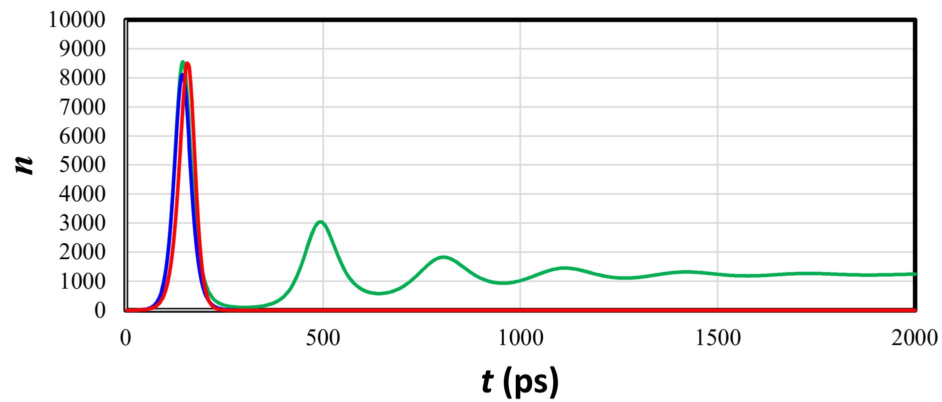


Simulation of resistive quenching

- Reasonable results (need at least few tens of kΩ) are obtained.







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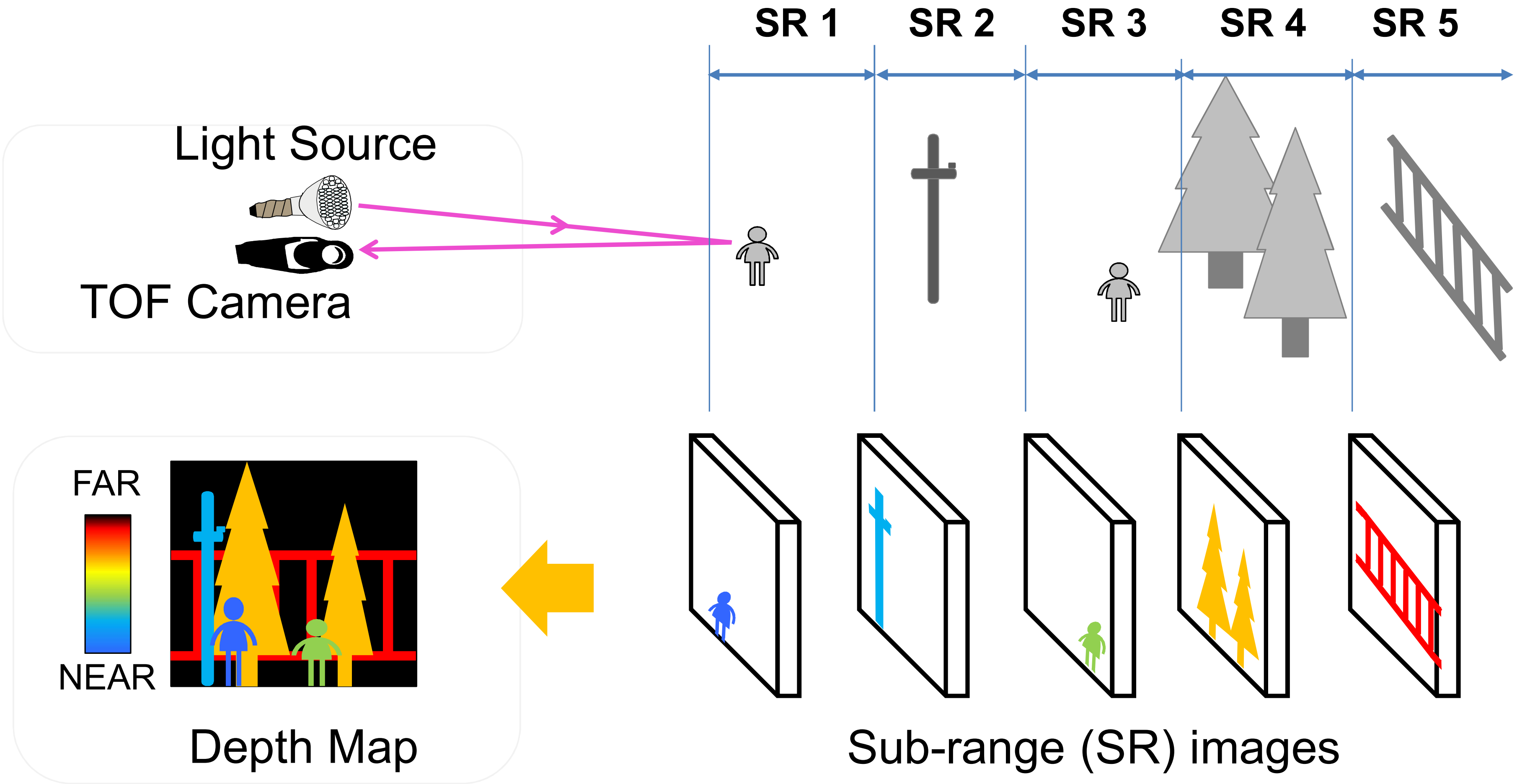
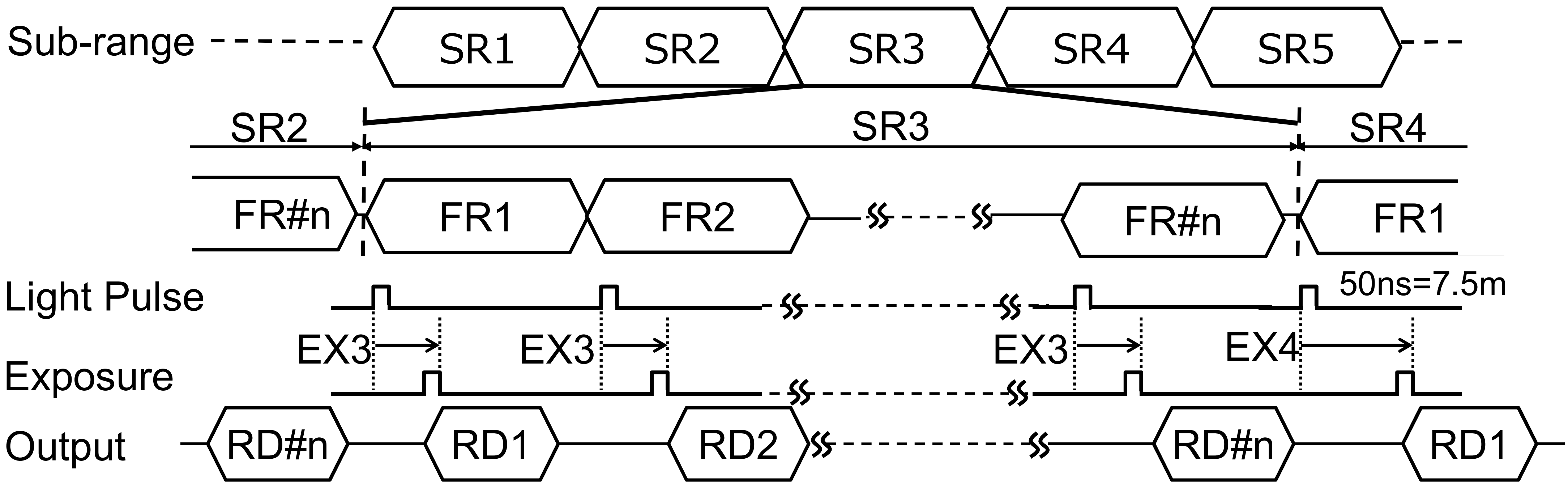
Principle of Sub-range synthesis method

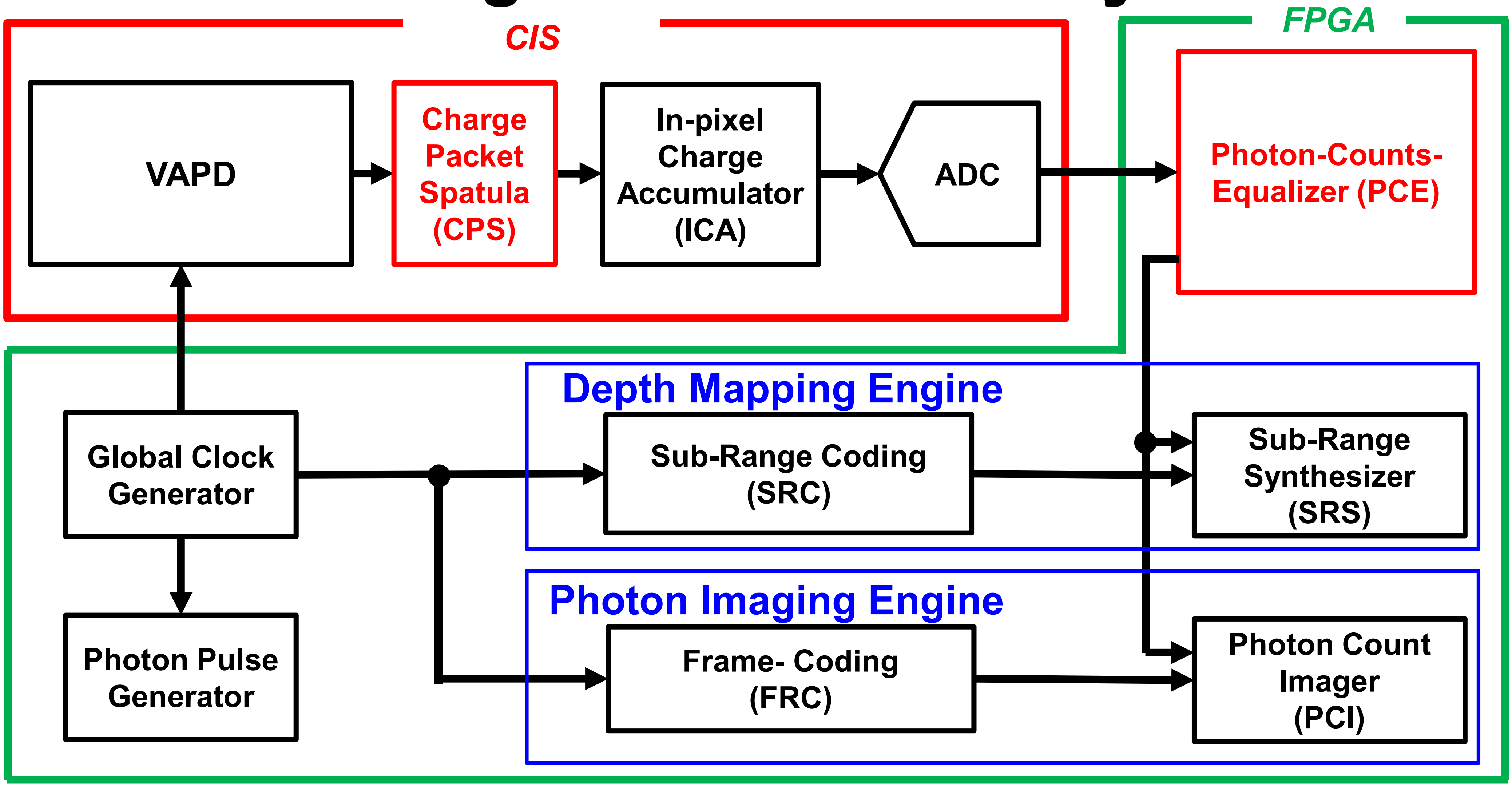


Sub-range image acquisition (typical)

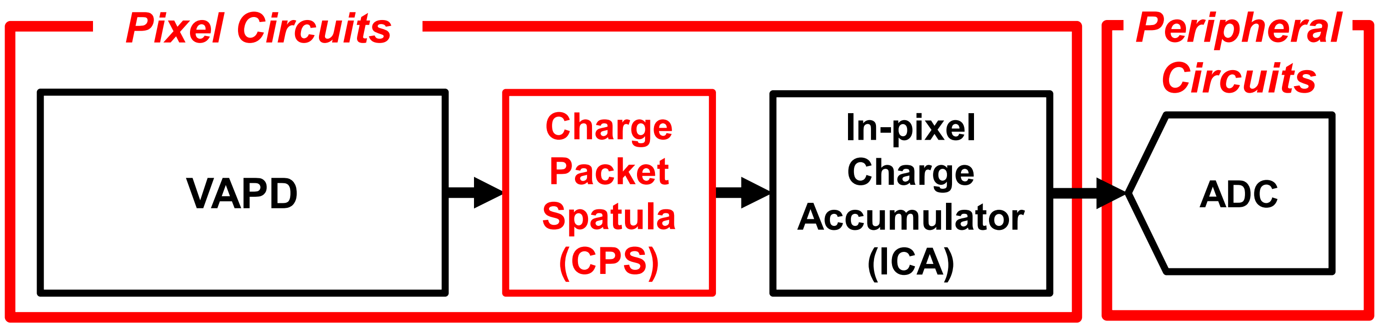
- Laser pulse : 50 kHz
- 2D Speed : 450 fps
- 3D SRS : 30 fps (15 SR images)

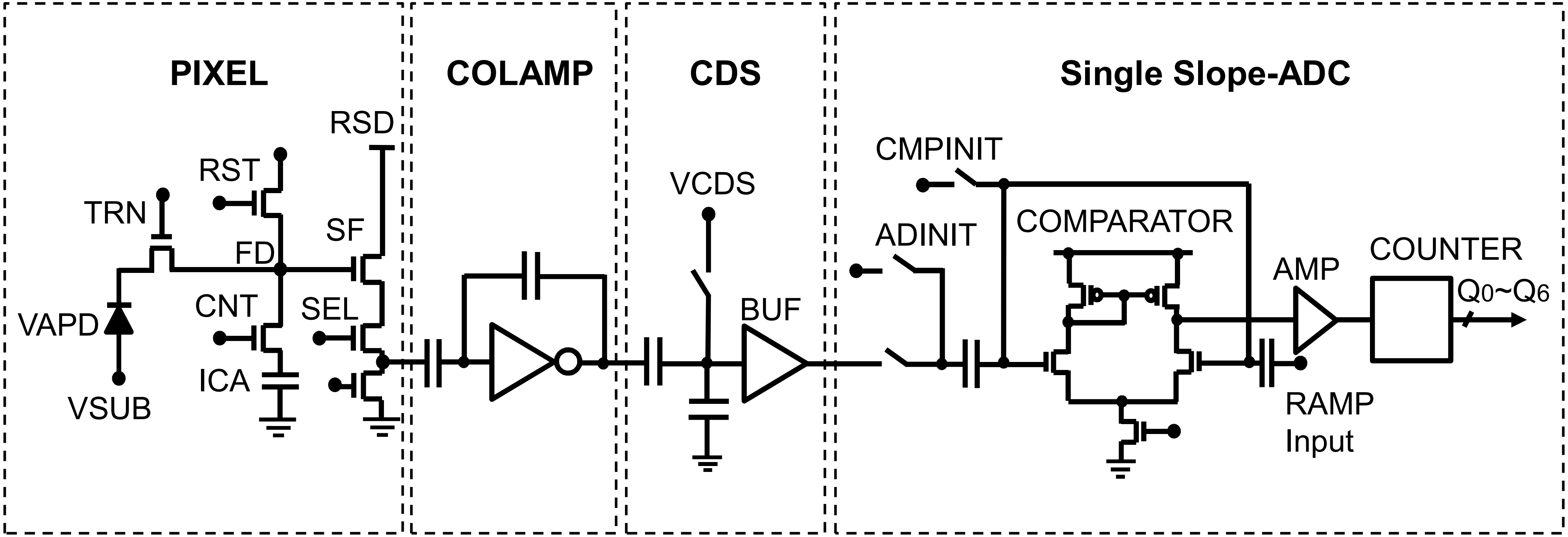


Block diagram of APD-ToF system



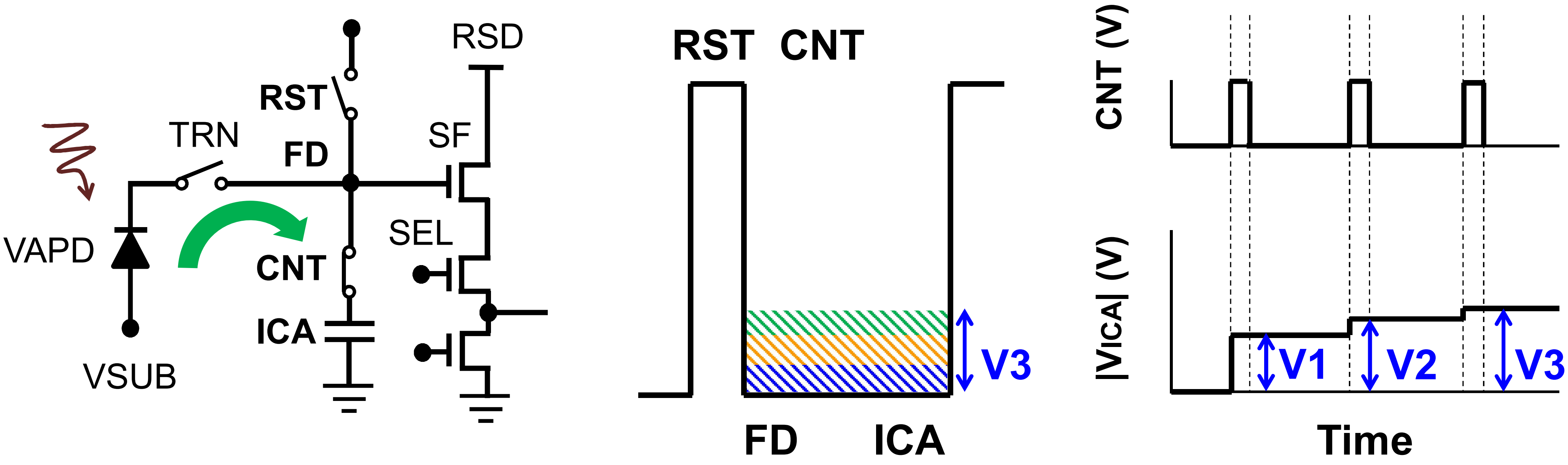
Circuit diagram of VAPD-CIS





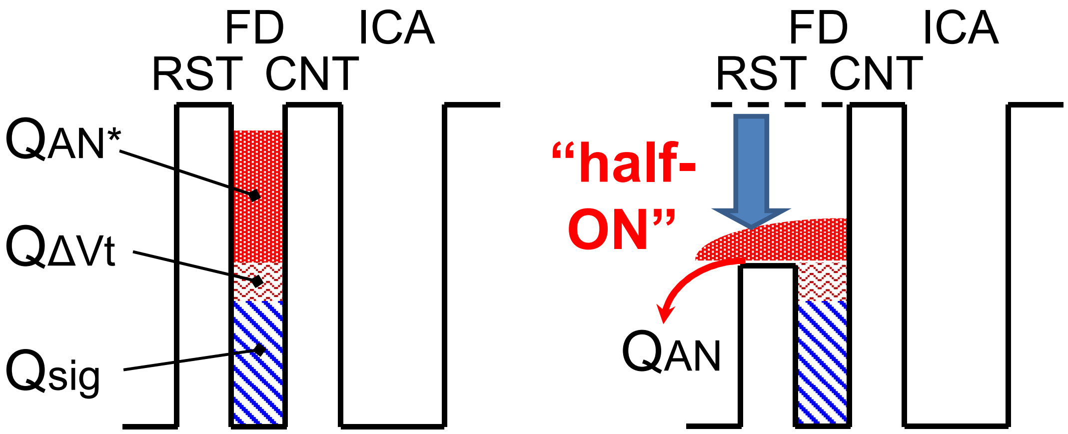
In-pixel charge accumulation (ICA)

- Non-linearity due to charge sharing operation. (Shown after 3rd counting.)



Charge packet spatula (CPS) by RST

Principle of Operation



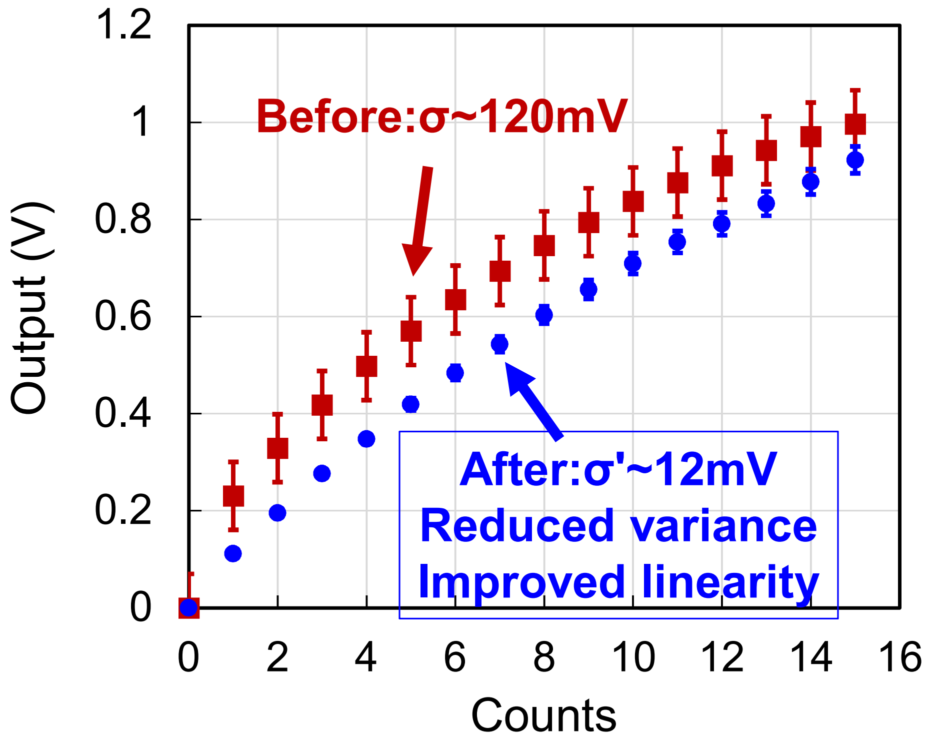
AN*: Avalanche Noise

$Q_{sig}+Q_{AN}+Q_{\Delta Vt}$ in FD

Q_{AN} is drained.

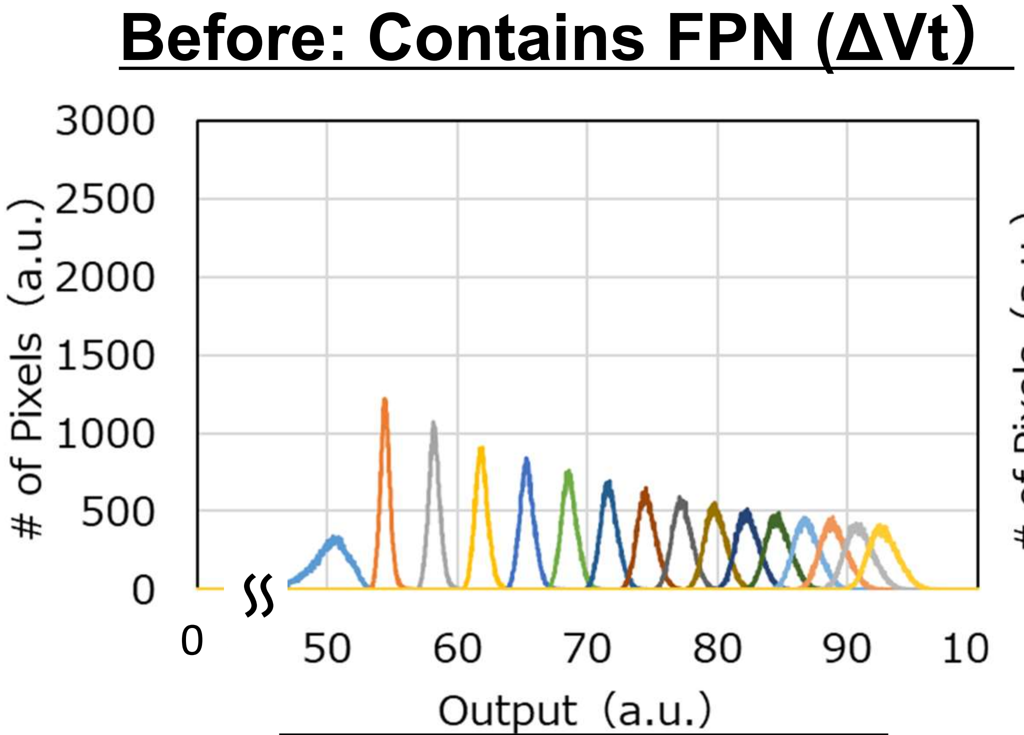
Effectiveness

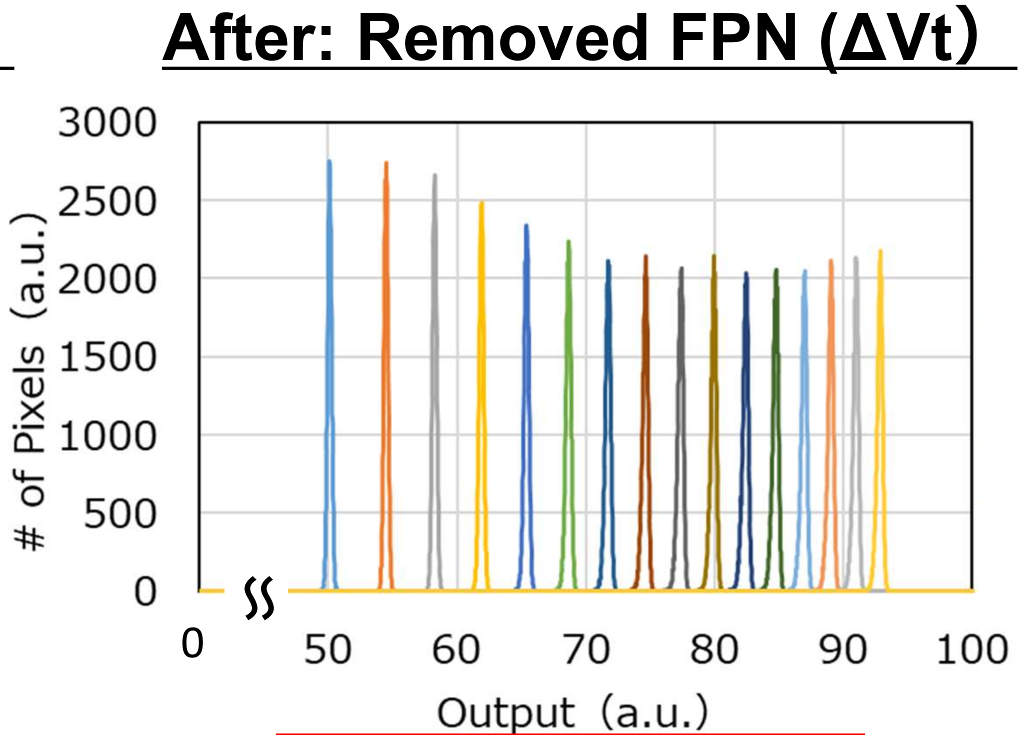
(Before and after CPS)



Off-chip Photon counts equalizer (PCE)

◆ **Fixed pattern noise due to Vt variation is removed.**



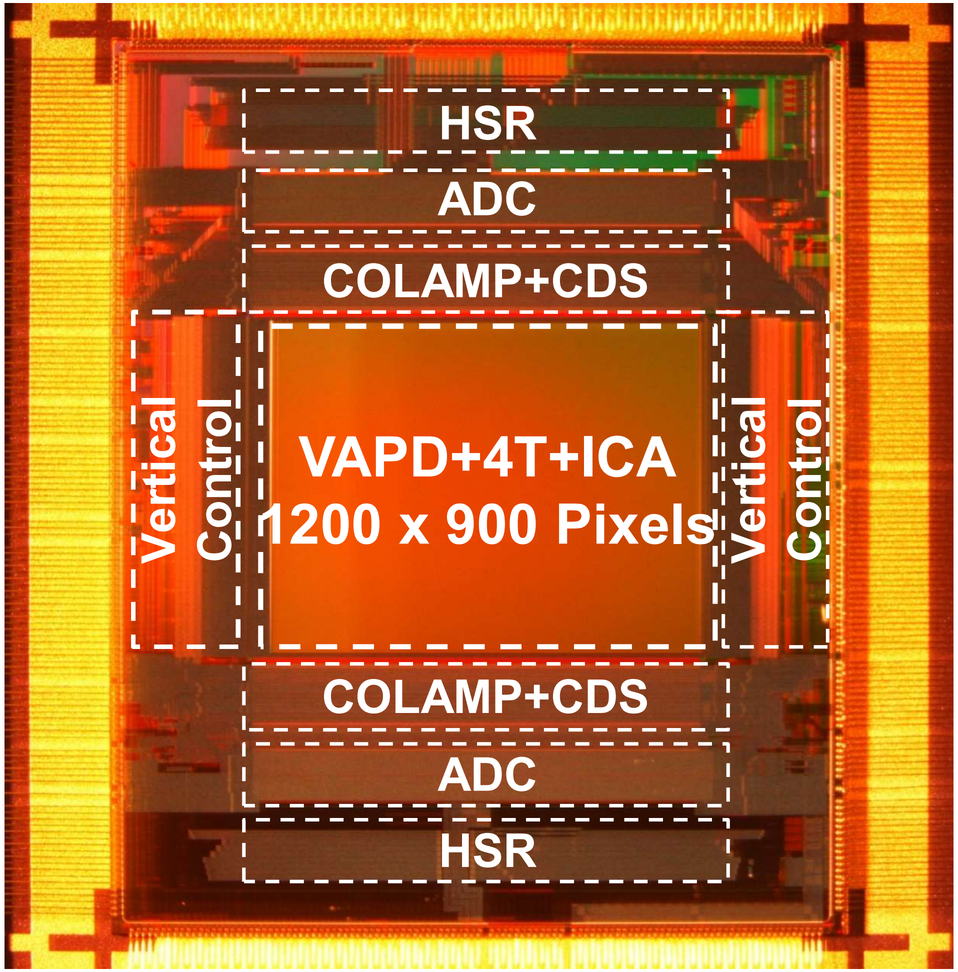


- **Broad**
- **Inhomogeneous**

→

- **Narrow**
- **Homogeneous**

Chip photograph of VAPD CMOS image sensor



Chip specification (Direct/Indirect-mixed-CIS)

	Direct+Indirect mixed TOF CIS
CMOS Technology	65nm
Pixel Size	6μm
2D Resolution	1200x900
Pixel Type	VAPD (=SPAD)
APD Mode	Geiger
TOF Type	Direct + Indirect
Ranging Scheme	Direct: Photon Counting Indirect: Phase Difference
Maximum Range	250m
Depth Resolution@ Max. Range	1.5m
Depth Resolution@ Min. Range	10cm
2D Frame Rate	450fps

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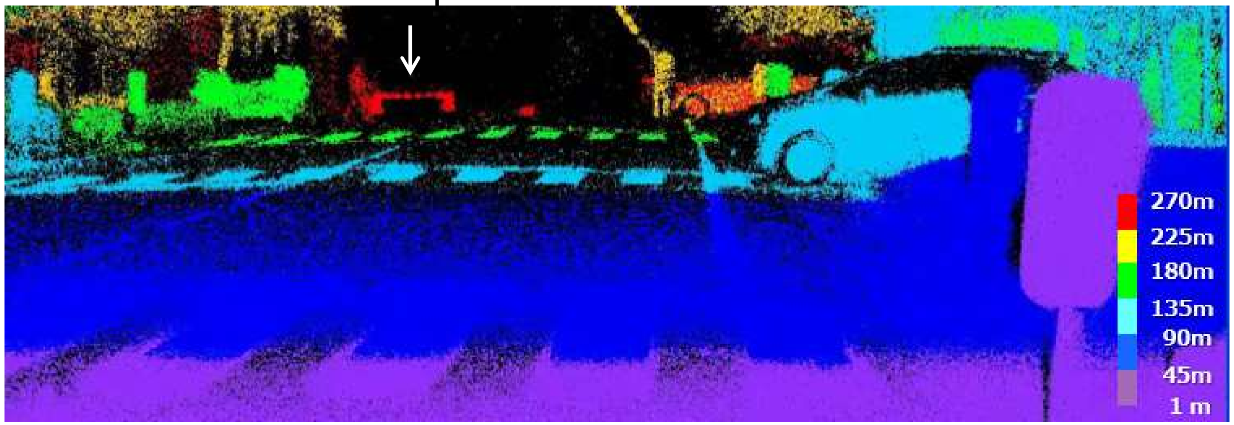
Long range performance (Dark scene)

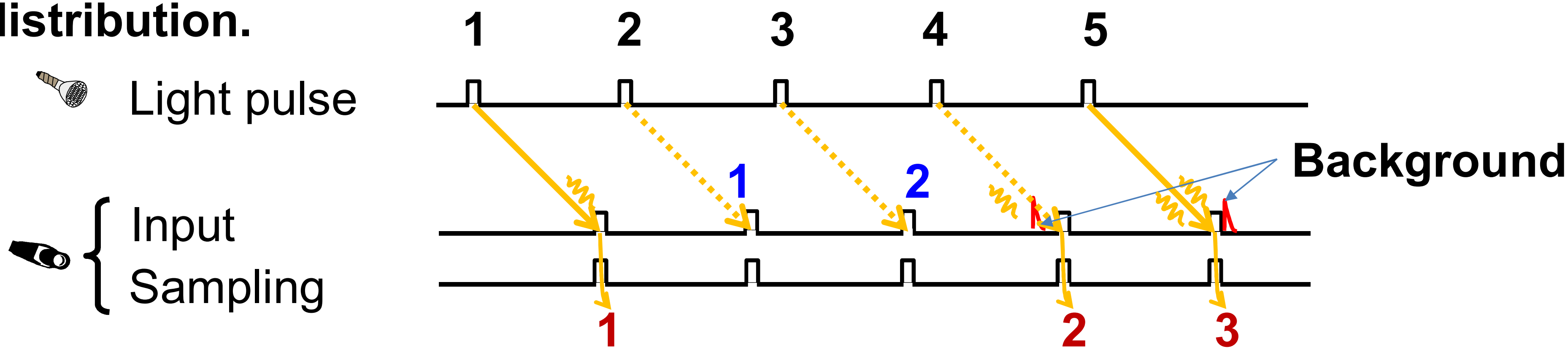
◆ **10cm lateral resolution@250m.**

10cm pole



Signal detection process=Binominal distribution

◆ Arrival/detection of each photon is a probabilistic process with a binominal distribution.



<u>**Signal+Background detection probability**</u>

5 samplings
3 successful Signal+BG
1 missed Signal

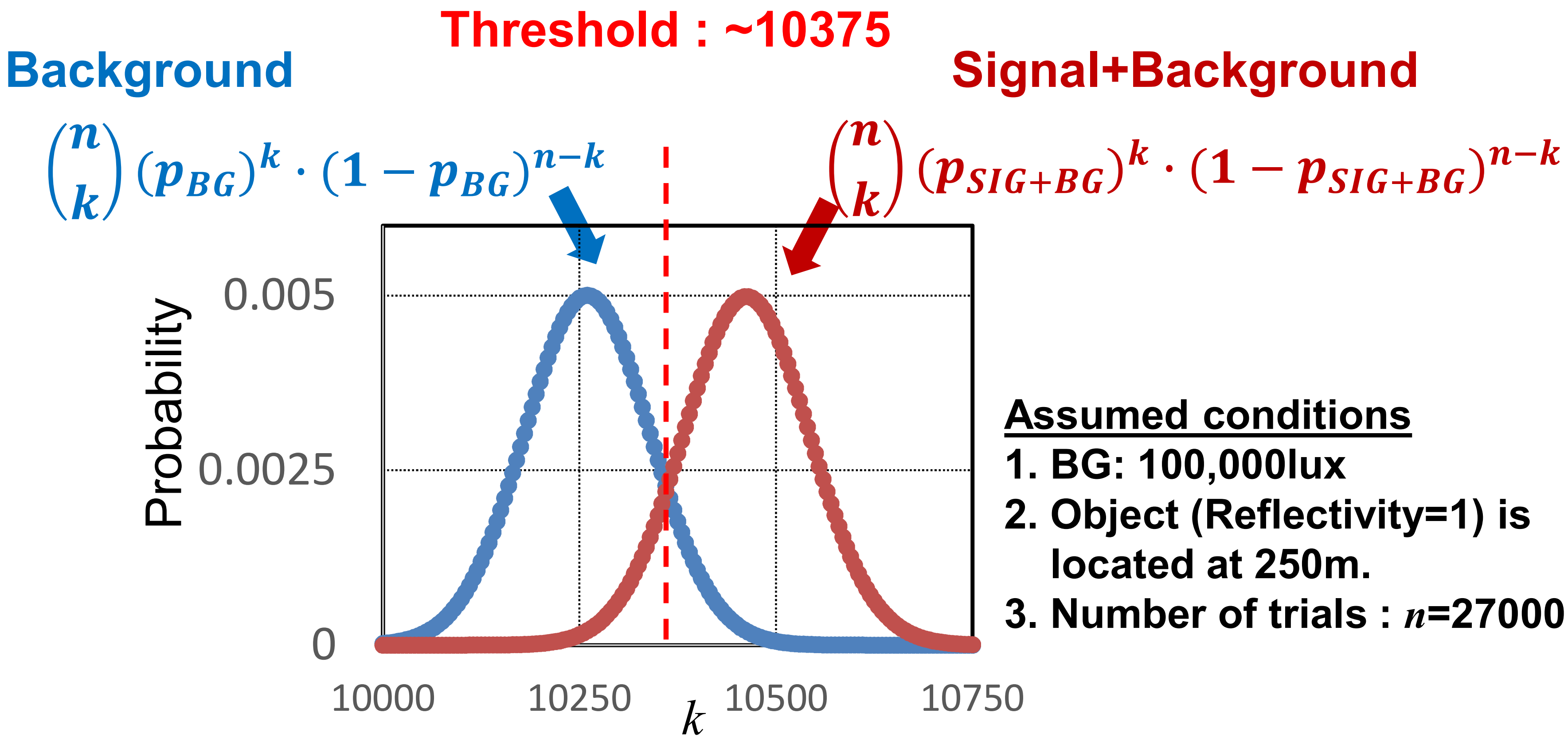
$$\binom{5}{3}(p_{SIG+BG})^3 \cdot (1-p_{SIG+BG})^2$$

General

$$\binom{n}{k}(p_{SIG+BG})^k \cdot (1-p_{SIG+BG})^{n-k}$$

To distinguish signal from background

- ◆ More counting for SIG+BG than for BG.

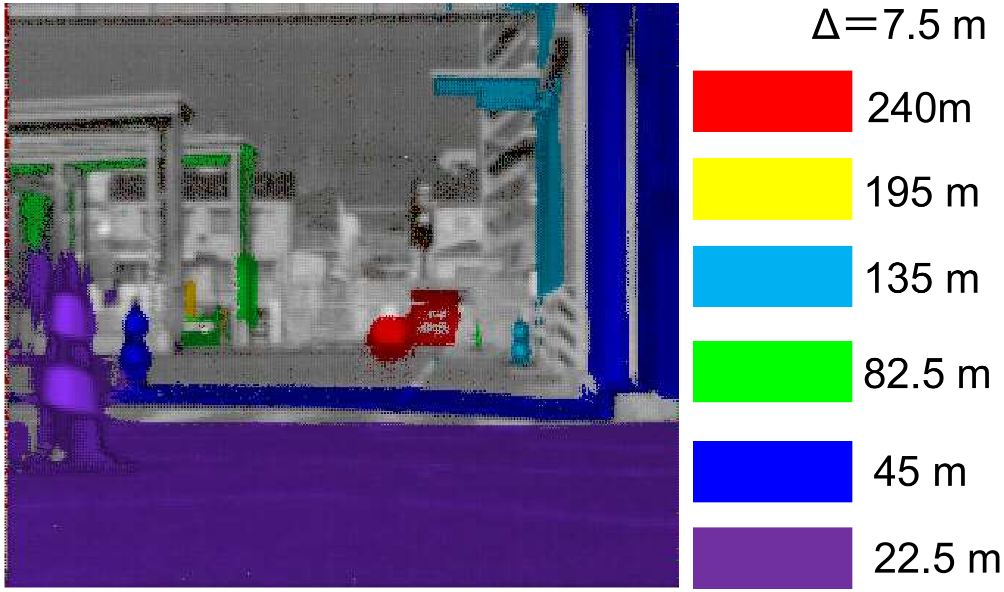


Assumed conditions

1. BG: 100,000lux
2. Object (Reflectivity=1) is located at 250m.
3. Number of trials : n=27000

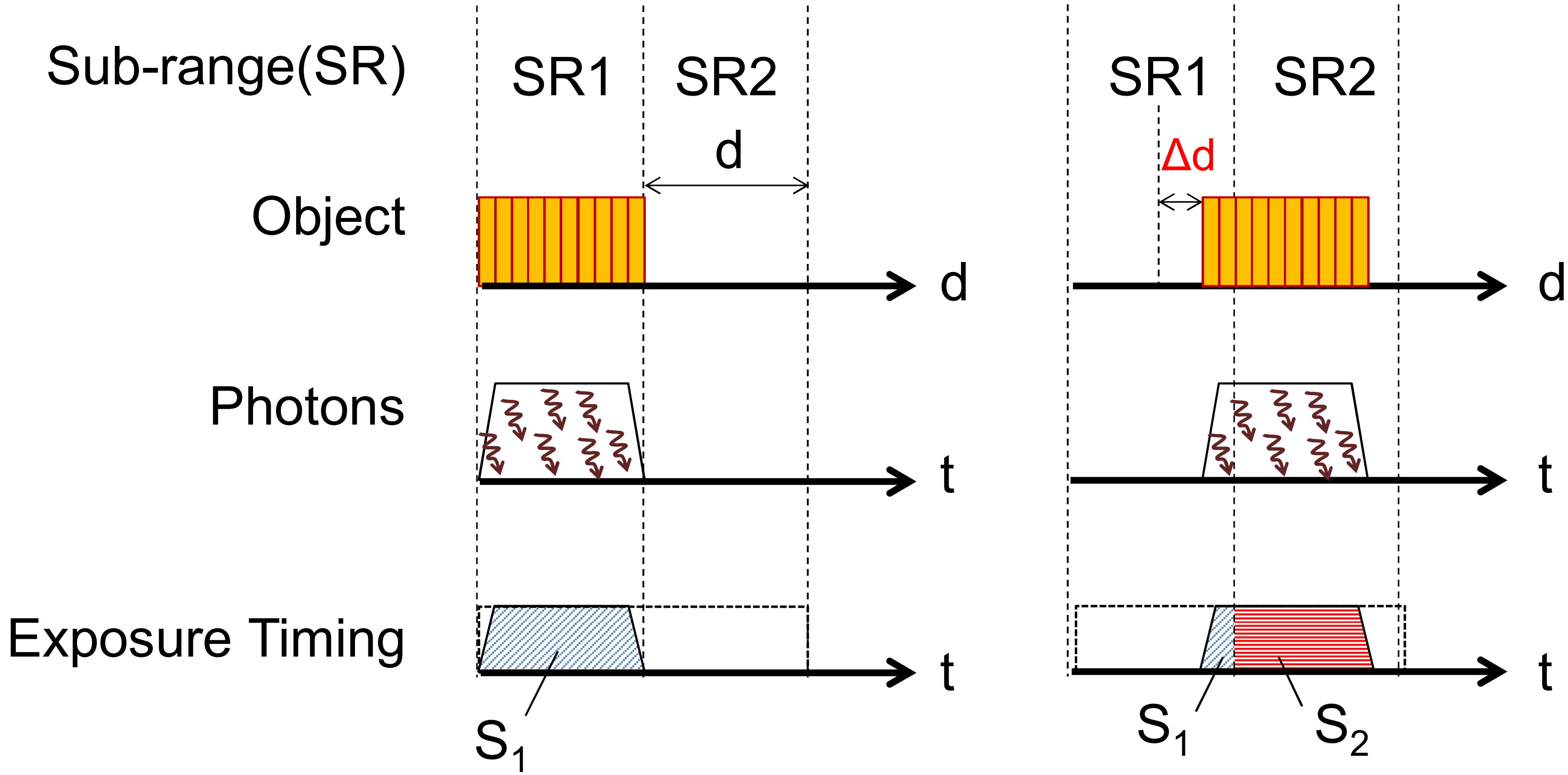
Long (~240 m) ranging under daylight (93000lux)

Gradation Image



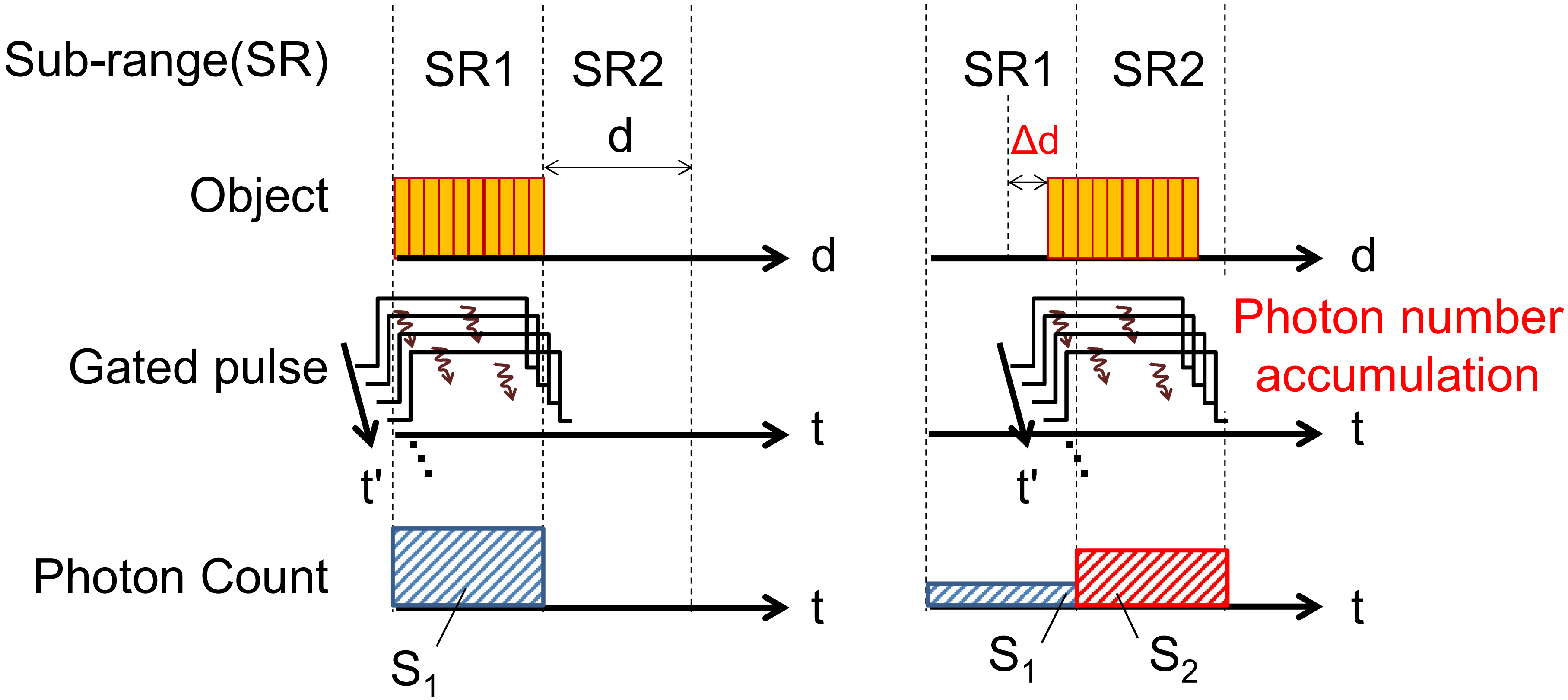
Gradation+TOF
Synthesized Image

Phase differentiation operation



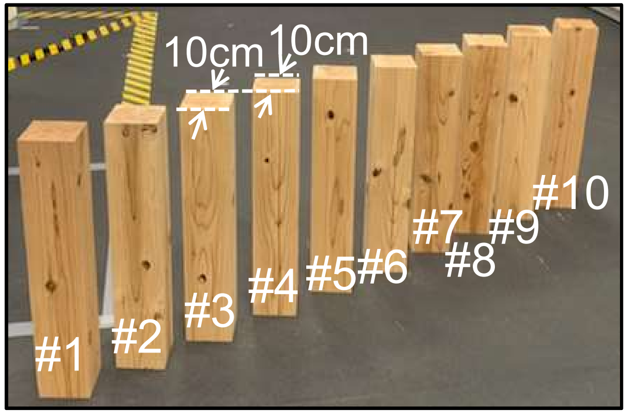
$\Delta d = d \times \{(S_1 - S_2)/(S_1 + S_2)\} \times 1/2$

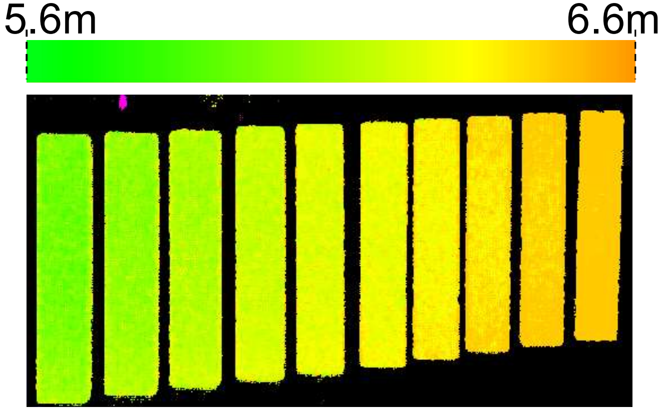
Phase differentiation by multiple photon gating

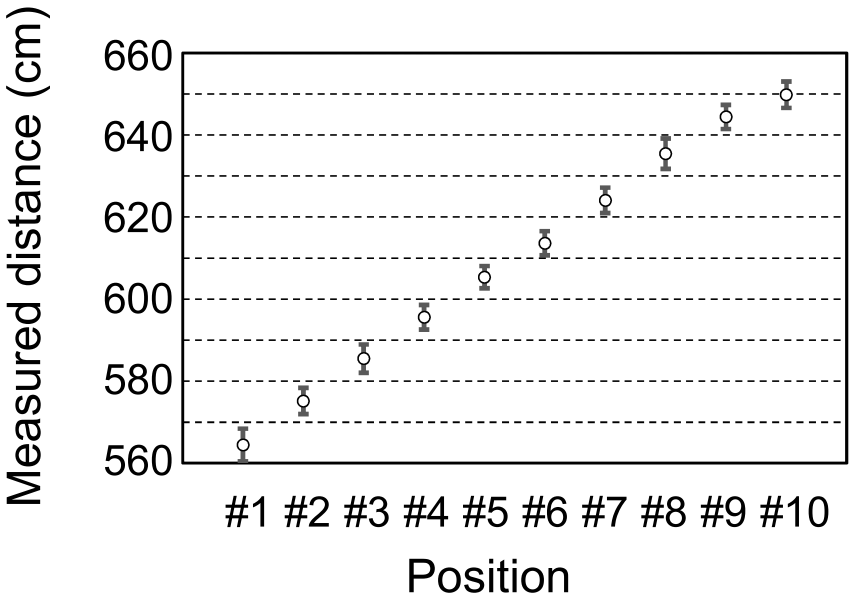


$$\Delta d = d \times \{(S_1 - S_2)/(S_1 + S_2)\} \times 1/2$$

Verification of I-ToF operation and improved Δz



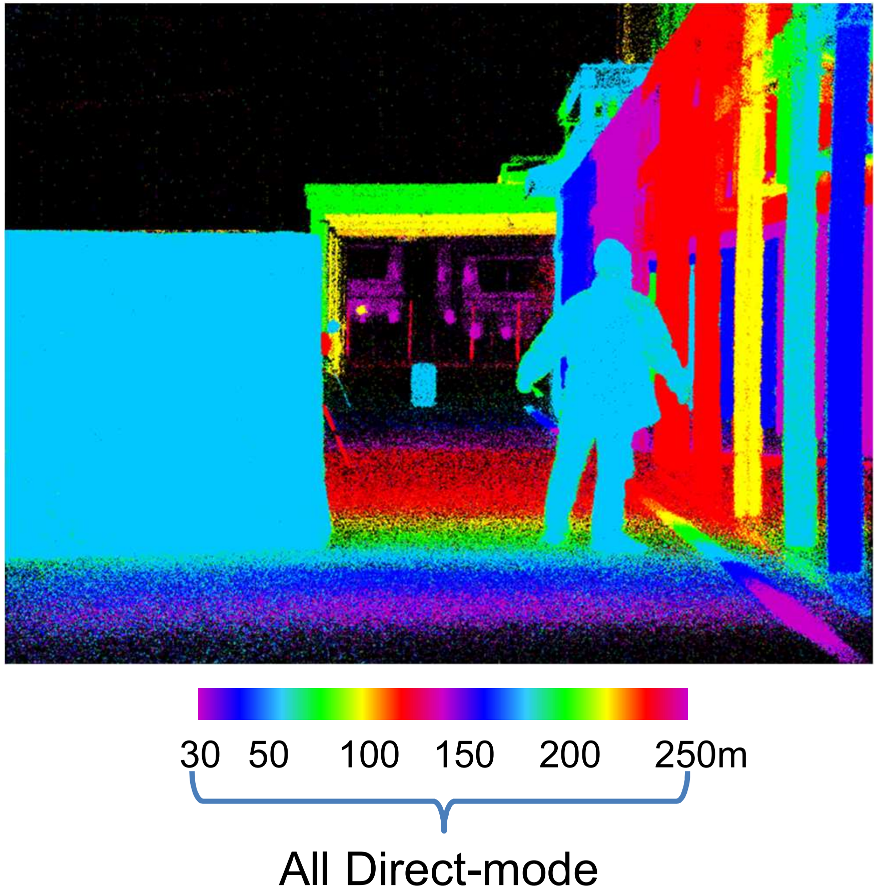




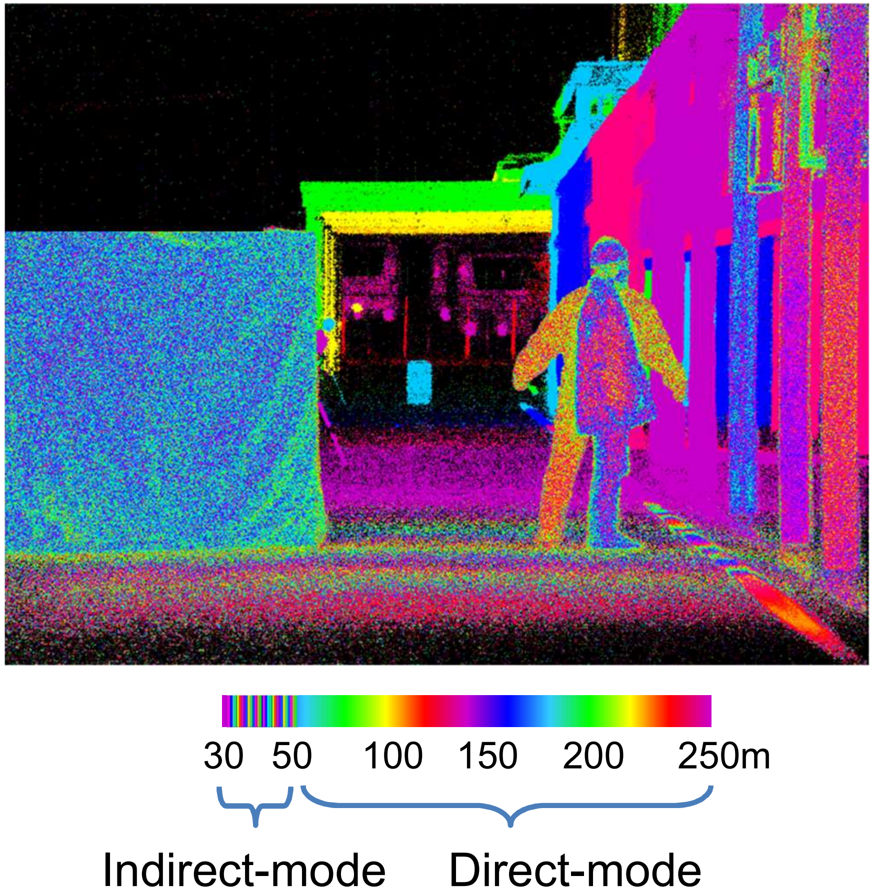
Std.Dev.:<7.4cm
Error:<1.4cm

Demonstration of mixed mode (long range)

Geiger-mode Direct-ToF image



Geiger-mode Direct-ToF-Indirect-ToF Mixed image



Summary

1. A <u>1.1 Mpixels</u> vertical avalanche photodiode (VAPD) CMOS imager is demonstrated.
   - 10cm resolution@ Z~250 m

2. Charge control methods
   - Capacitive quenching
   - Charge packet spatula (CPS)
   - In-pixel photon count accumulator (ICA)

3. System Technologies
   - Photon-Counts-Equalizer (PCE)
   - Sub-range synthesis (SRS)+Phase difference detection
   - D-ToF/I-ToF mixed mode

     ΔZ：1.5m～7.5m（Long range~250 m）

     ΔZ：1cm～10cm（Short range~20m）

Thank you very much.