Design and Fabrication of Solid-State Photomultiplier(SSPM) composed of multi-pixel InGaAs SPAD

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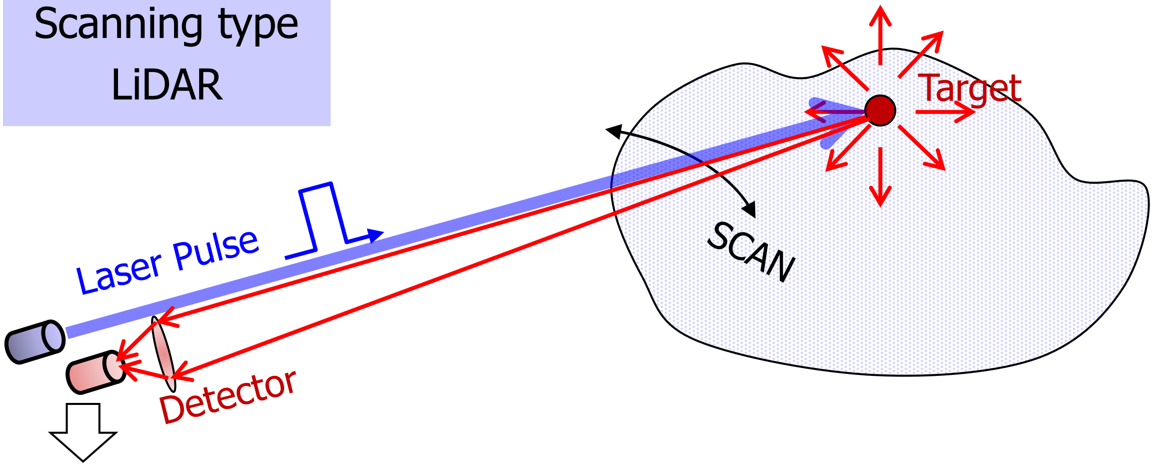
WOORIRO Co., Ltd.

OUTLINE

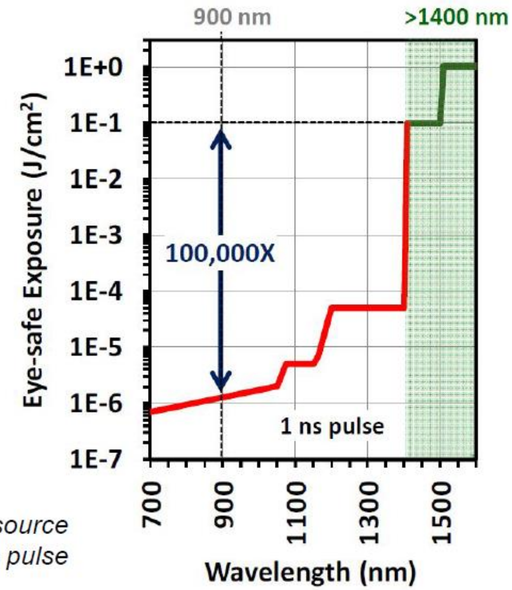
- √ Background
- √ InGaAs SPAD as a pixel element
- √ SPAD-based SSPM design and fabrication
- √ Test results of 64-pixel SSPM
- √ 203-pixel SSPM with honeycomb arrangement of pixels
- √ Summary and future works

Background : Why InGaAs-based SPAD?

Scanning type LiDAR



3D image



Point source
1 ns pulse

- √ The scattered laser beam from target returns to detector to measure intensity and distance by TOF
- √ In this configuration, the laser pulse output and detector's sensitivity (detectable number of photons) determine the measurable distance.
- √ Because SPADs internally amplify tens to hundreds of thousands of times, they can detect single photon levels. Thus, long distance image available by using SPAD pixel.
- √ Another point to point out is that InGaAs(P)-SPAD is the best alternative to long-range LiDAR at wavelengths above 1400 nm. The reason is that it still meets the eye-safe condition even at the high power of that wavelength.

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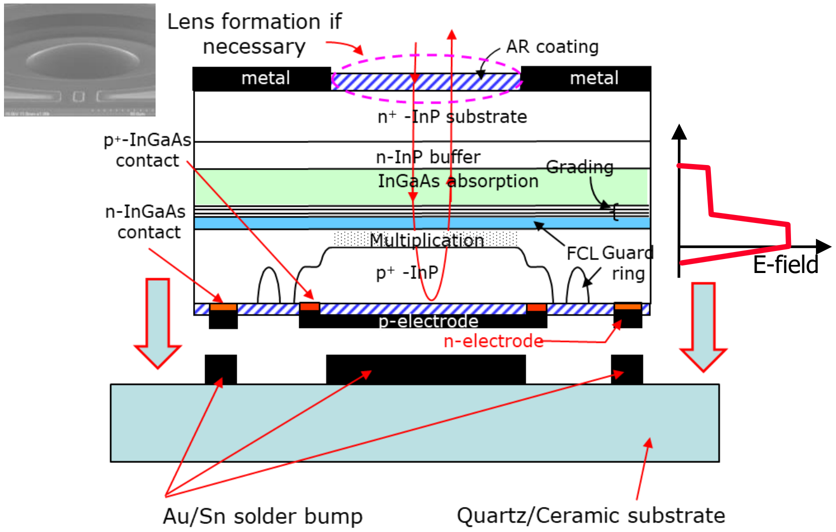
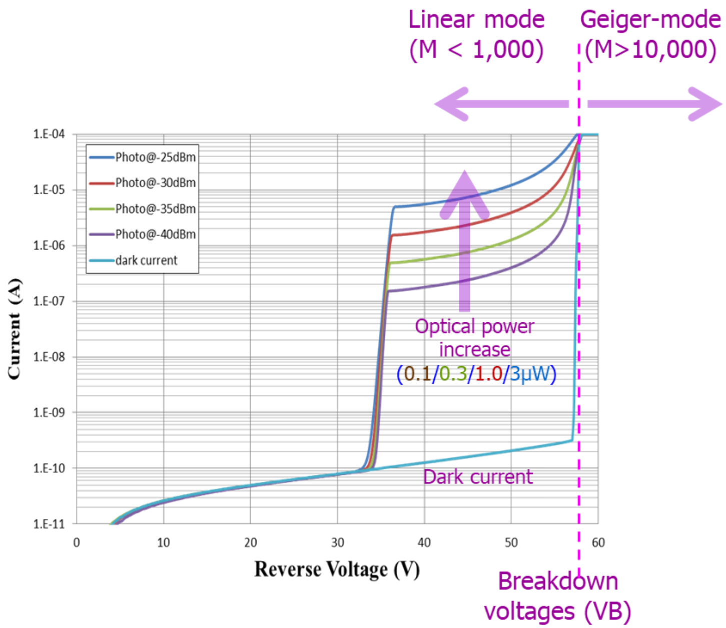
InGaAs SPAD(Single Photon Avalanche Diode)





Features of WOORIRO SPAD

√ Hi-Lo based FGR structure was used to eliminate possibility of tunneling at the maximum field region.

√ Floating Guard Ring was adopted to reduce DCR noise caused by edge breakdown.

√ For high QE, backside illumination structure was used

√ And InP-backside lens was formed directly (SSPM : to increase FF)

√ Very low dark current @RT & 98% of VB

√ SPDE(Single Photon Detection Efficiency) > 30% @below 1kHz DCR

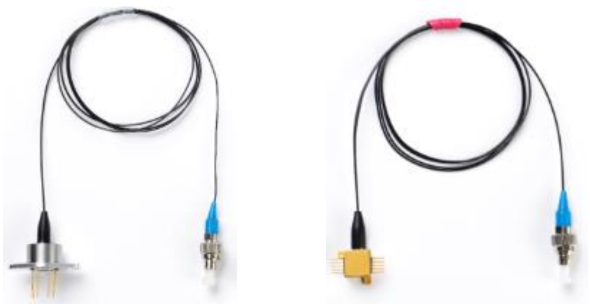
√ DCR (Dark Count Rate) < 1kHz @ 30% SPDE

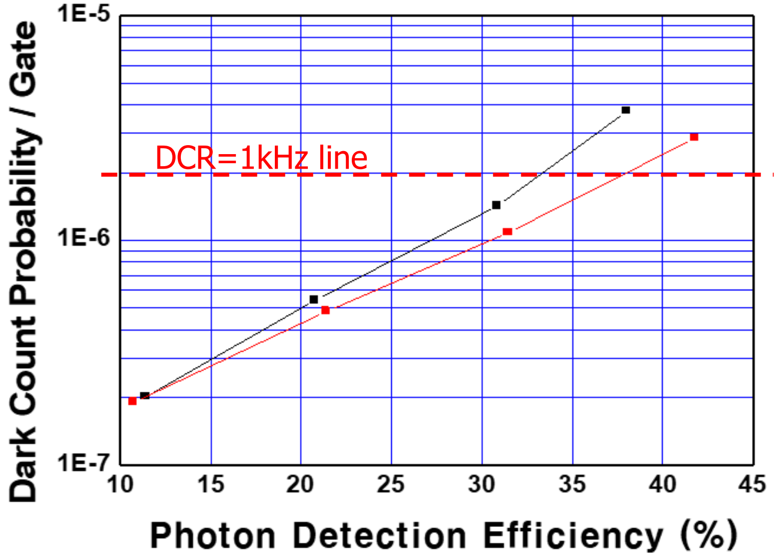
√ For high-speed application of SPAD, DA-SPAD has been proposed and realized at 1GHz gate frequency. [C.W. Park et al., Optics express, vol.27, 18201(2019)]

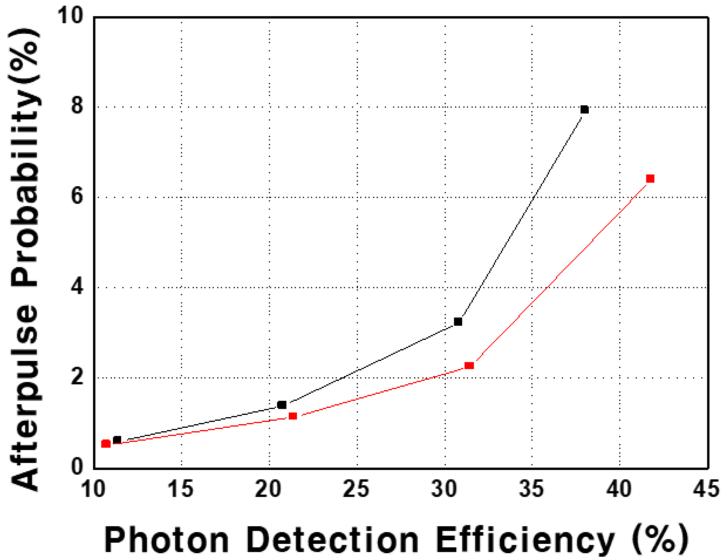
InGaAs SPAD performance

TECT CONDITION

- √ Gate repetition rate : 10MHz / 2ns / 6.6V
- √ Optical Input : 150ps, 0.1photon/pulse, 100kHz
- √ Chip temperature : -40°C
- √ Conventional gating technique
- √ Tested samples : SMF-pigtailed module (TO8)





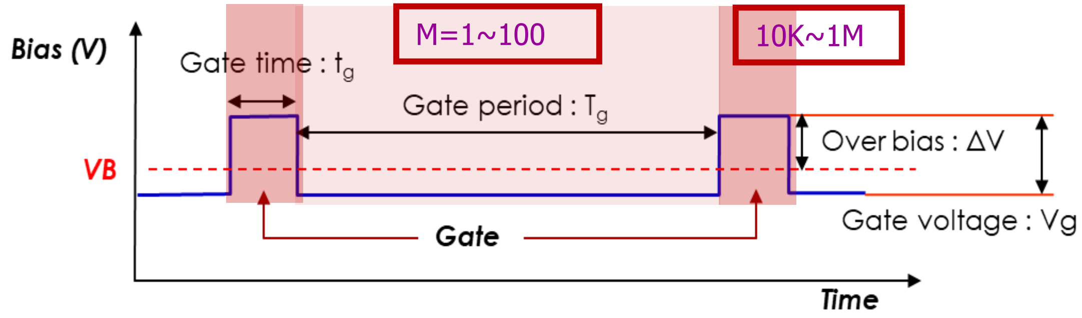


- √ Very Low DCP or DCR noise at high detection efficiency.
- √ Based on SPAD structure of good performance, InGaAs-SSPM chip has been designed and fabricated.

SPAD vs NFAD : classified by quenching mechanism

1) Active quenching (Gated mode) : Used for QKD

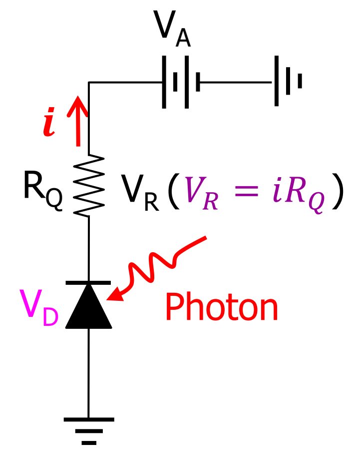
- √ Gain control is made periodically.
  [10,000 ~ 1,000,000 ↔ 1 ~ 100]
- √ SPAD only is used without resistor.
- √ This quenching method is used for QKD (Single photon incidents on SPAD periodically)



2) Passive quenching (Negative Feedback : NFAD)

- √ A series resistor(R_Q) is used for negative feedback.
- √ A large current (i) is generated by multiplication of millions of times
  - → bias drop by V_R ($V_R = iR_Q$).
  - → bias V_D in junction would be reduced from V_A to $V_A - iR_Q$.
- √ This bias drop is recovered when current is reduced ⇒ Ready-state
- √ This method is suitable to use for non-periodic photon incidence such as photon counting or laser range-finding(LRF).

Long-range LRF, Sensor, etc.



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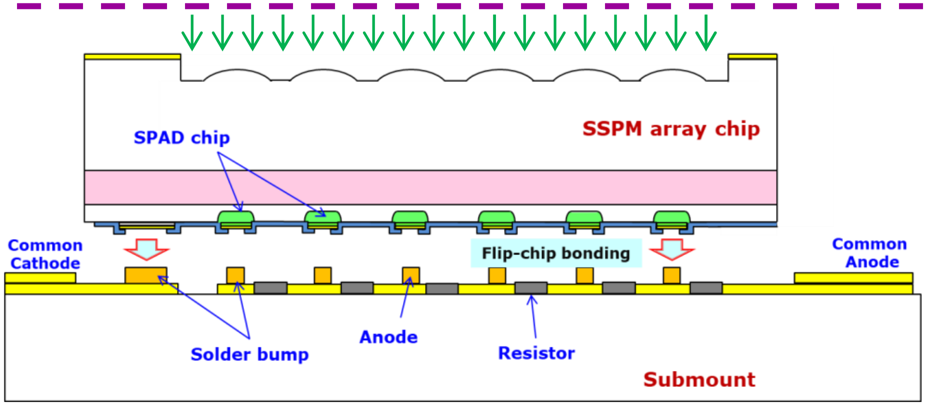
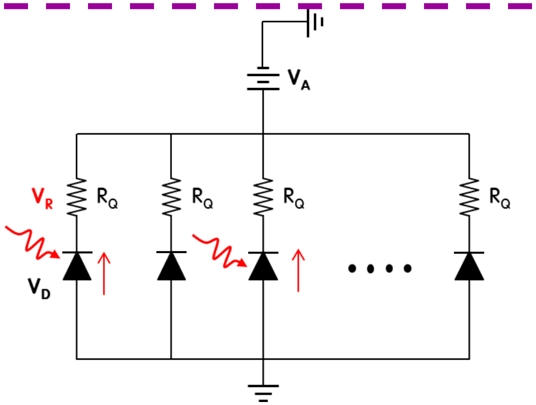
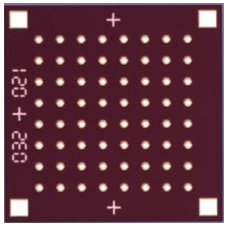
SPAD-based SSPM design consideration

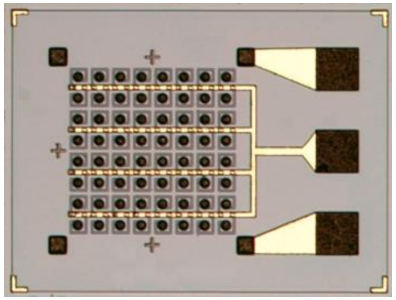
- √ SSPM(Solid-State Photo-Multiplier) : is composed of multi NFAD pixels.
- √ Backside lens was formed on substrate to increase FF(Fill Factor).
- √ Each pixel has a corresponding quenching resistor.
- √ The current from each pixel is summed.
- √ Some pixels experience an avalanche event, but adjacent pixels that do not have an avalanche event stay on standby. These pixels act quickly when a photon is incident on that pixel.



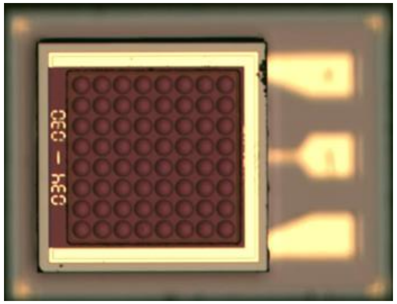




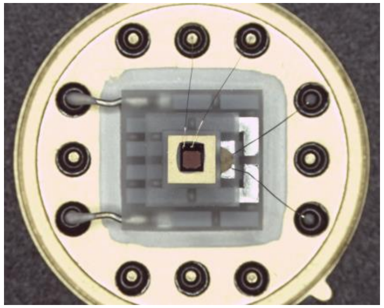
Chip(front)



Submount/Carrier



Chip-on-Carrier



TO8 header

SPAD-based SSPM design consideration

√ WSSPM(W: Wooriro) uses InGaAs as its absorption layer and InP as multiplication layer.

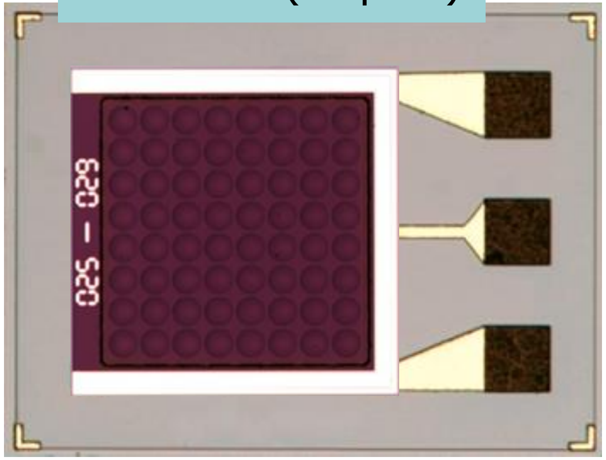
√ WSSPM uses hundreds of SPAD and the corresponding resistor chips as micro-pixel elements.

√ WSSPM employs isolation etching to reduce crosstalk among pixel elements.

√ WSSPM increase FF(Fill Factor) by forming the backside InP-lens directly on the back InP substrate.

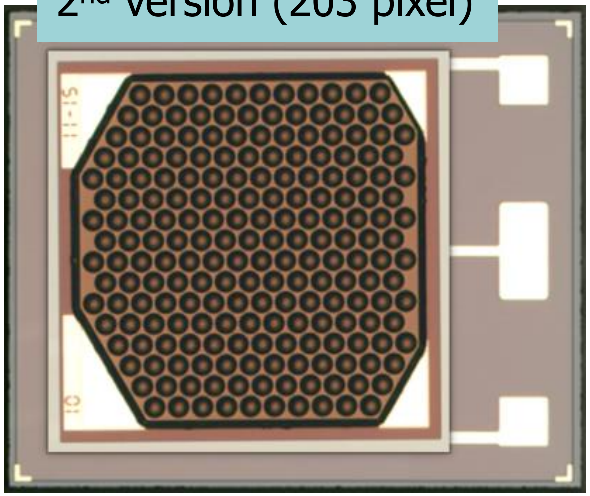
√ Since the active size can be reduced due to the BS-lens, the performance such as PDE and Afterpulse of the pixel SPAD can be improved.

1^{st} version (64 pixel)



- Pixel pitch : 51 μm
- Lens diameter : 48 μm
- FF ≅ 69% (100% light collection in the lens)

2^{nd} version (203 pixel)



- Honeycomb structure [Regular Hexagon unit cell]
- Lens diameter : 48 μm
- FF ≅ 80% (100% light collection in the lens)

SPAD-based SSPM design consideration

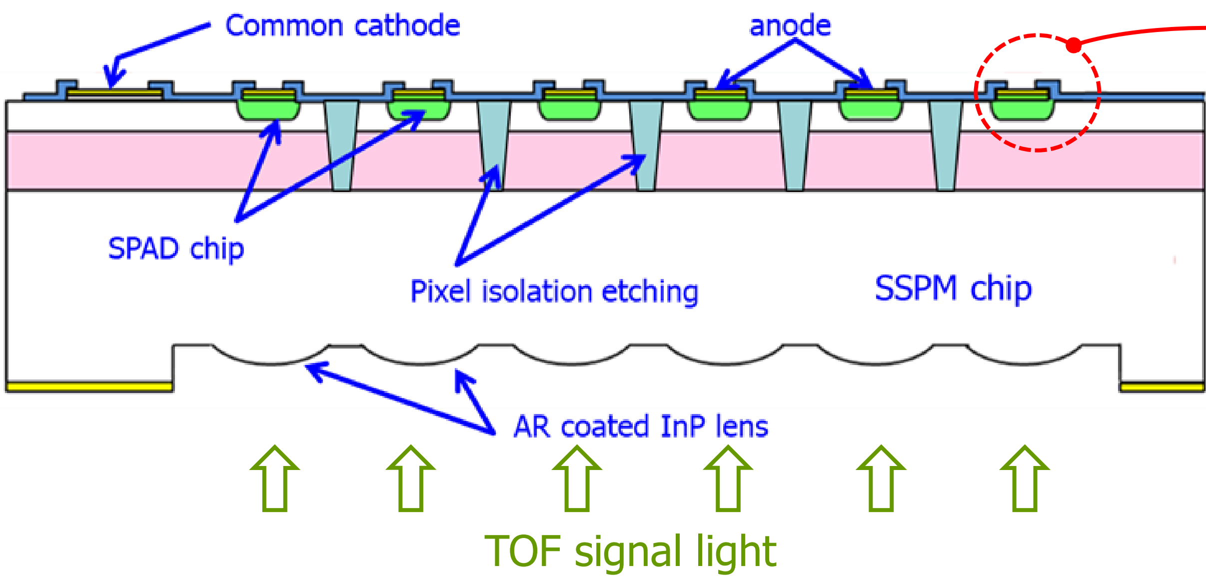
√ All the pixel chips have their own anode metal and mirror metal, respectively.

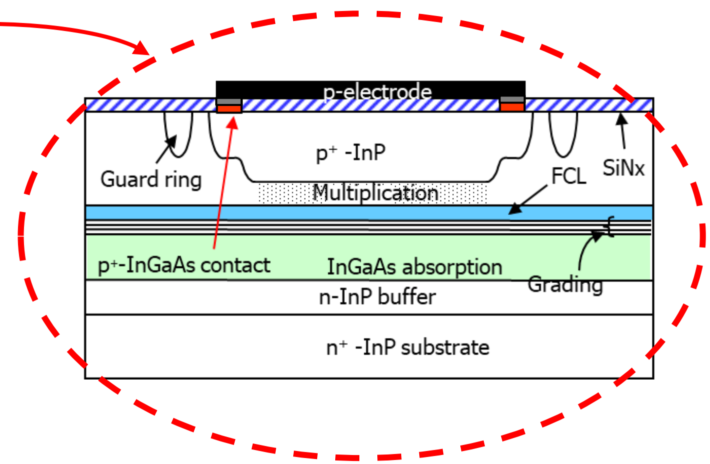
√ Except for the anode and cathode contact metals, all areas on the front side of the chip are protected with SiNx.

√ Every SPAD chip has its own FGR.

√ All SPAD chips have absorption regions separated from each other by separation channels formed by wet chemical treatment after dry etching.

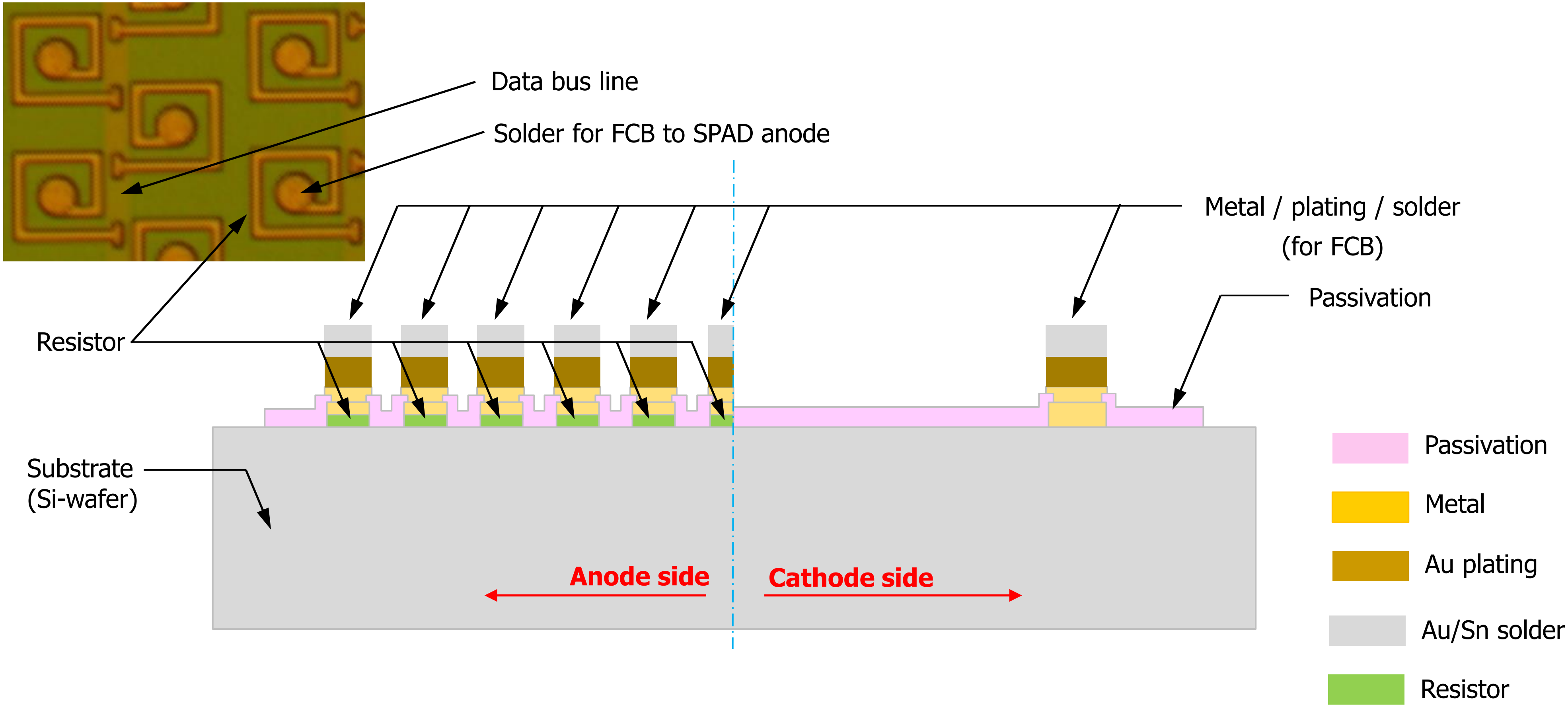
√ Isolation-etched surface is passivated with SiNx thin film and the etched area is filled with polyimide.





SPAD pixel unit

SPAD-based SSPM design : Si-submount



√ The resistor is made of polysilicon and is formed on p-Si with high resistance.

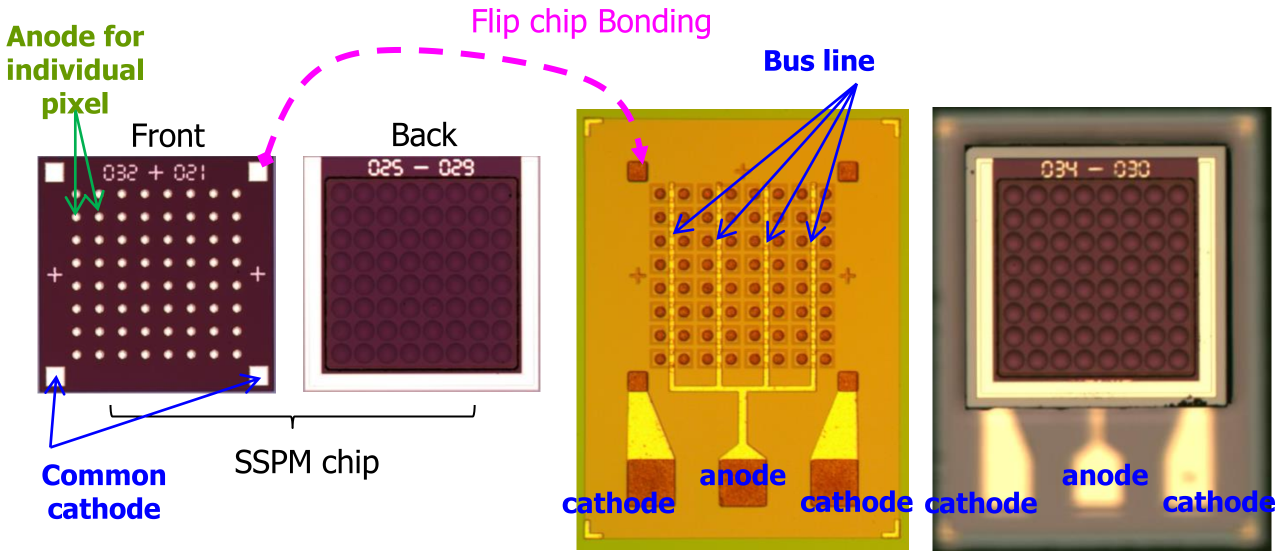
√ The resistivity is controlled by boron implantation.

√ There exists SiO2 between Si-Substrate and polysilicon resistor.

√ The magnitude of resistor can be changed by changing the width or length of the line. 2MΩ was best in our case.

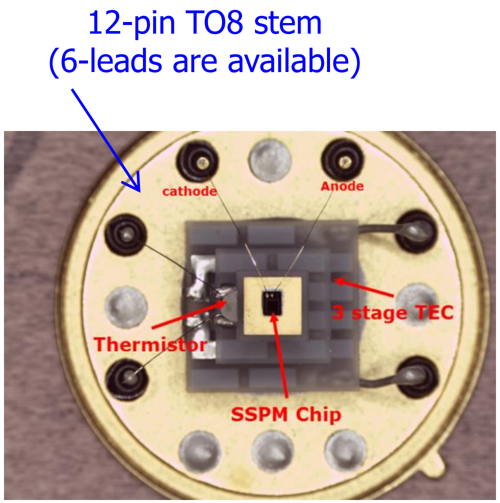
SSPM CoC and Module fabrication (64-pixel)

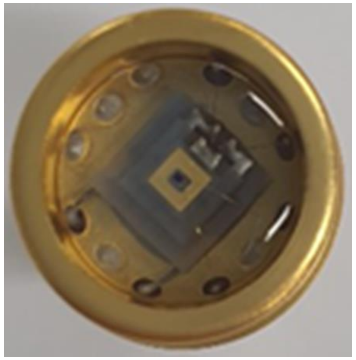
- √ The role of bus line is to sum the signals and to supply common bias(or GND) to anodes of each pixel.
- √ Flip-chip bonding of SSPM chip and submount is carried out.
- √ The CoC is mounted on TO8 header with 3-stage TEC and thermistor.
- √ Window cap sealing by resistance welding for hermetic and chip protection.



Silicon submount

Flip-chip bonded CoC





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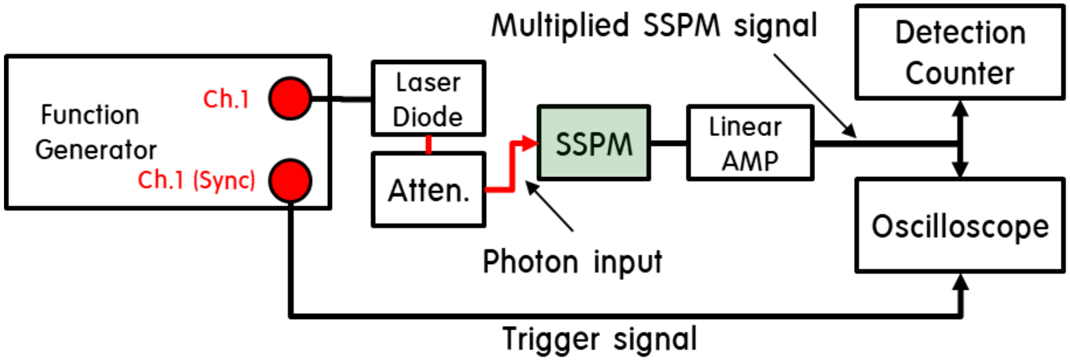
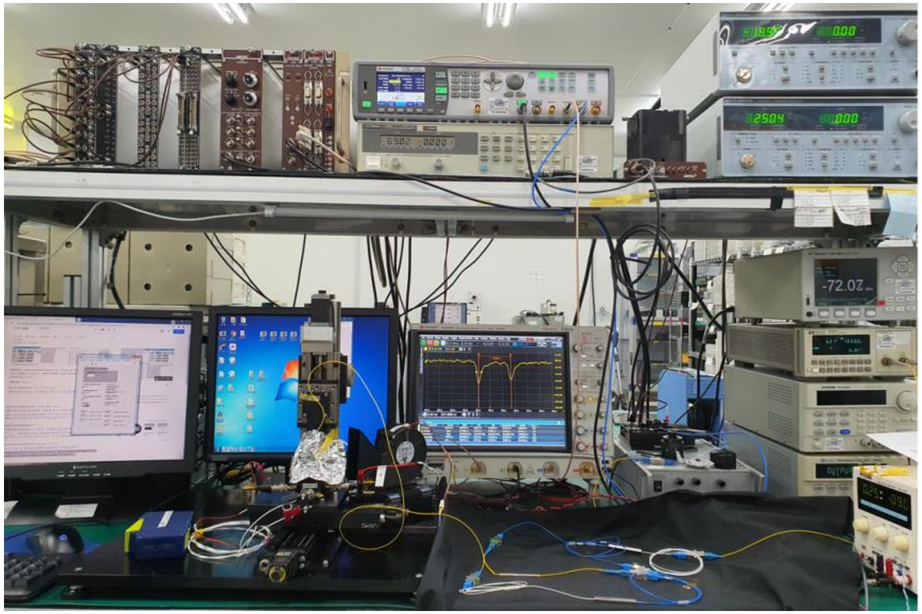
64-pixel SSPM Test

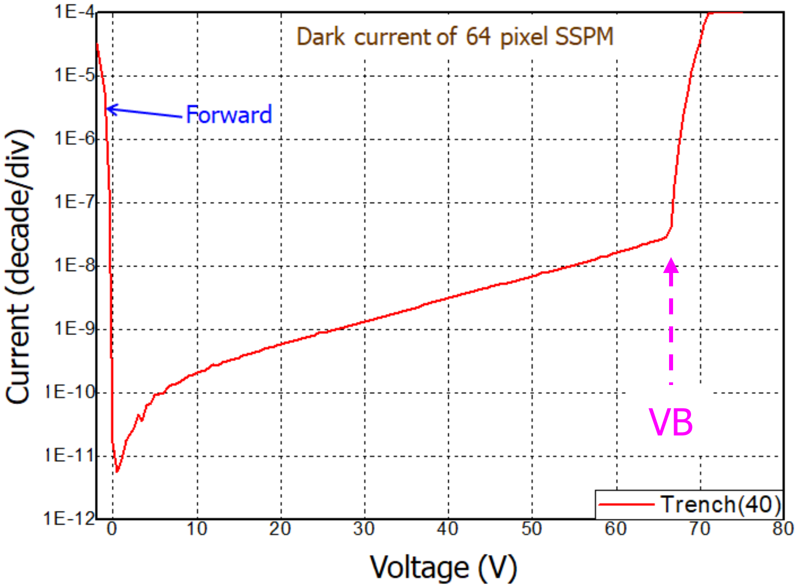
Block diagram of test set-up



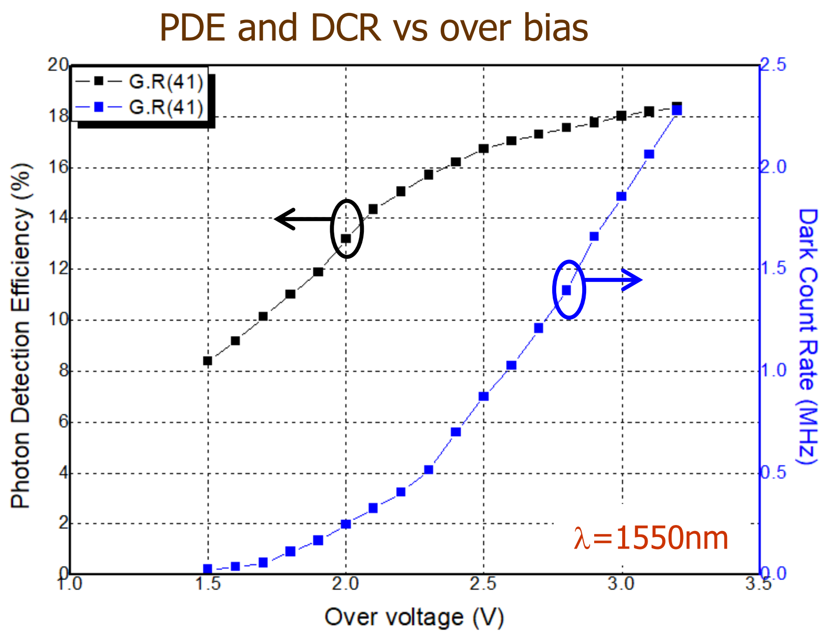
Test equipment

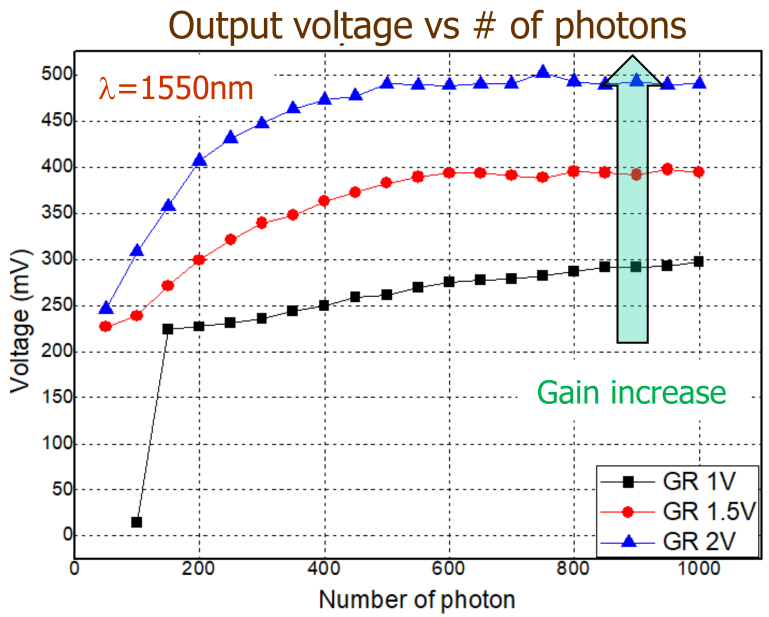


- √ Photon incidence through 62.5μm MMF without any beam steering.
- √ Overbias(V_{apply} - VB) was controlled 2.0 or 2.5V for the performance optimization.
- √ Breakdown voltage was defined by the curvature of dark current.
- √ Averaged dark current of unit pixel : ~ 20nA/64pixels ≅ 300pA at RT



PDE, DCR and linearity of 64-pixel SSPM





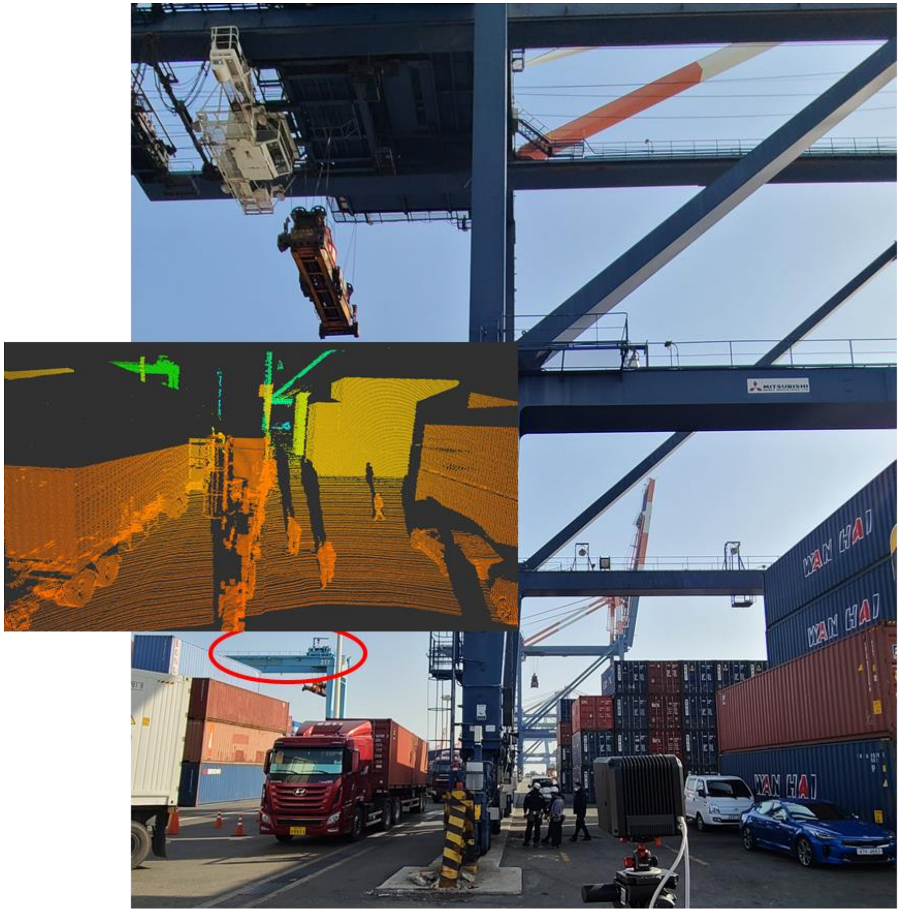
√ DCR is not bad even at 18% of PDE.

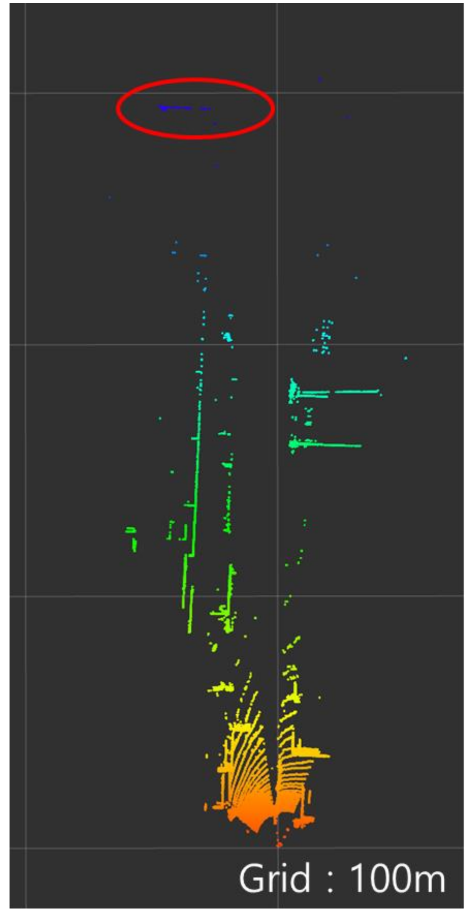
√ The photon number resolving range is small ⇒ because # of pixel is small

√ **New design ⇒** Increase # of pixels / Increases the distance between active region and trench mesa surface / Decrease active size / Increase FF (honeycomb arrangement of pixel)

Point cloud 3D image (64-pixel SSPM)

(Outdoor Application)



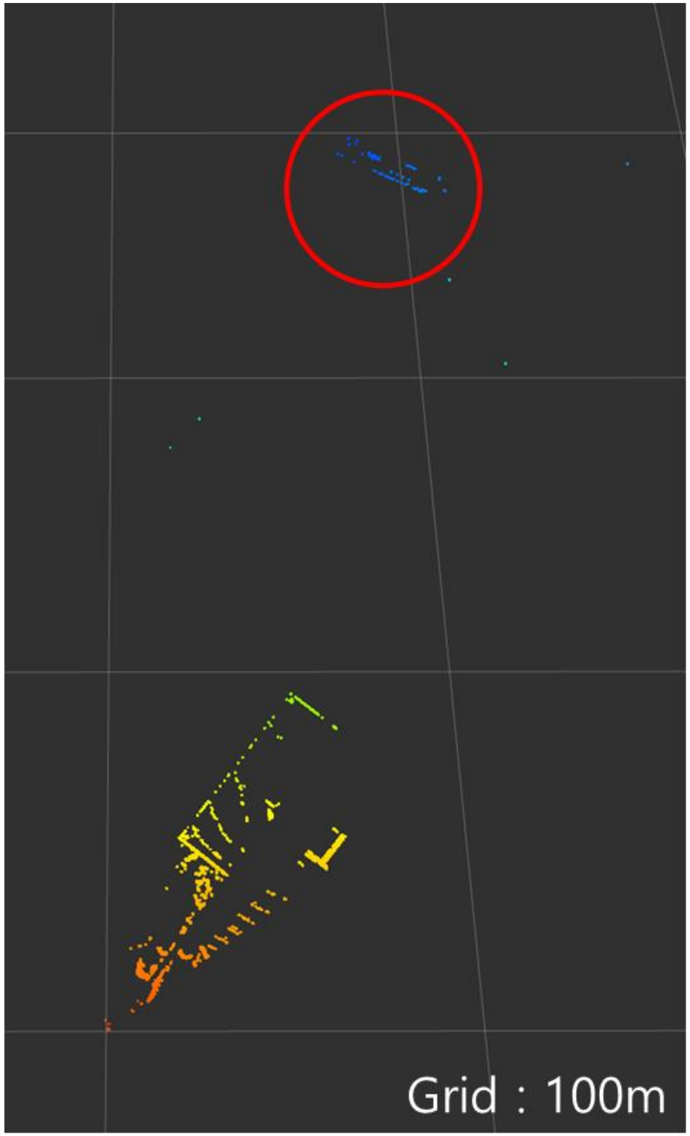


√ Point cloud 3D images were generated by SOS Lab (LiDAR-related start-up company) using 64-pixel SSPM.

√ A 200-pixels WSSPM will show better performance, but 3D point cloud tests were not done yet.

Point cloud 3D image (64 pixel SSPM)

(Outdoor Application)



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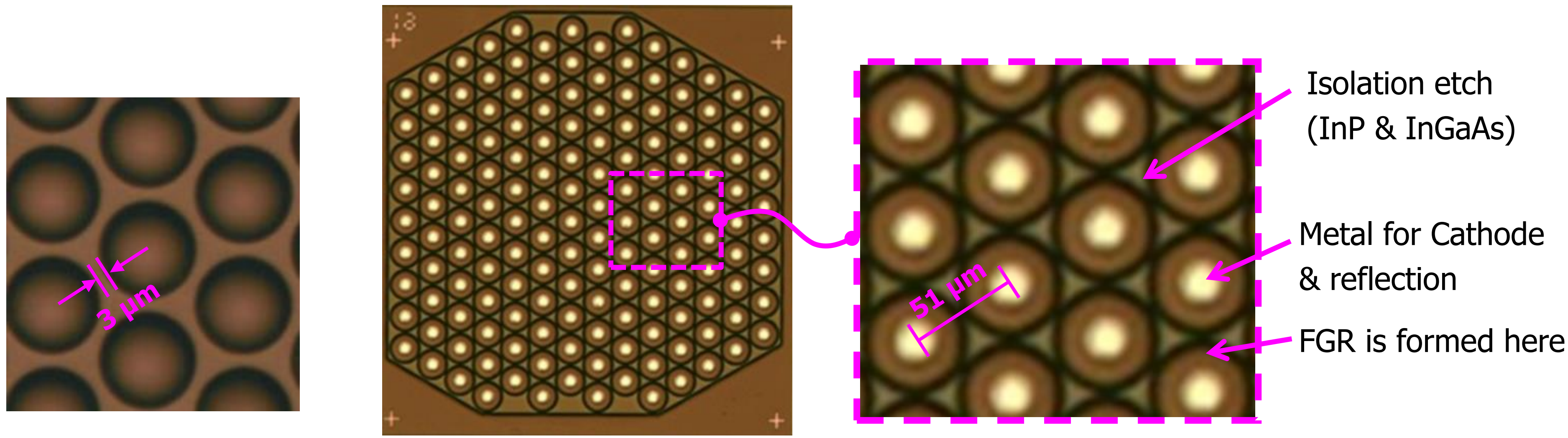
SPAD-based 203 pixel SSPM (honeycomb arrangement)

- √ 64 pixels ⇒ 203 pixels of NFAD.
- √ Honeycomb arrangement of pixels.
- √ FF of the new SSPM is increased from 69% to 80% by lens arrangement in honeycomb structure

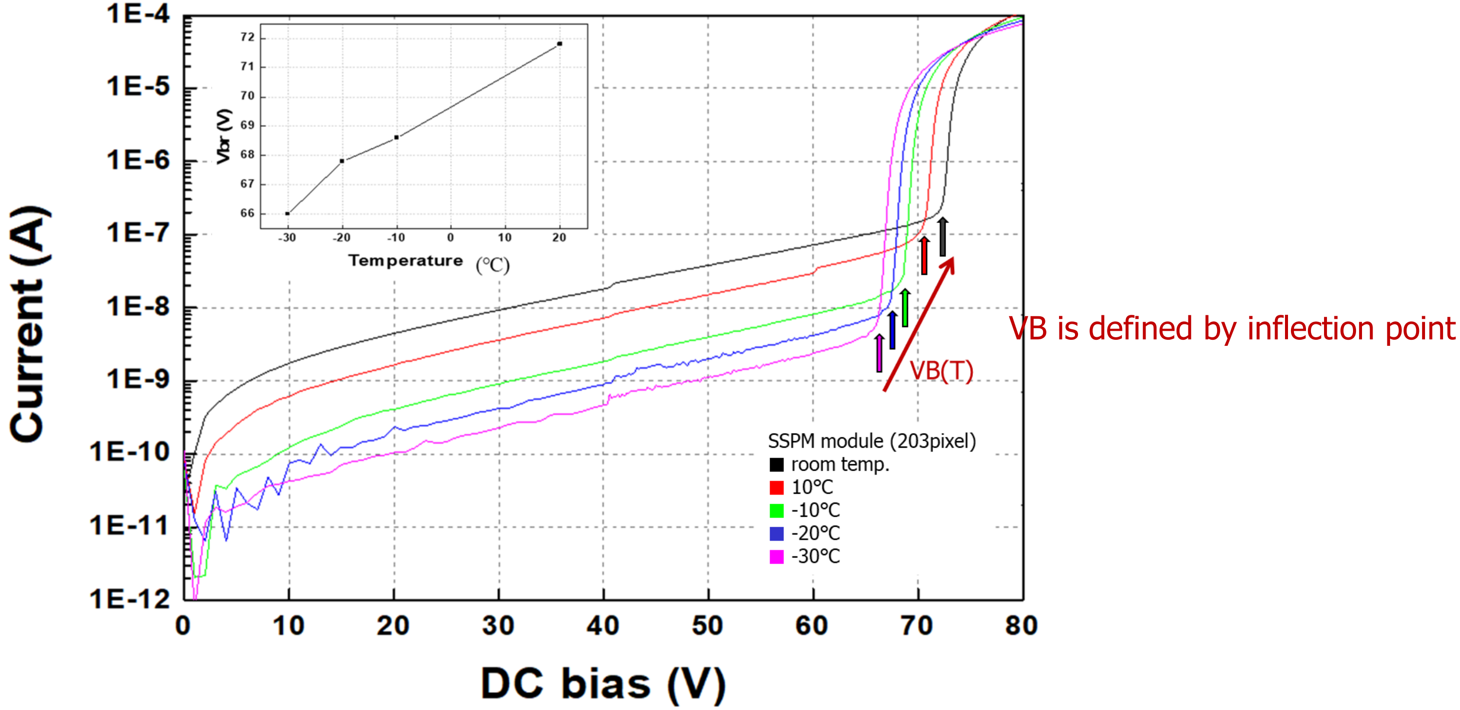


Backside lens image | Chip front image | Chip front image

FIG. Honeycomb arrangement of SSPM Pixels

SPAD-based 203 pixel : Dark current

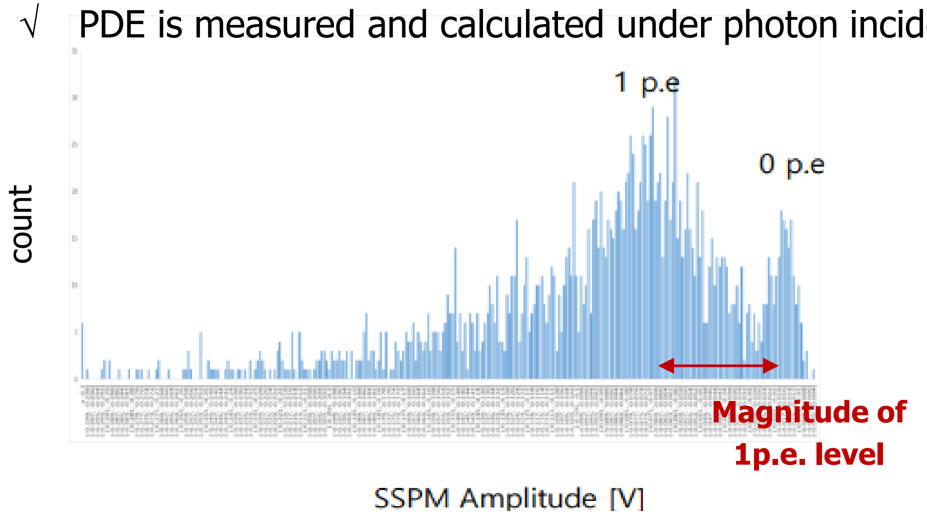
- √ At voltages above VB, the total resistance is ~ 2MΩ/200 ≅ 10kΩ if individual resistors have 2MΩ.
- √ Temp. coefficient was measured ~ 117 mV/°C

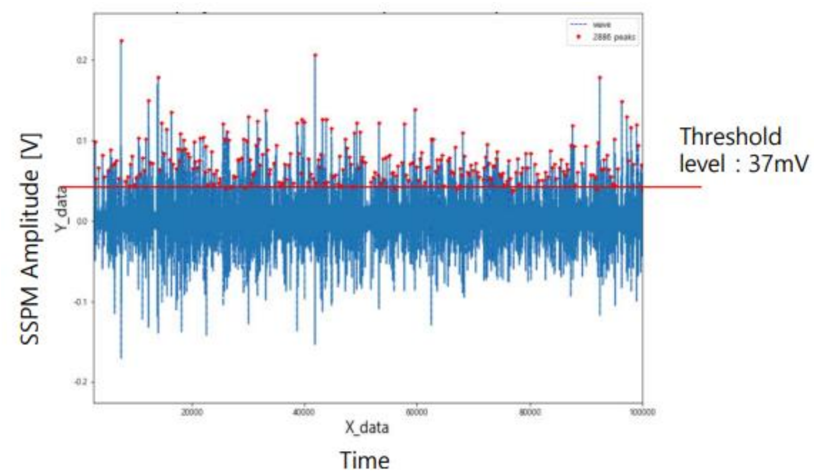


Vbr [V]				Dark current [A] @0.9Vbr				Temp. coeff. [V/℃]	
RT	-10℃	-20℃	-30℃	RT	-10℃	-20℃	-30℃		
71.8	68.6	67.8	66	9.77E-8	9.33E-9	4.48E-9	2.24E-9	**0.117**	⇨ I_D(203-pixel)
				480 pA	46 pA	22 pA	11 pA		⇨ I_D(single pixel-Average)

SPAD-based 203 pixel : PDE and DCR

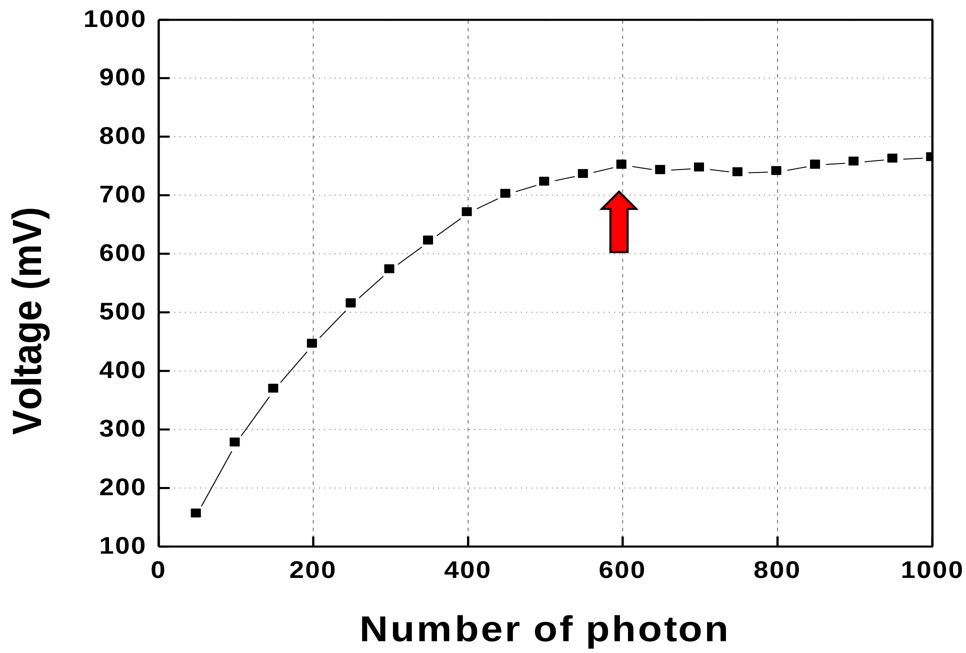
- √ To measure PDE and DCR, the magnitude of the output level(1-p.e.) for single photon is measured. For ex., sample #6 has 74 mV of 1-p.e. level.
- √ Threshold voltage for discrimination is taken as a half of 1-p.e. In this case V_{th} =37 mV
- √ DCR is counted without photon incidence.
- √ PDE is measured and calculated under photon incidence. PDE ~ 25.6% @17.7MHz of DCR





Sample #	TEC Temp. [°C]	V_{bias} [V]	Number of Photon	1 p.e. Level [mV]	PDE[%]	DCR*[MHz] (Threshold Level 0.5p.e)
6	-20	68.7	7.8	64	18.7	5.5
		69.2	7.8	74	25.6	17.7
14		68.67	15.9	46	10.8	9.5
		69.66	7.8	70	16.9	10
		70.26	6.98	70	23.1	11

Photon number resolving result of 203-pixel SSPM

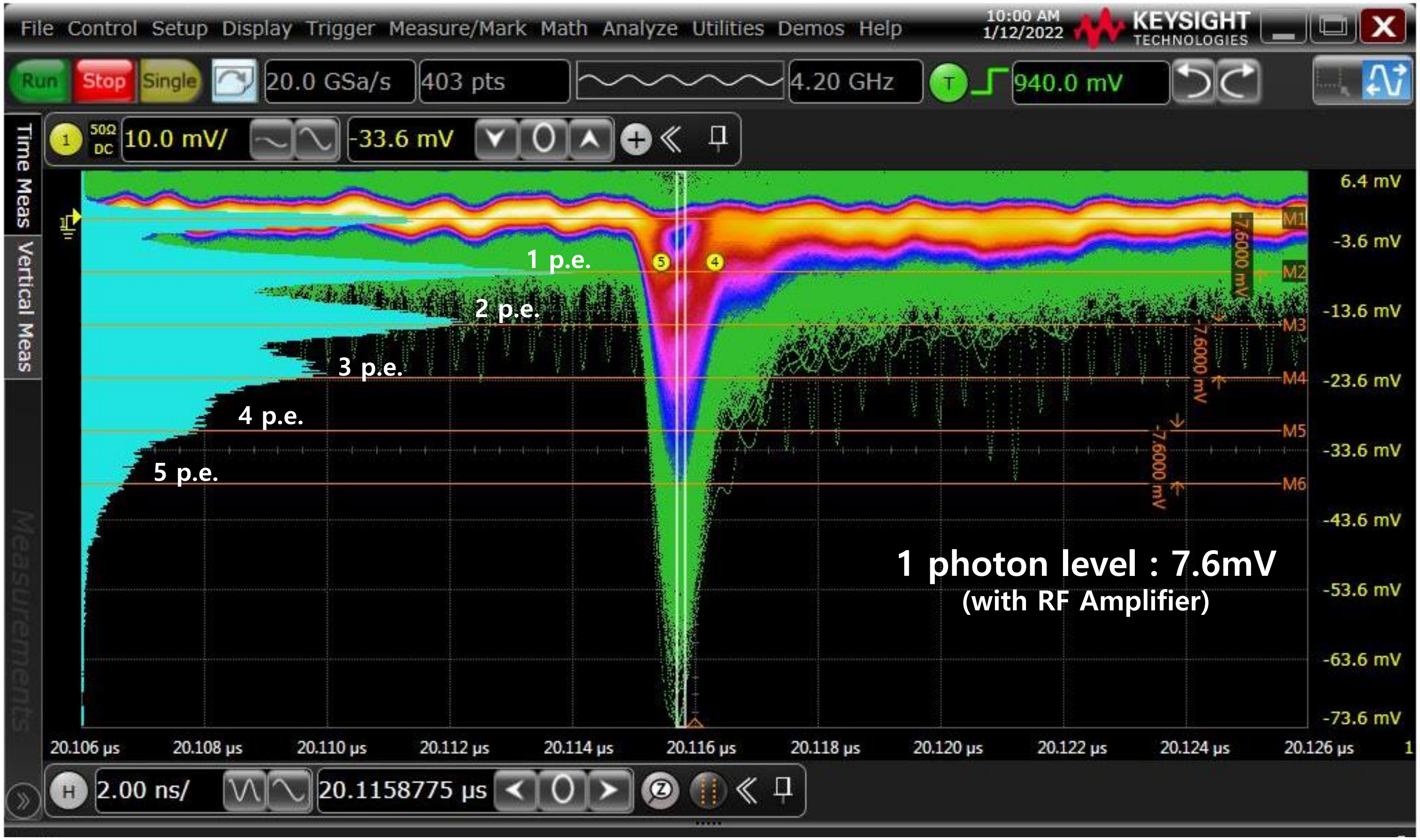


√ The maximum number of photons that can be counted is 600 for a 203-pixel SSPM.

√ We can say that as a photon number resolver, the linearity improves as the number of pixels increases.

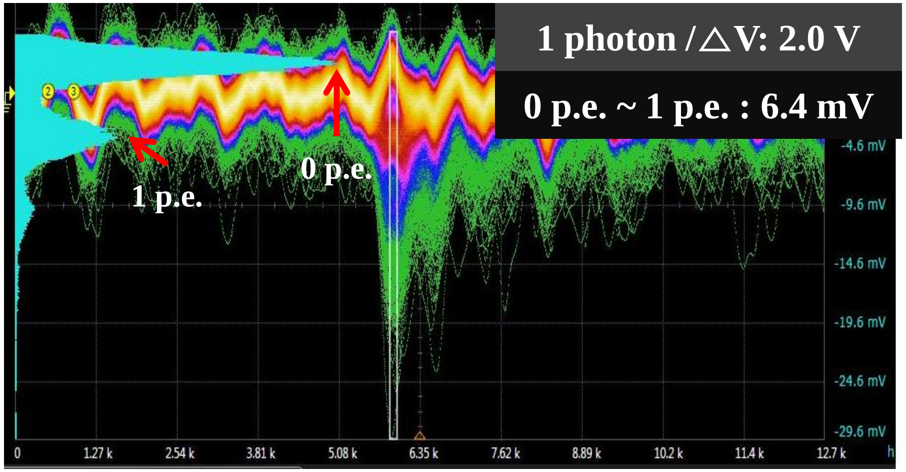
Photon number resolving performance of 203 pixels SSPM

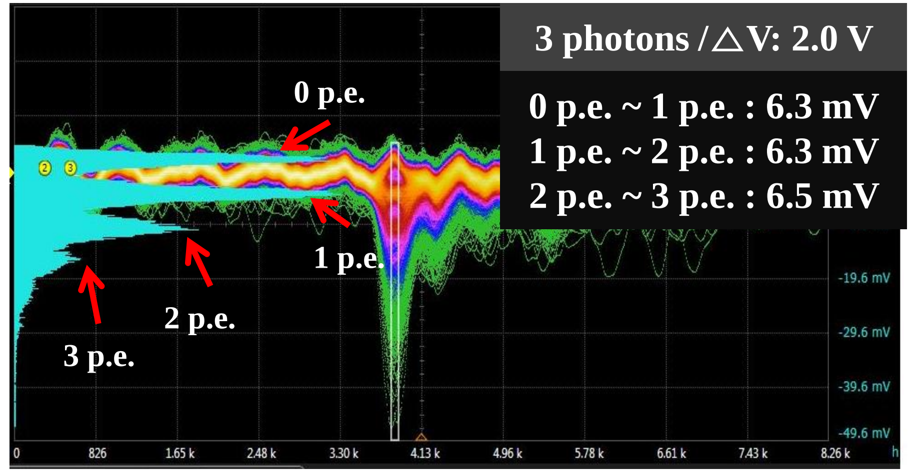
Optical Input : 280ps / 100kHz / 5 photon
Over bias : 2.5V
TEC surface temperature : -20°C

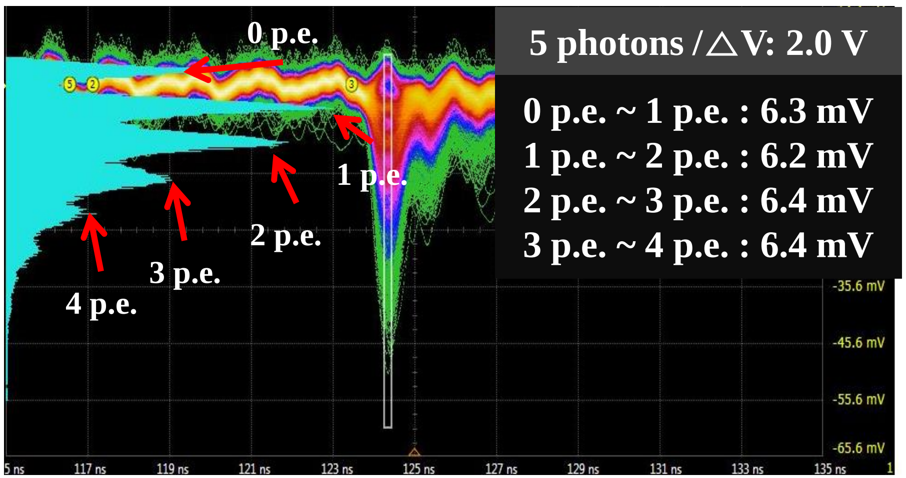


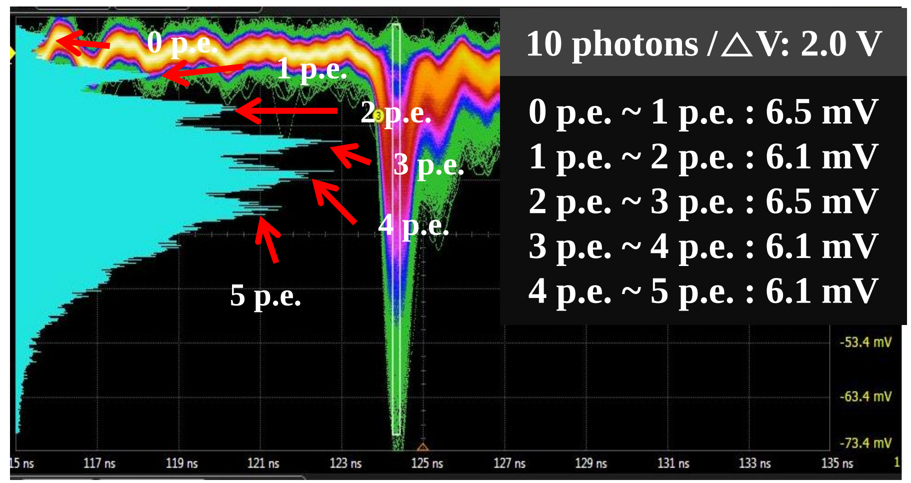
Photon number resolving performance of 203 pixels SSPM

Optical Input : 280ps & 100kHz / Over bias : 2.0 V / TEC surface temperature : -20°C









1. SSPM can count photon number
2. The amplitude of SSPM output increases if # of incident photons increase.
3. Can obtain intensity information from analysis of cumulative statistics.

Summary and future works

Summary

- √ InGaAs SPAD-based SSPMs with excellent performance were successfully fabricated.
- √ SSPM is composed of InGaAs-SPAD chip array and resistor chip array fabricated on Si-substrate.
- √ The 2nd ver. of SSPM(203 pixels) showed 25.6% of PDE @ 17.7 MHz DCR.
- √ The 2nd ver. of SSPM was not applied to 3D LiDAR Rx, yet.
- √ A 3D point cloud image of an object 300 meters away was successfully obtained by using the 1st ver. of SSPM(64-pixel).

Further Works

- √ More compact and smaller pixel to optimize PDE and DCR.
- √ Reliability study and failure analysis.

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Thank you very much for your attention