HSTD11 & SOIPIX2017
OIST, OKINAWA
11th International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking Detectors (HSTD11) in conjunction with 2nd Workshop on SOI Pixel Detector (SOIPIX2017)
Dec. 11 (Mon) - Dec. 15 (Fri), 2017
Okinawa Institute of Science and Technology Graduate University (OIST), Okinawa, Japan

Prototype of a 250 μm Pitch 36-channel SiPM Array Using SOI Technology for Photon Counting CT

Akihiro Koyama[1], Kenji Shimazoe[1], Hiroyuki Takahashi[1], Ryutaro Hamasaki[2], Tohru Takeshita[3], Ikuo Kurachi[4], Toshinobu Miyoshi[4] Isamu Nakamura[4], Shunji Kishimoto[4],Yasuo Arai[4]

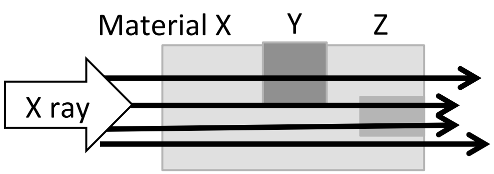
[1]The University of Tokyo
[2]The Graduate University for Advanced Studies
[3]Shinshu University
[4]High Energy Accelerator Research Organization

Outline

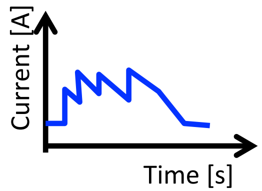
- ✓ Introduction
- ✓ Device Design
- ✓ Measurement Results
- ✓ Conclusion

Hard X-ray (20-120 keV) imaging

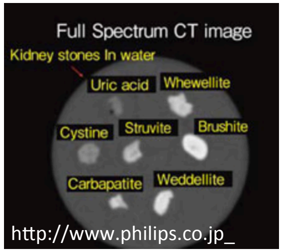
- Conventional medical X-ray Computed Tomography (CT)
  - Integrate all transmitted X-ray's energy and calculate attenuation coefficients

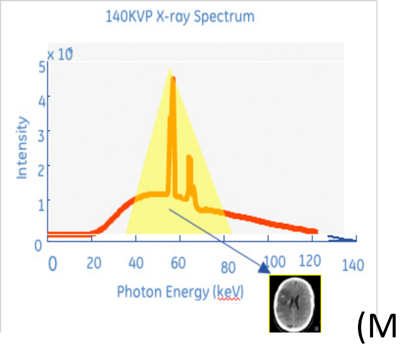


Energy integration



Monochromatic





Density information
(Morphological feature)

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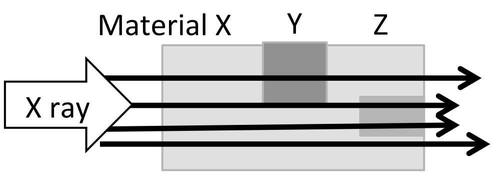

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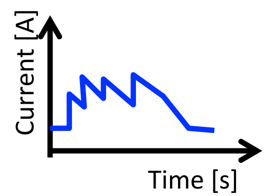

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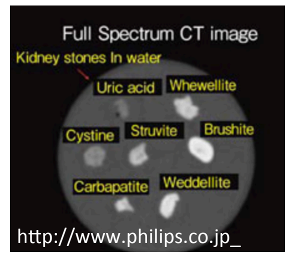

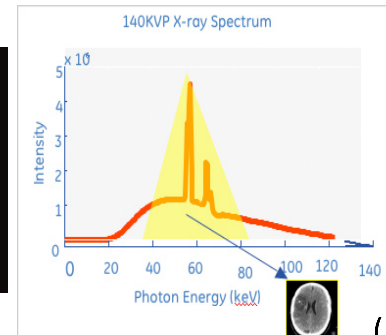

Density information
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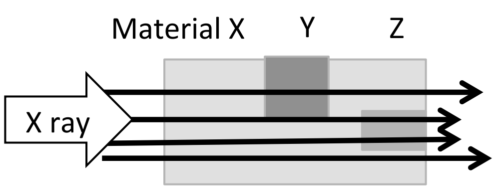
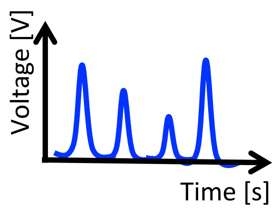
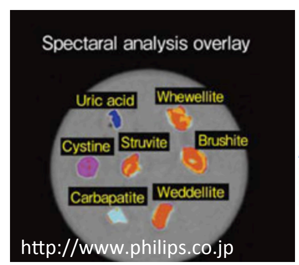
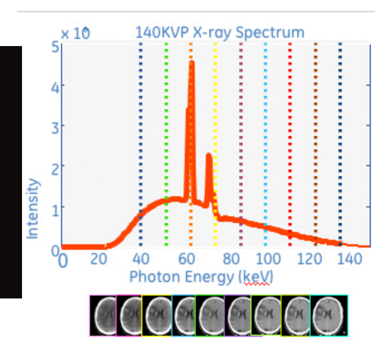
- Photon counting Computed Tomography (PCCT)
  - Discriminate each transmitted X-ray's energy and provide spectrum information

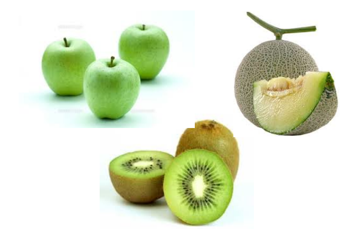


Pulse counting









Material information

→ Attenuation characteristics at each energy depends on materials

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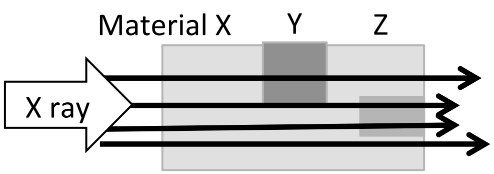

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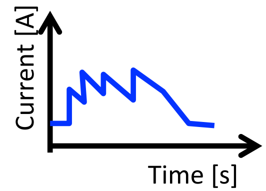

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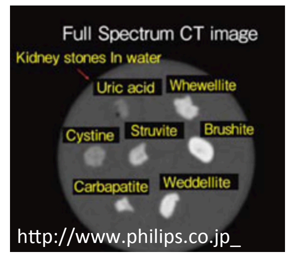

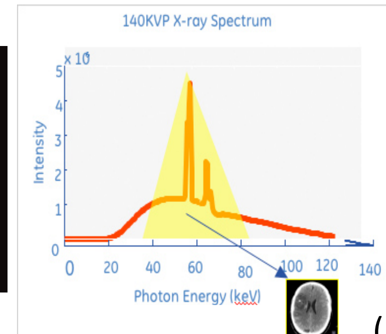

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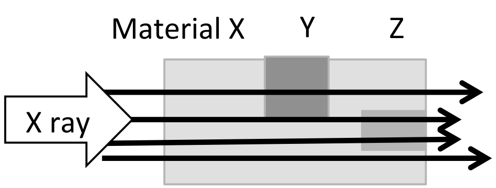

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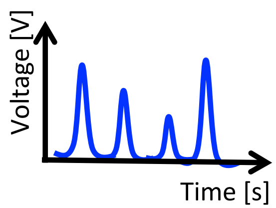
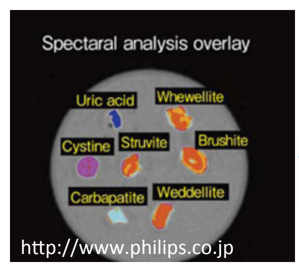
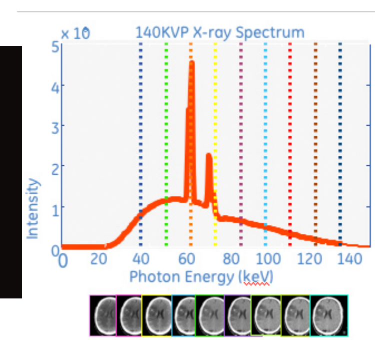
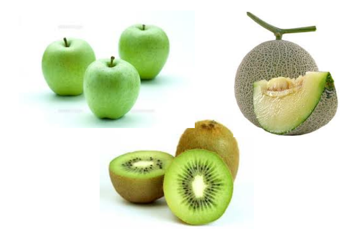




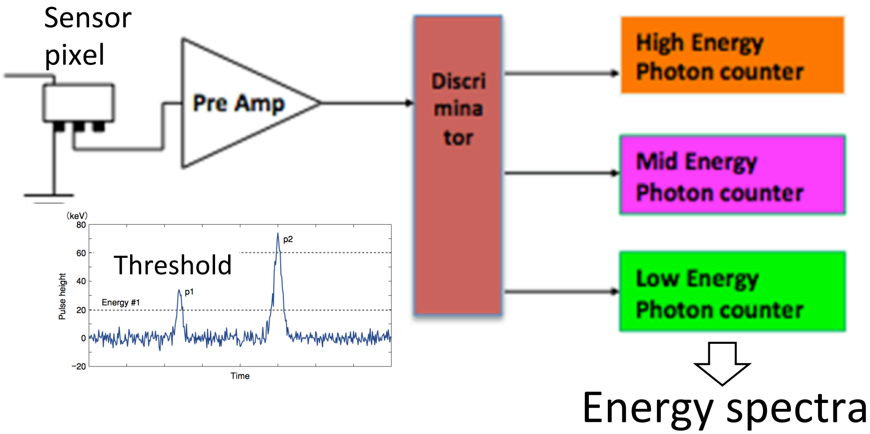


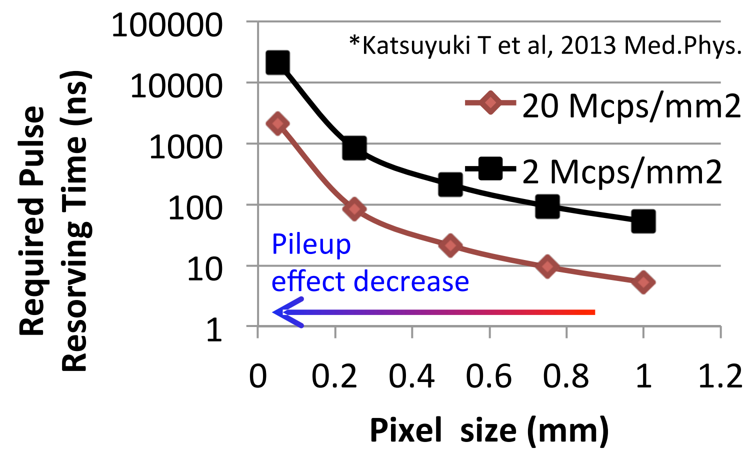


Material information

Inspection of material composition in the object by spectrum shape analysis
Contrast enhanced image can be achieved at low radiation dose

The principle of X-ray photon counting

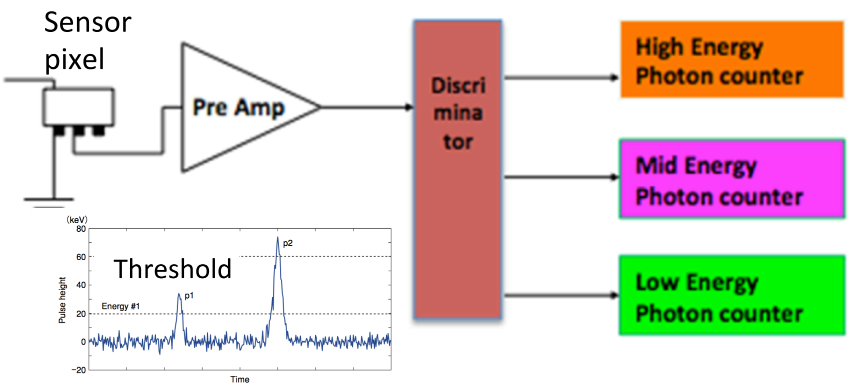


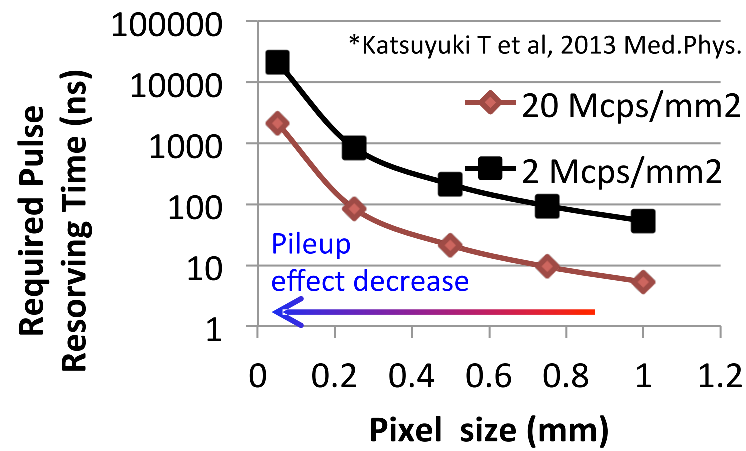


Pixel size: One factor that greatly affects count rate performance

The smaller pixel size, the less spectra deterioration due to pile up effect

The principle of X-ray photon counting





Desirable events

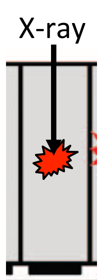
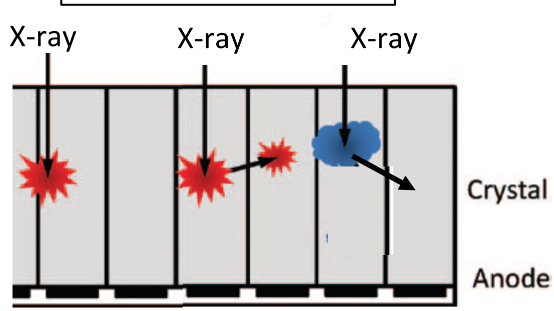


Photo absorption

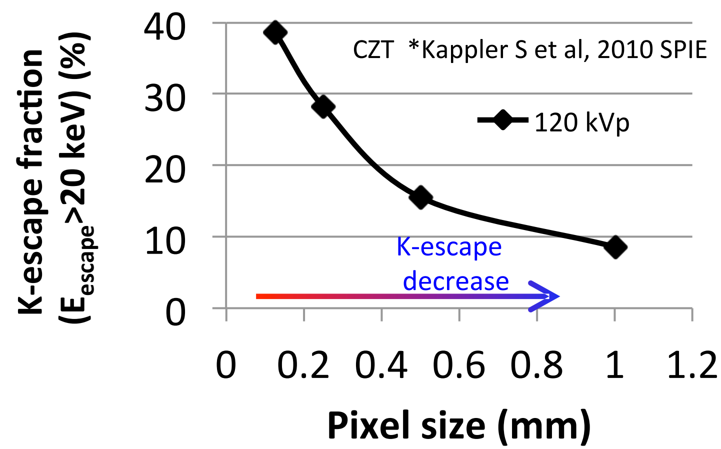
Undesirable events



Interaction near boundary

K-Escape

Compton Scattering



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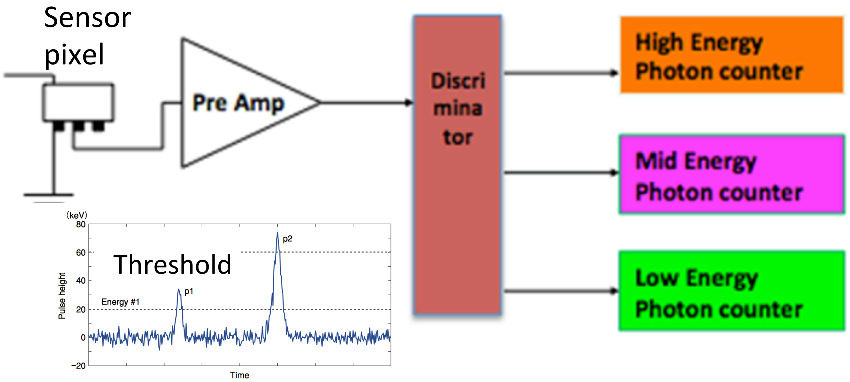

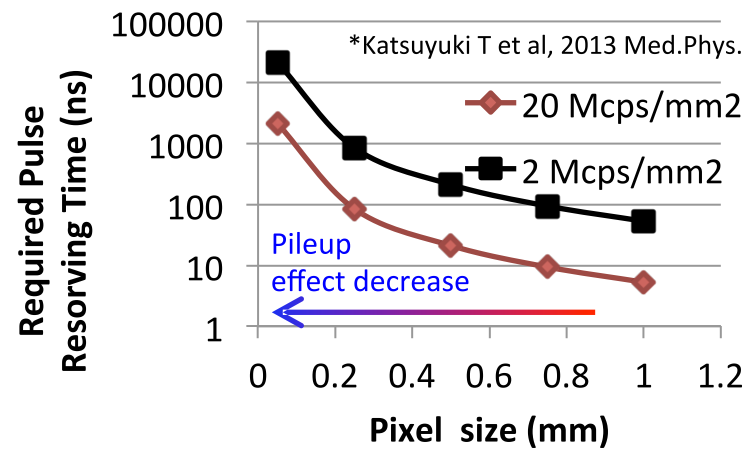

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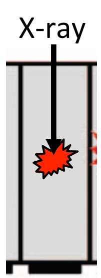

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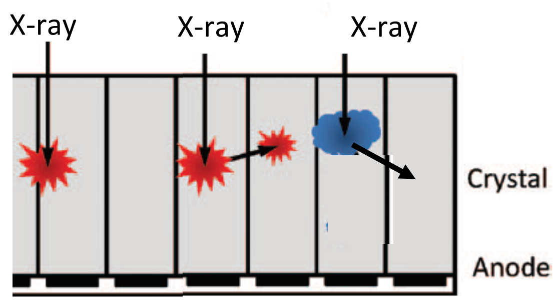

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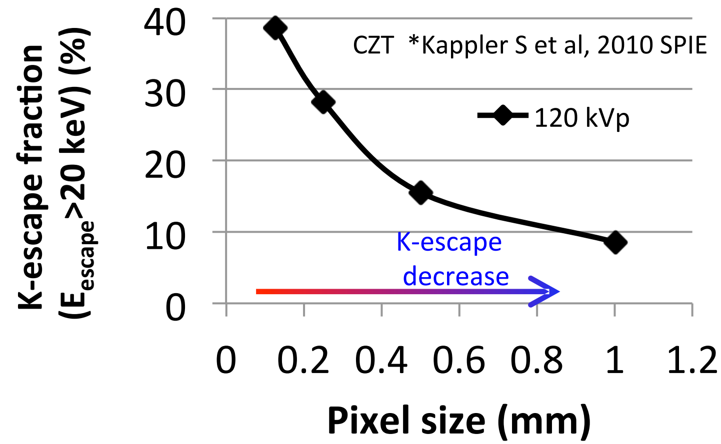
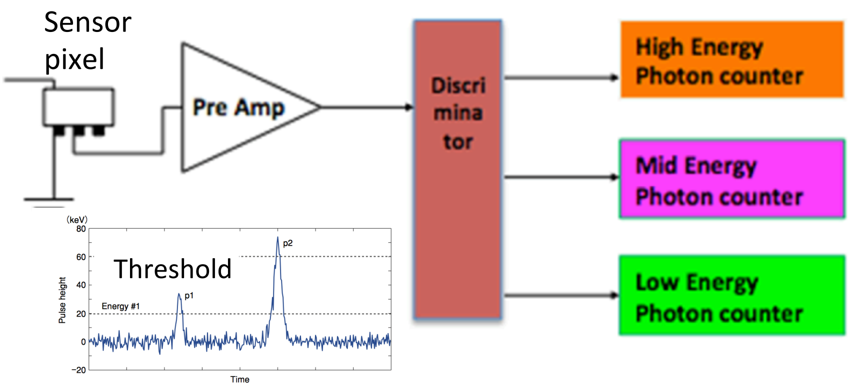
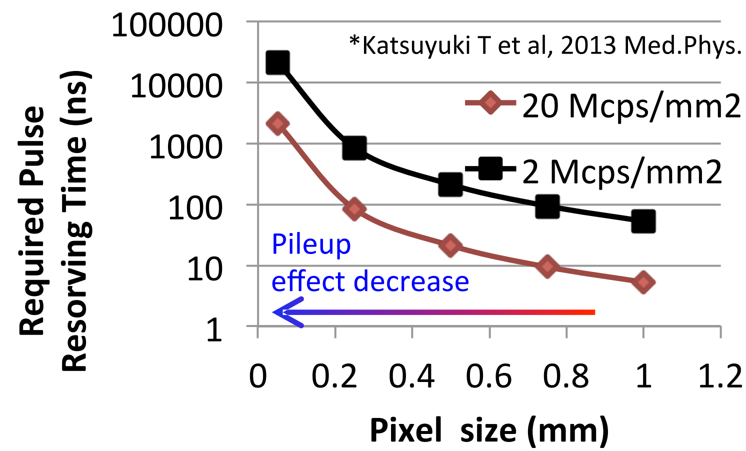
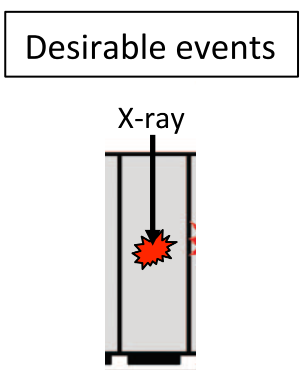


A small pixel size is not always desirable since the spectra would be degraded due to the charge sharing, K-escape x-ray, and Compton scattering

The principle of X-ray photon counting







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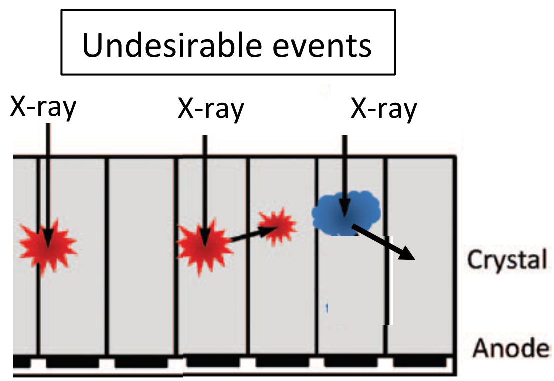

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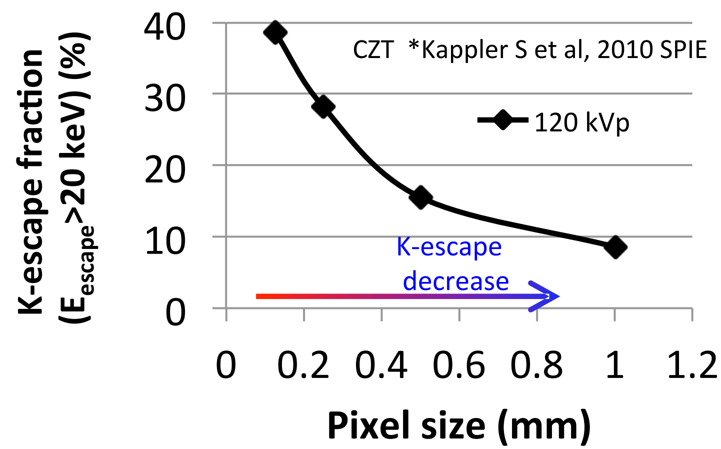

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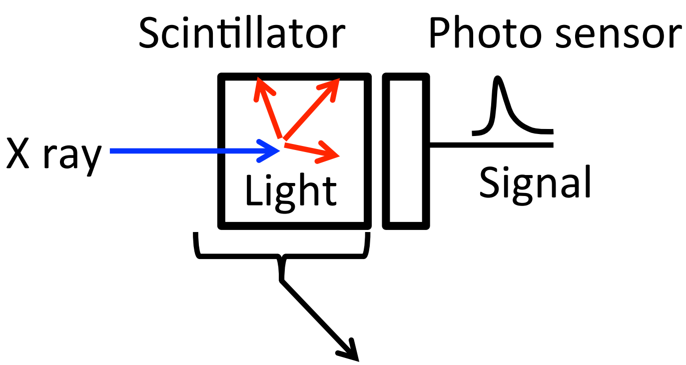
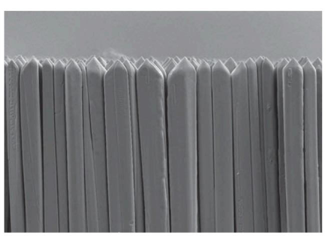
→ Target value is 2 Mcps/mm^2 with pixel size of 0.2-0.5 mm

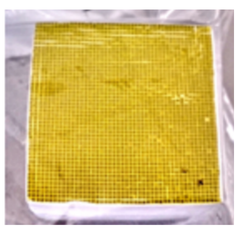
Indirect conversion detector

- Detector system of clinical X-ray CT : Scintillator + Photo sensor

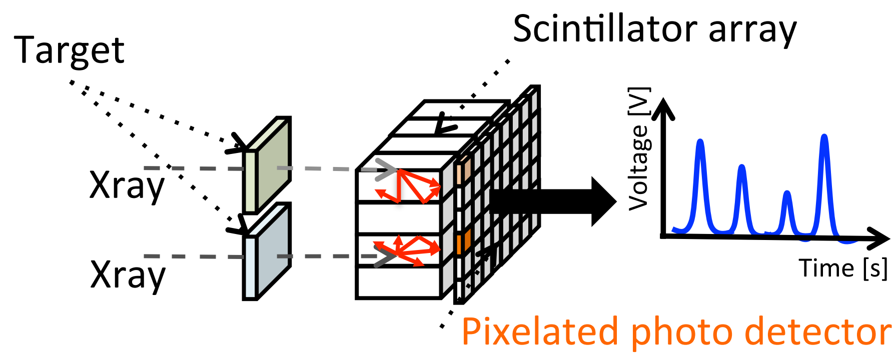




Columnar CsI
~ 10μm pitch

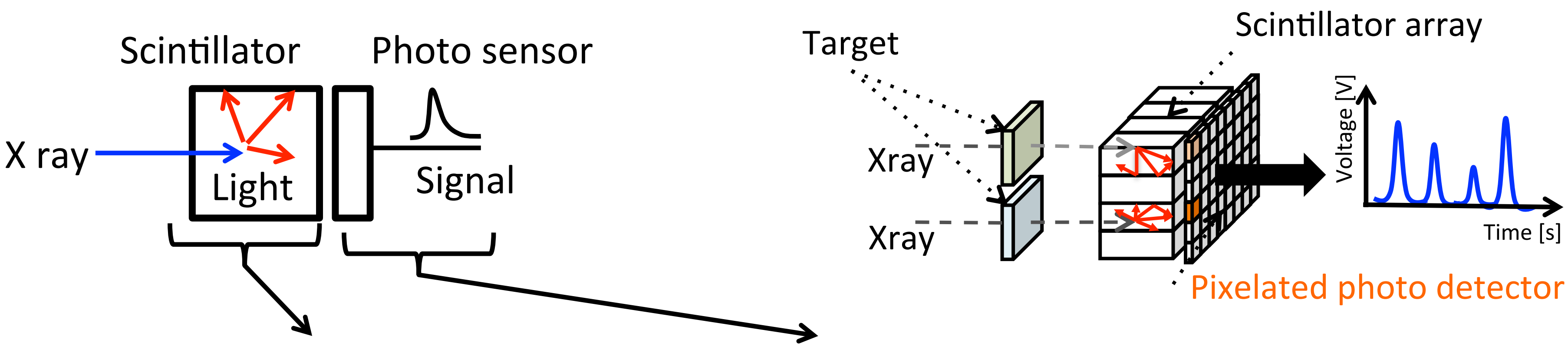


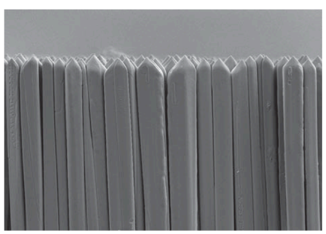
$Gd_3Al_2Ga_3O_{12}$
~250 μm pitch



Indirect conversion detector

- Detector system of clinical X-ray CT : Scintillator + Photo sensor
- How to achieve X-ray photon counting ?





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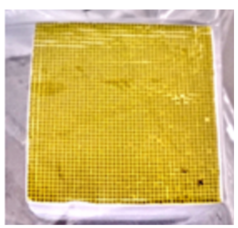

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Photo sensor Requirements

- ✓ High sensitivity to weak light
- ✓ Fast response (< 1 µs)
- ✓ Small pixel availability (< 0.5 mm)

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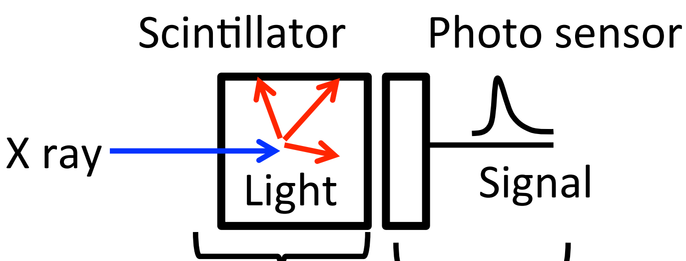

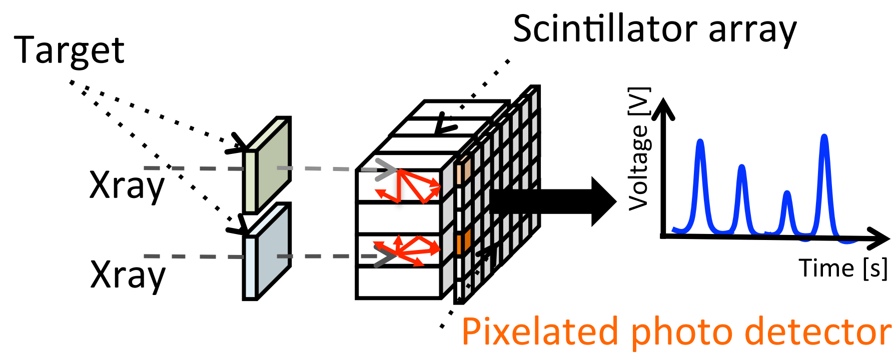

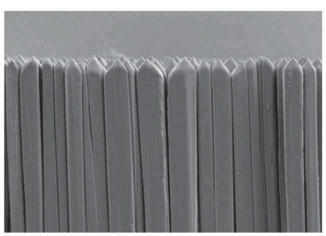

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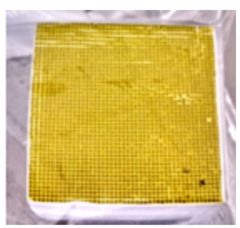

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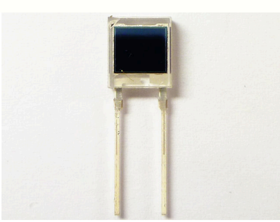
Small pixel size availability and high detection sensitivity are required for photo sensor to read light output of sub-mm pitch scintillators

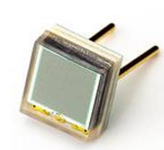
Silicon Photomultiplier (SiPM)

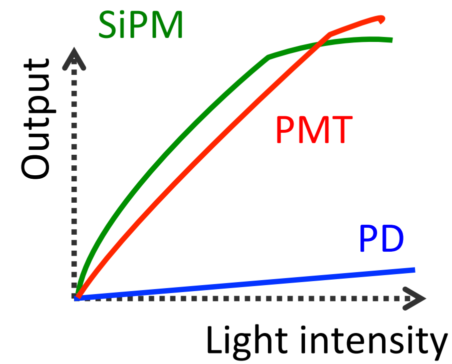
- In order to minimize photo sensor size ....
- Silicon base sensor has attractive features for small pixel size, while photo diode has worse sensitivity (no internal gain) toward weak light
- Silicon photomultiplier (SiPM)

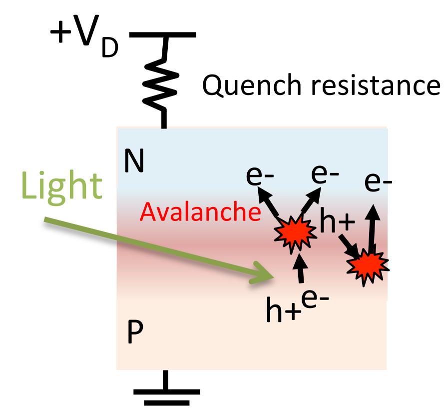
→ achieves photo electron multiplication characteristics (avalanche) by operating photo diode at higher voltage than breakdown voltage

	Photo Multiplier Tube (PMT)	Silicon PIN Photo Diode (PD)	Silicon Photomultiplier (SiPM)
Gain	10^6	1	10^6
Form factor	Bulky	Compact	Compact
Sensitive to magnetic fields?	Yes	No	No
Noise	Low	Low	High
Rise time	Fast	Medium	Fast









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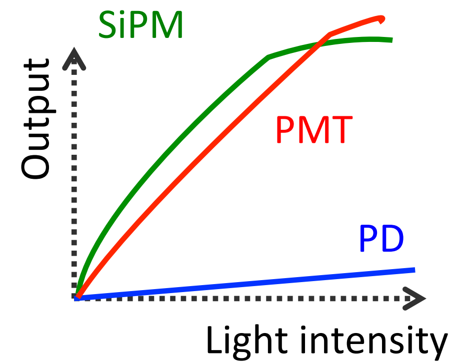
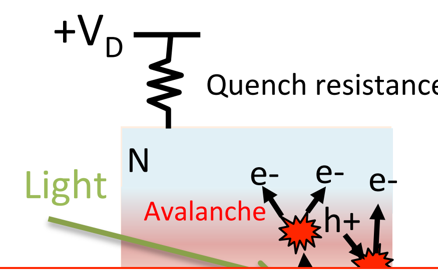
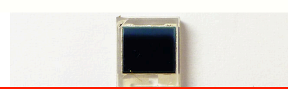




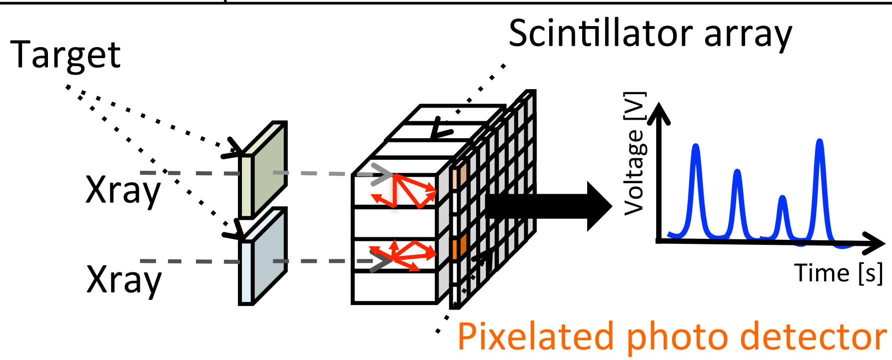


Geiger avalanche multiplication provides large gain comparable to PMT
Development of sub-mm pixel SiPM took great interests

Objective

- X-ray Photon Counting using indirect detector
  → Development of sub-mm pitch Silicon photomultiplier

Requirements	
Pulse resolution time	< 1 μs
Pixel size	< 0.5 mm
Detectable light output levels	1000 ~ 2000 photon from scintillator (GAGG:Ce)
Multiplication Gain	$10^{5\sim7}$

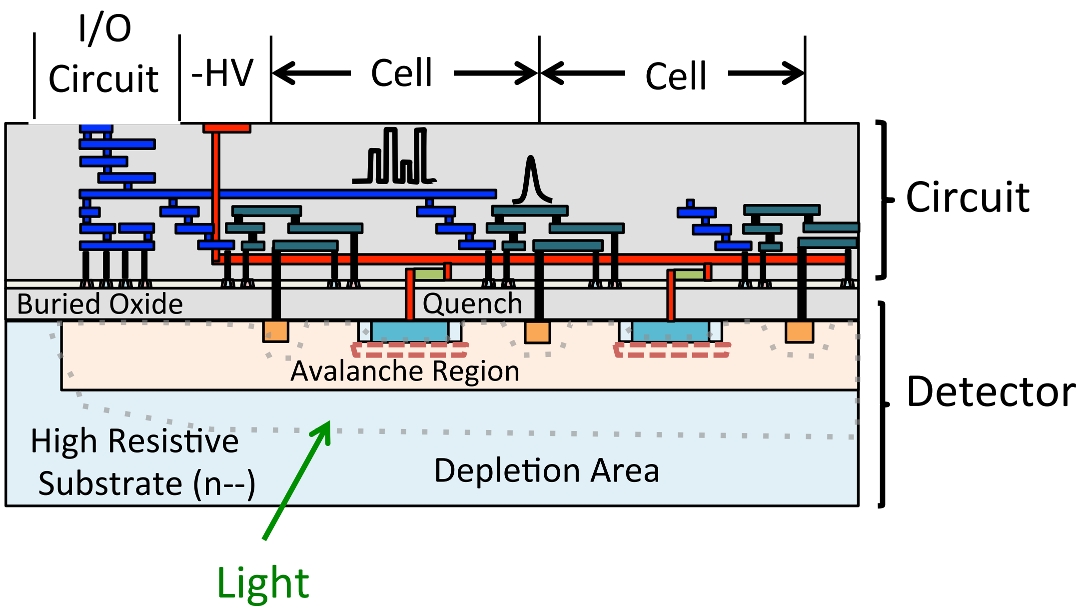


Development of low noise, fast and high sensitivity photo sensor under 1 us pulse resolution time, sub-mm pixel size and high sensitivity are needs to be achieved

Silicon on Insulator (SOI)-SiPM

For monolithic sensor design including SiPM and processing electronics....

- Silicon on Insulator (SOI)
  - Semiconductor wafer technology that separate circuit layer from bulk layer by buried oxide layer
  - By using bulk layer as detector, 3-D integrated system can be achieved



Merits of SOI-SiPM

- **High degree integration and fast response (10-20 % faster than bulk CMOS circuit)** [Y.Fukuda,, SOI-CMOS Device Technology]
- **Control power supply of circuit (30 % less power than bulk CMOS circuit)** [S.Baba, Next-generation low-power consumption SOI devices]
- **Back-illumination structure availability (10-20 % higher detection efficiency than bulk CMOS wafer)**

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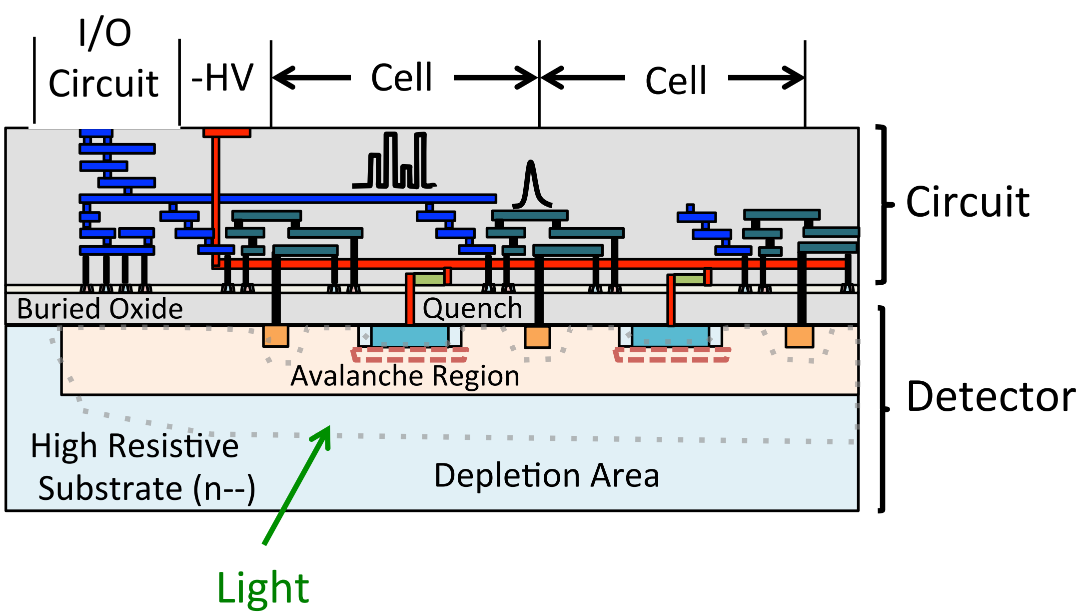


Merits of SOI-SiPM

- **High degree integration and fast response (10-20 % faster than bulk CMOS circuit)** [Y.Fukuda,, SOI-CMOS Device Technology]
- **Control power supply of circuit (30 % less power than bulk CMOS circuit)** [S.Baba, Next-generation low-power consumption SOI devices]
- **Back-illumination structure availability (10-20 % higher detection efficiency than bulk CMOS wafer)**

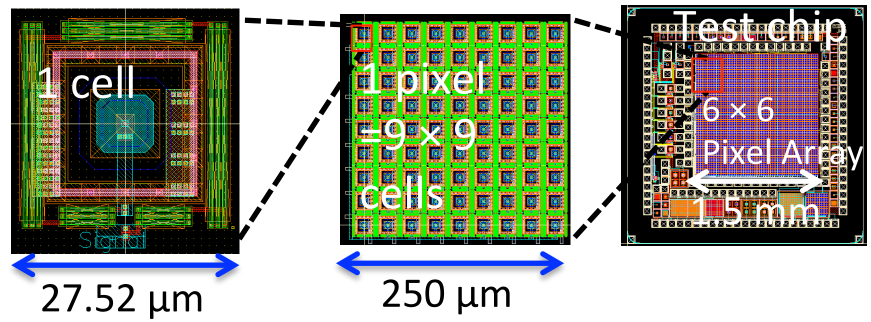
SOI provides 3-D monolithic integrated SiPM with readout circuit
Smaller pixel size and fast electronics will be achieved

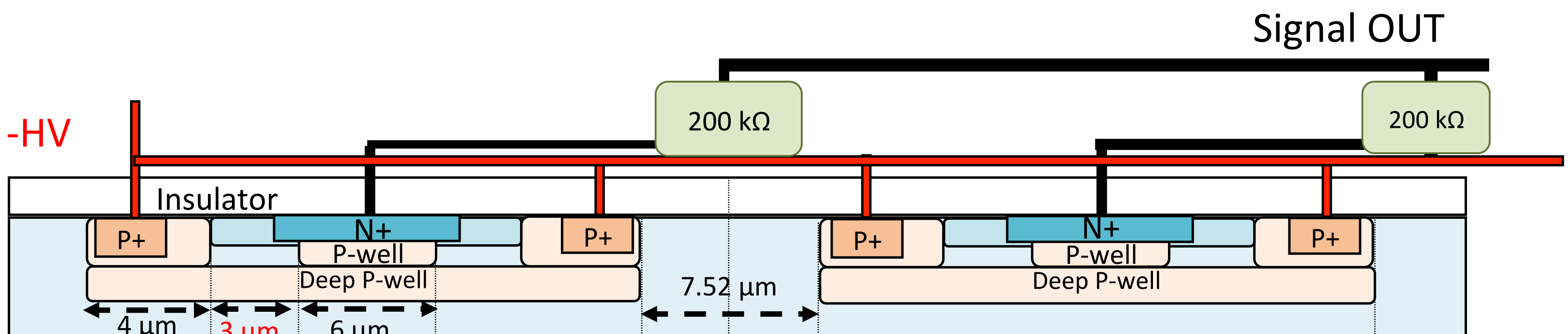
Sub-mm pitch SOI-SiPM prototype

36 CH SiPM Array was designed and fabricated by 0.2 µm SOI process (LAPIS)

- Total Size: 1500 x 1500 μm^2
- Single channel (Pixel)
  - Num. of microcells: 81 (9 x 9)
  - Channel pitch: 250 x 250 μm^2

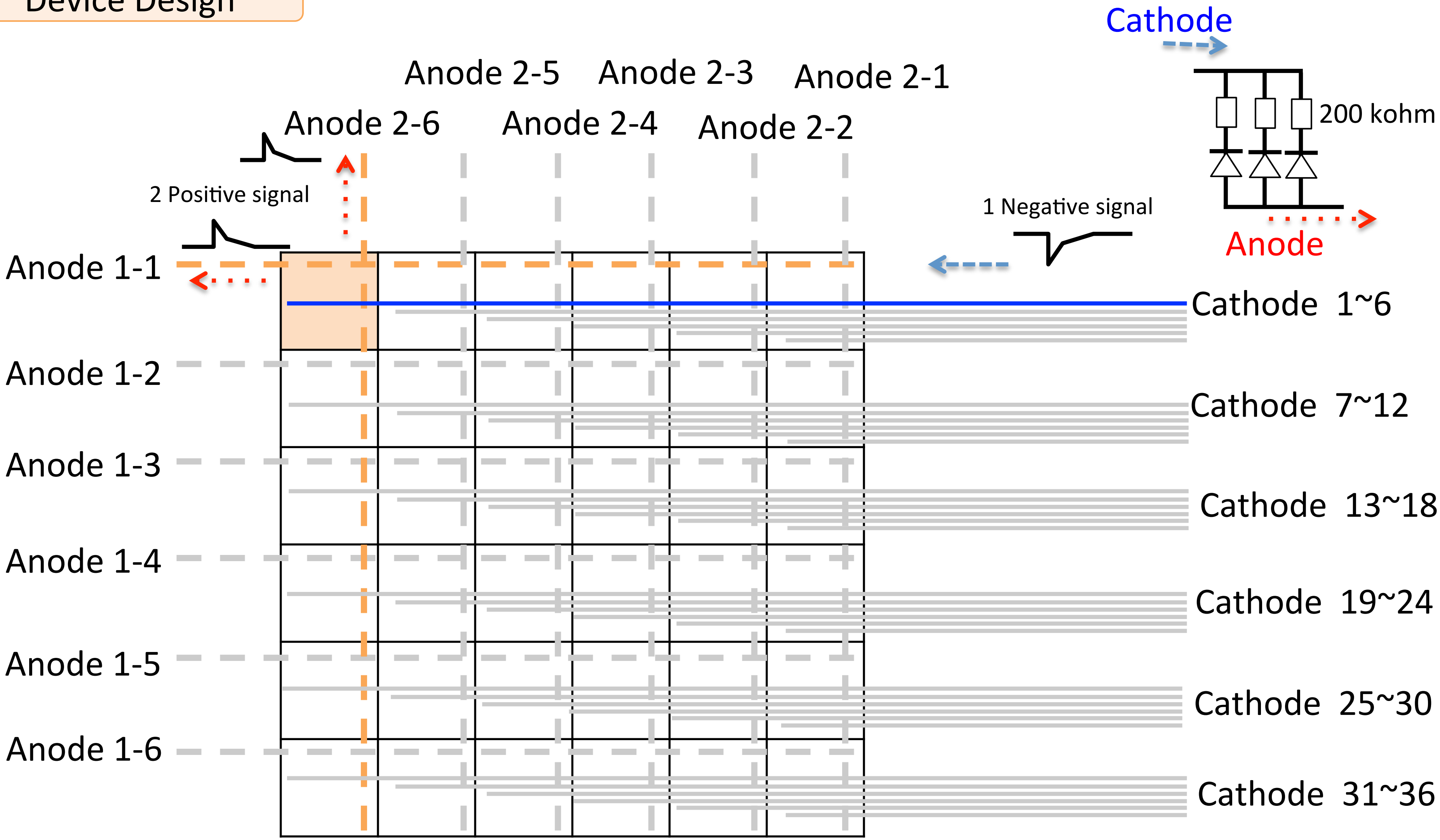
- Single microcell
  - microcell size: 27.52 x 27.52 μm^2
  - Active area: 15 x 13 μm^2
  - Quench : 200 kohm





	Wafer Concentration [/cm^3]
N type	6.9×10^{12}

Device Design



For feasibility study of signal readout, two read out methods selectable design was applied

Cathode : 36 CH discrete negative signal readout (36 line)

Anode : X-Y strip line readout (12 line)

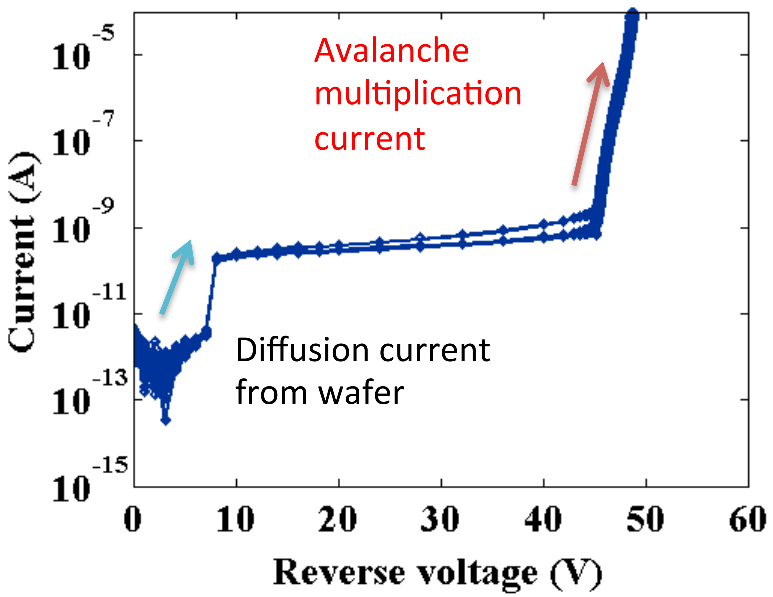
→ Applicable to various fields (Not only PCCT, but also PET or LIDER...)

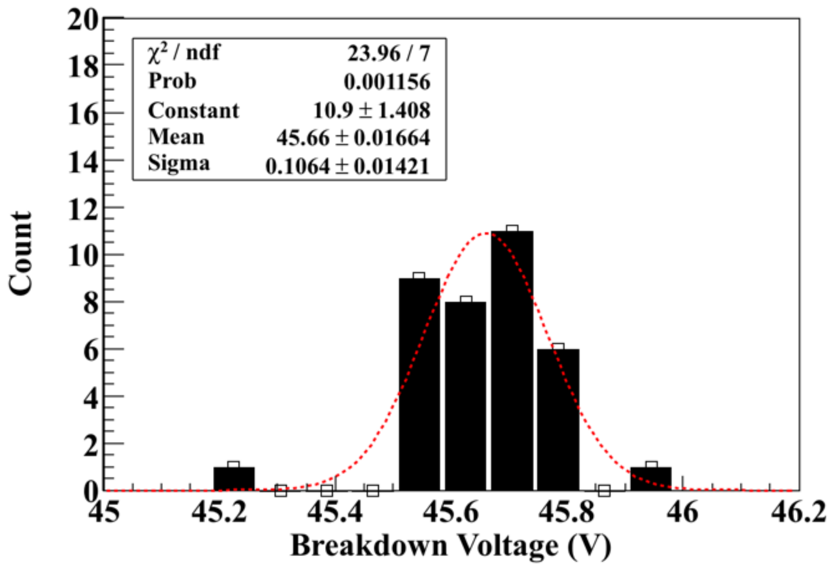
Current-Voltage characteristics (Position dependency)

- Measured breakdown voltage and leak current distribution among 36 CH
- 50 mV step, Temperature: 25 ℃
- Breakdown voltages were extracted by using relative derivative methods

$$\frac{d}{dV_R}\log(I) = \frac{dI}{dV_R} \times \frac{1}{I}$$

(V_R : bias voltage)
(I : leak current)





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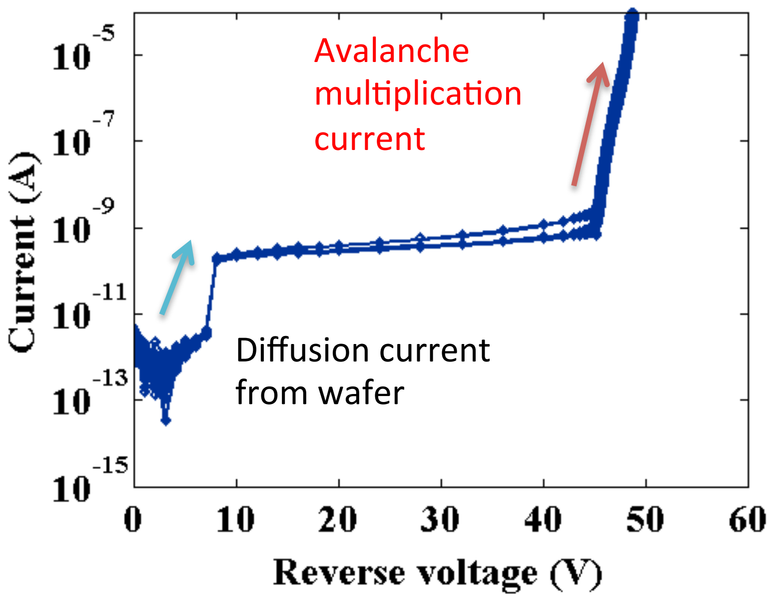
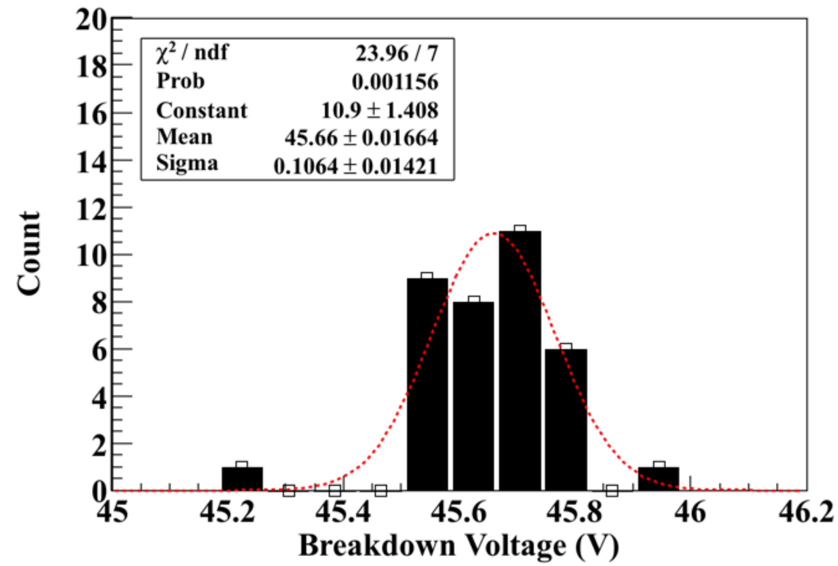


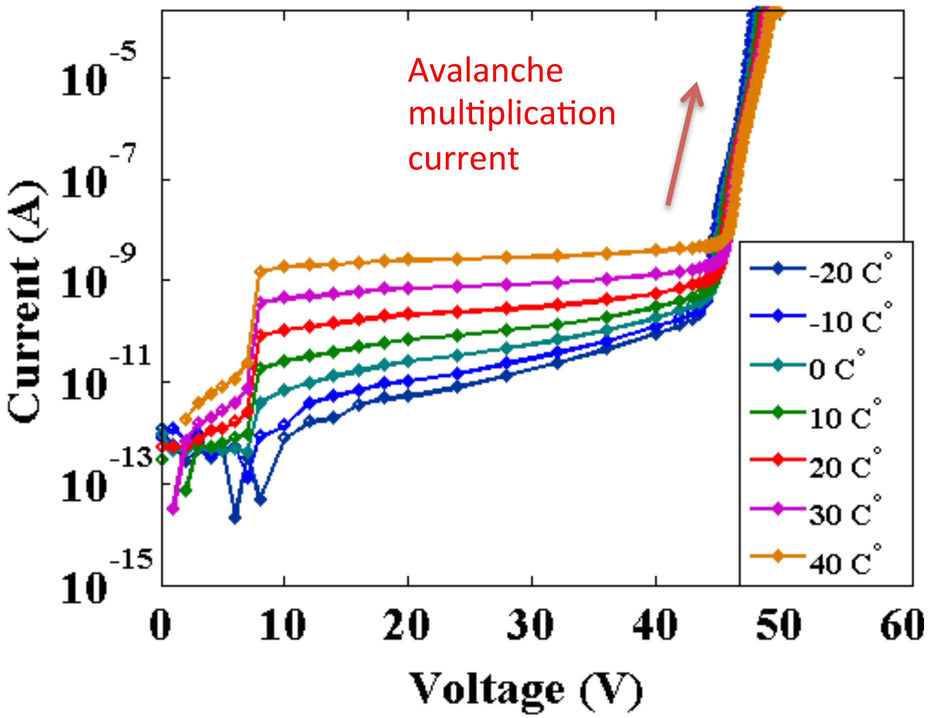


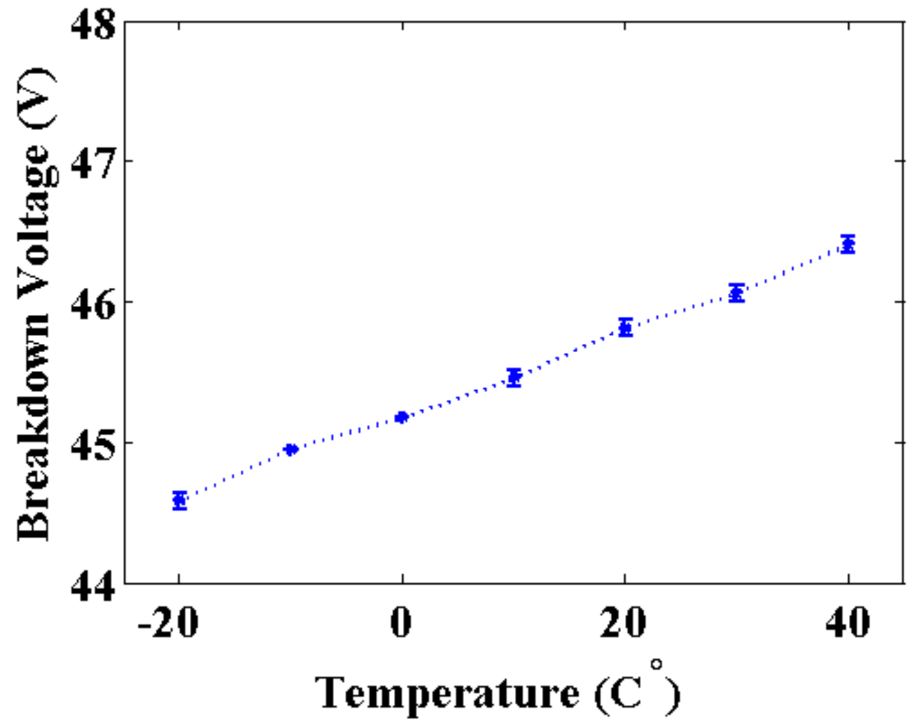
Average breakdown voltage of 45.66 V (±100 mV) was measured among 36 CH

Dark current was 8 nA (±3 nA) at breakdown voltage

Current-Voltage characteristics (Temperature dependency)

- Temperature dependency of leak current was measured at 1 CH
- 50 mV step





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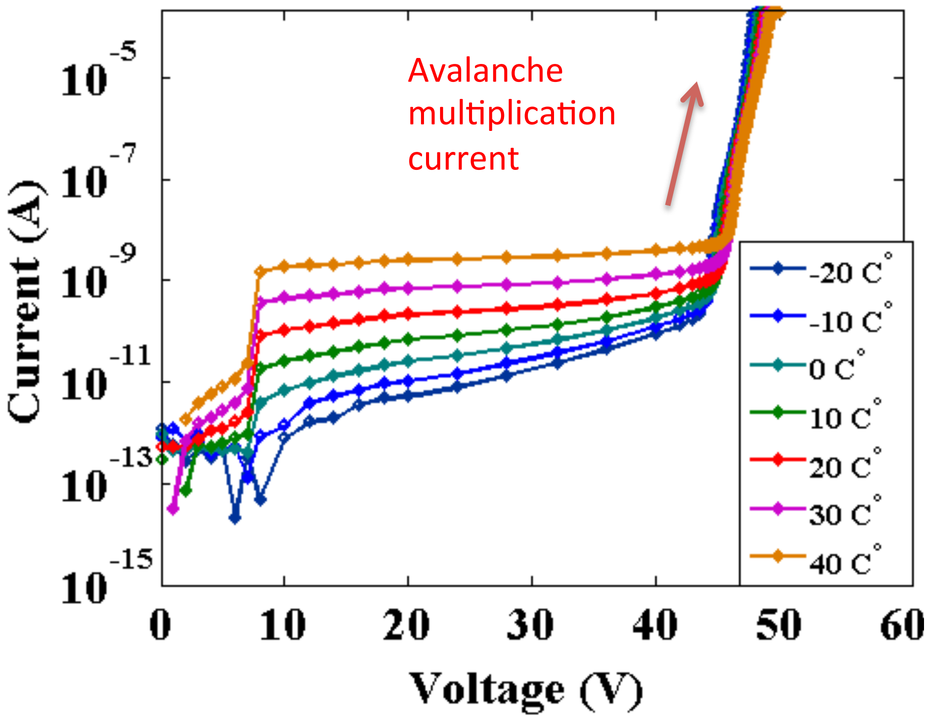
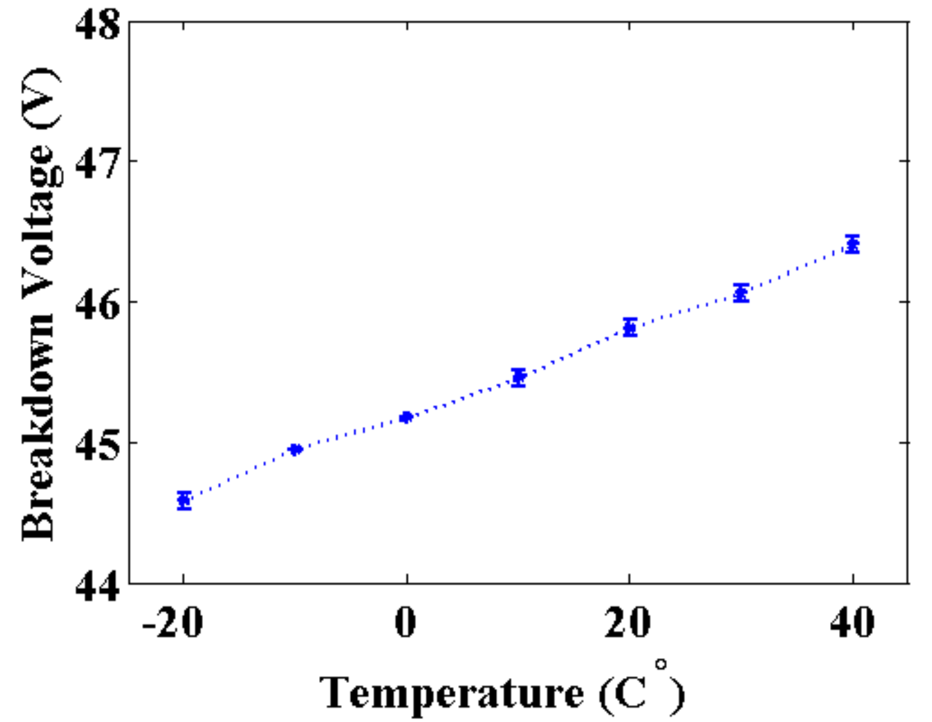
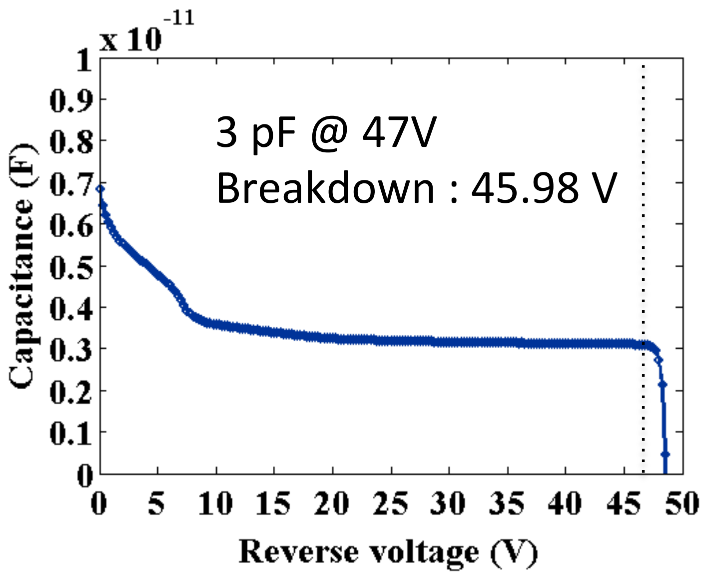




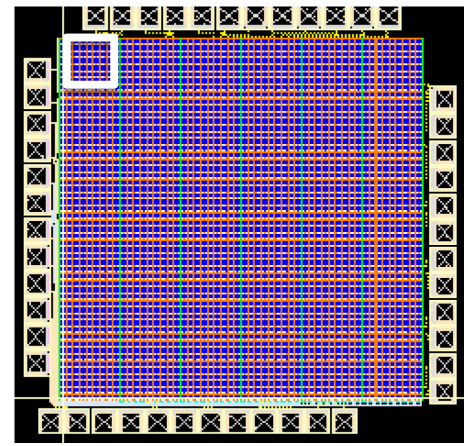
Leak current and breakdown voltage increase with temperature
Temperature dependency of breakdown voltage was 35 mV/℃

Capacitance-Voltage characteristics

- To estimate achievable gain from cell capacitance
- CV were measured three times, and average value was plotted
- 1CH : 81 cell
- Measured by using Keithley 4200SCS
- 25 ℃



Parasitic capacitance
between adjacent wires : 1.3 pF @ CH1



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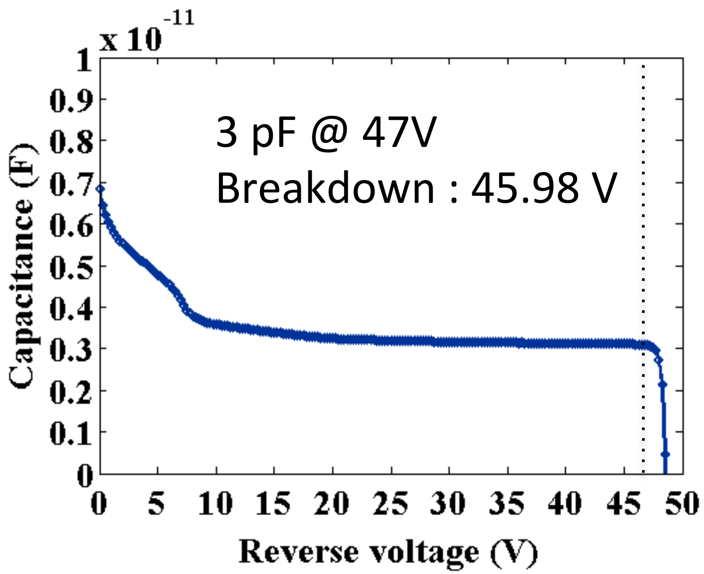

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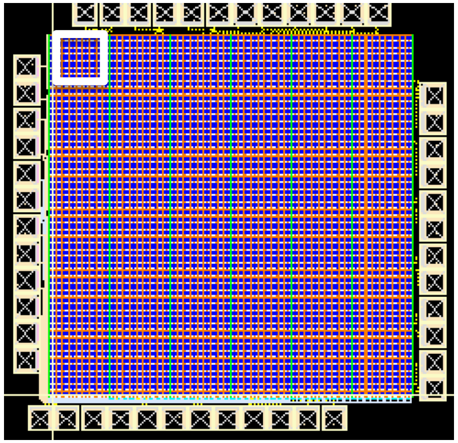
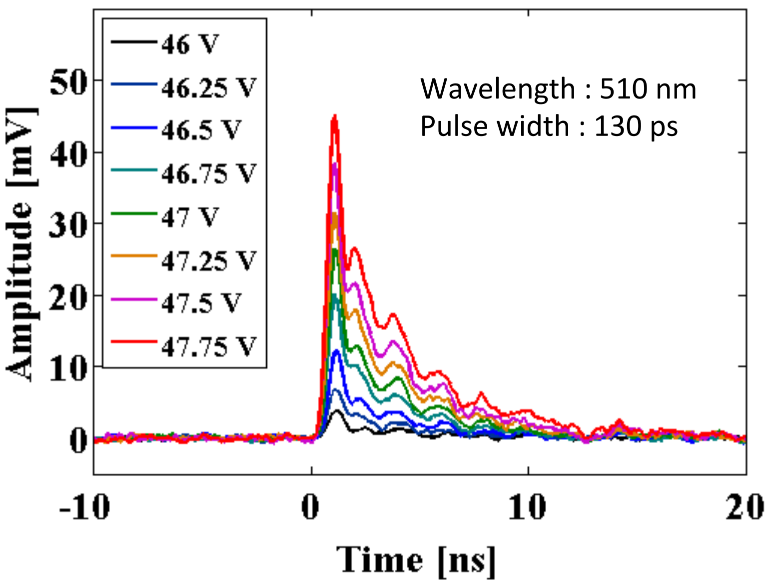


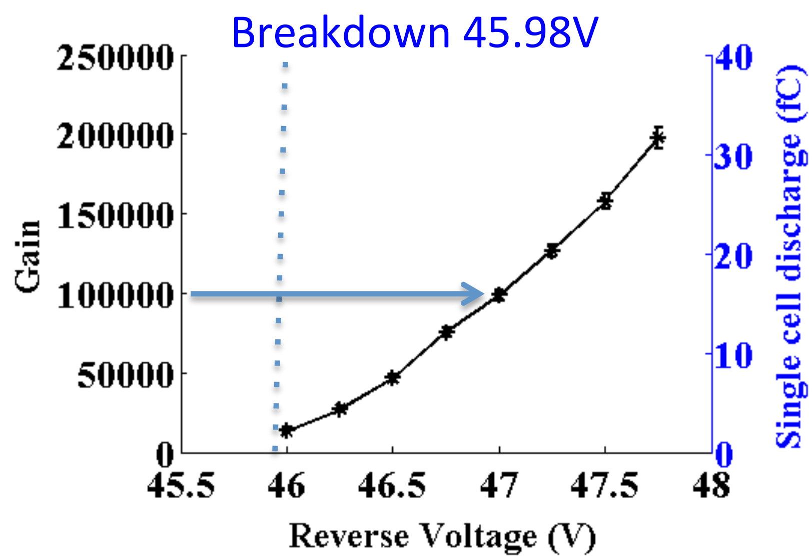
Cell capacitance of 20 fF was measured

→ Achievable gain at 47 V: 20fF x 1.02 V /1.6e-19 = 127,500≈ 10^5

Gain evaluation

- Output Charge per cell Q = ∫ [Waveform V / Oscillo input Z] dt / 81 cell
- Gain = Q / 1.6e-19 , 510 nm wavelength laser (1 kHz, intensity 15)
- Oscilloscope: LeCroy waverunner (10GS/sec, bandwidth 1GHz)
- HV: Keithley 6517A   Room Temp. = 25 degC
- Oscilloscope input : DC 50 ohm // SiPM load resistance 1k ohm





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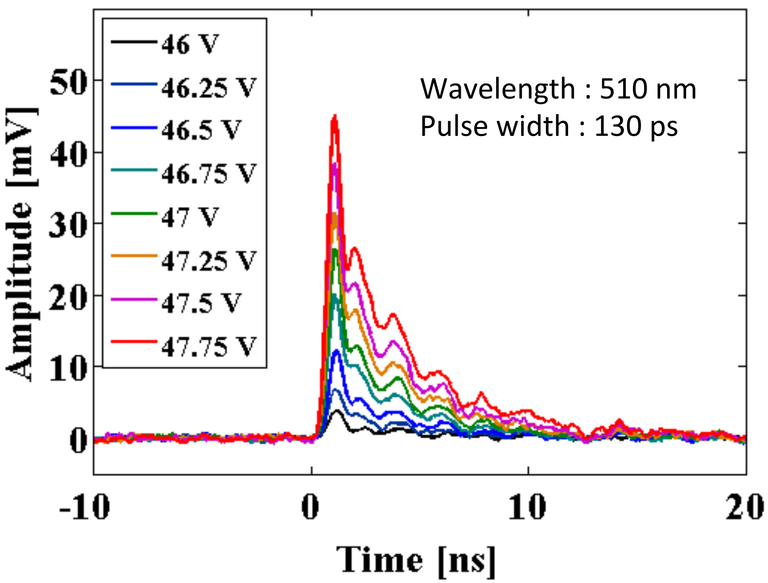
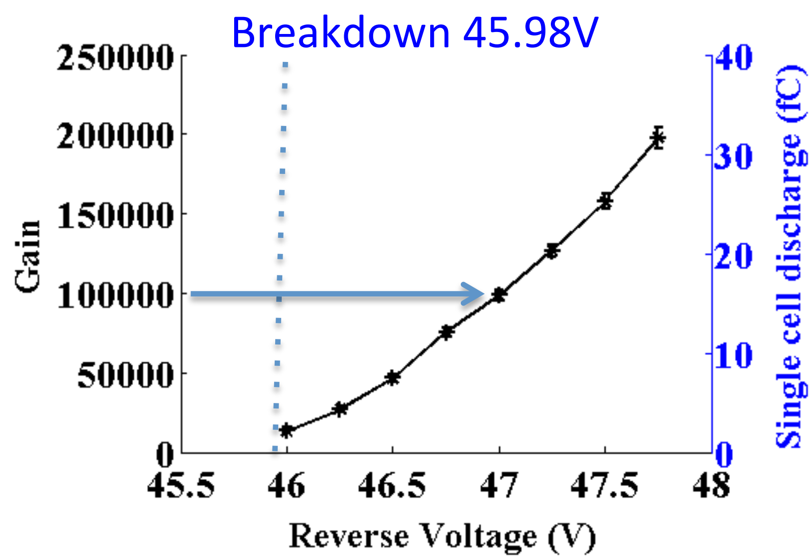


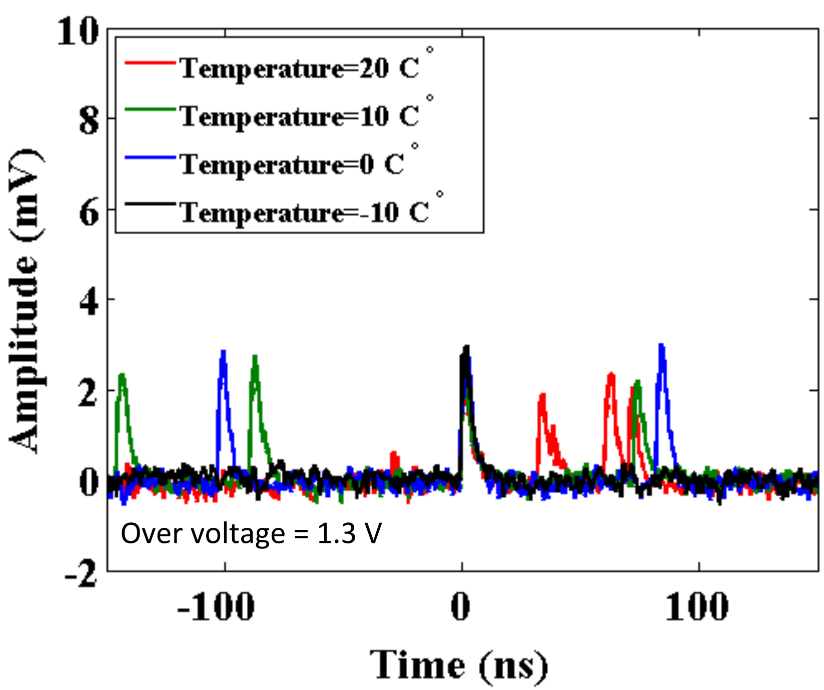


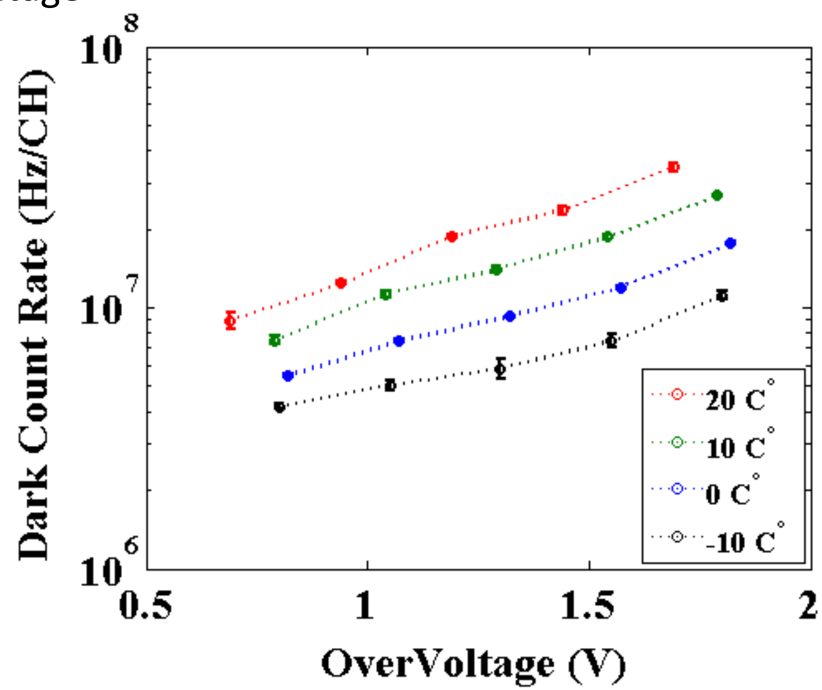
Multiplication gain of 10^5 with fast recovery time under 20 ns was measured at over voltage = 1 V

→ Matches to expected gain from cell capacitance

Dark count rate (DCR)

- Number of dark count pulse was recorded for 300 us × 3 times
- Temperature was controlled by temperature control box (ESPEC)
- Waveforms were acquired by oscilloscope (Lecroy 10GS/s, Bandwidth 200MHz)
- Preamplifier (KETEK Evaluation Kit, Gain=13) was connected to anode of SOI-SiPM
- Over voltage = Bias voltage - breakdown voltage





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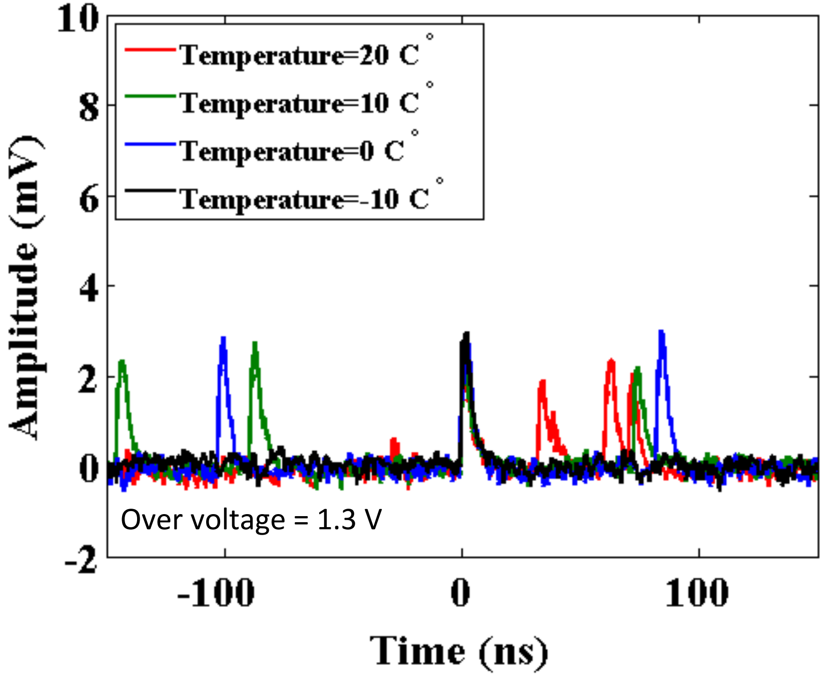
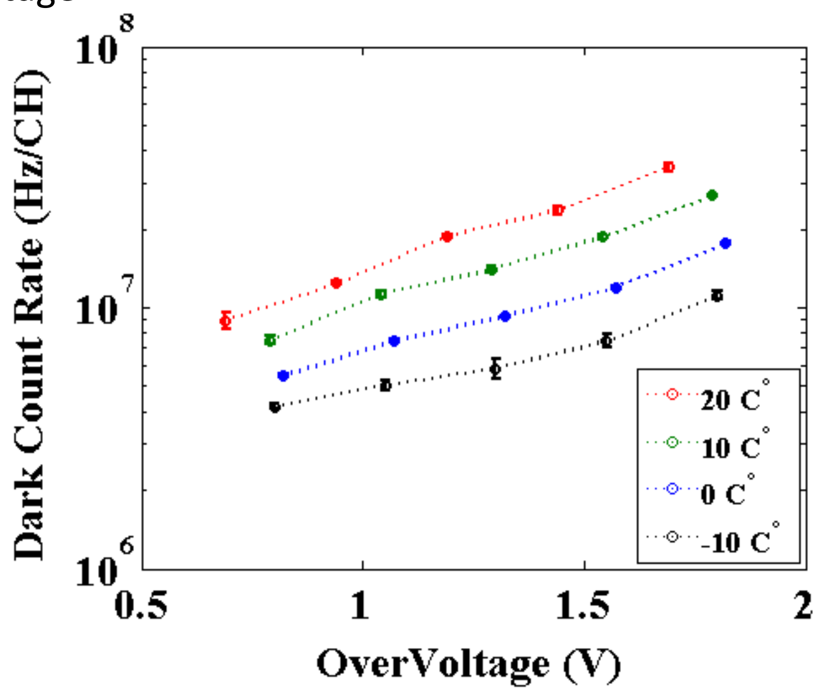




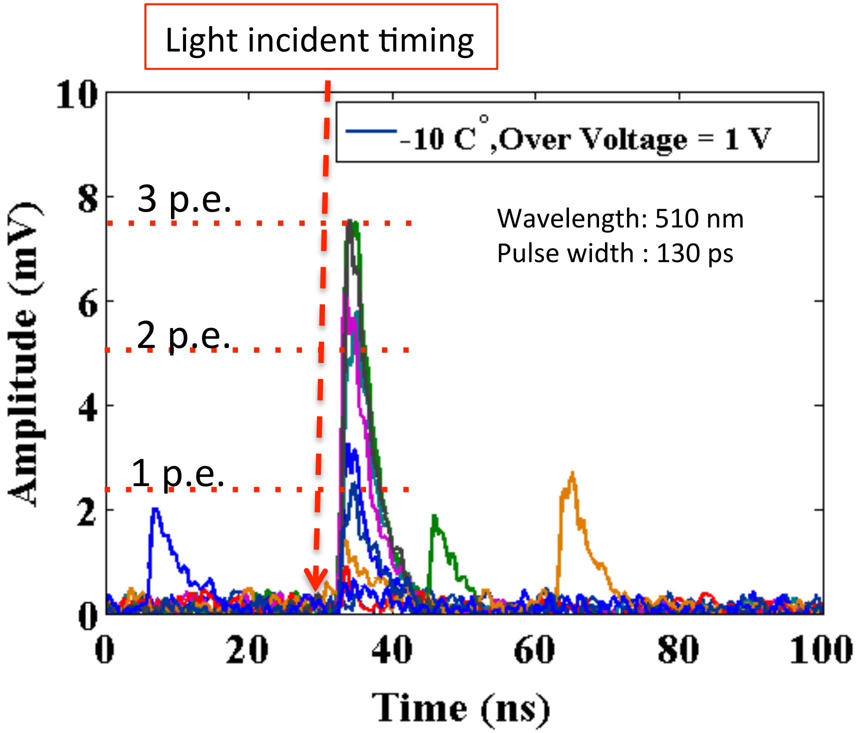
DCR increases with temperature

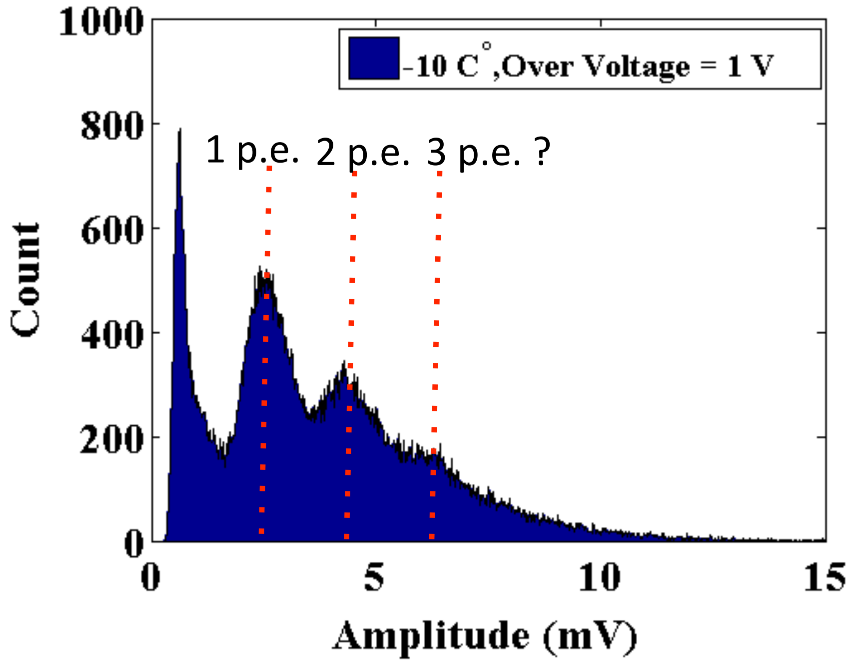
4-10 MHz/CH was observed at -10 ℃

Measurement Results

Photon spectrum (Preliminary)

- Measured by oscilloscope (Lecroy 10GS/s, Bandwidth 200MHz, 50 ohm DC)
- Preamplifier (KETEK Evaluation Kit, Gain=13) was connected
- Over voltage = Bias voltage - breakdown voltage





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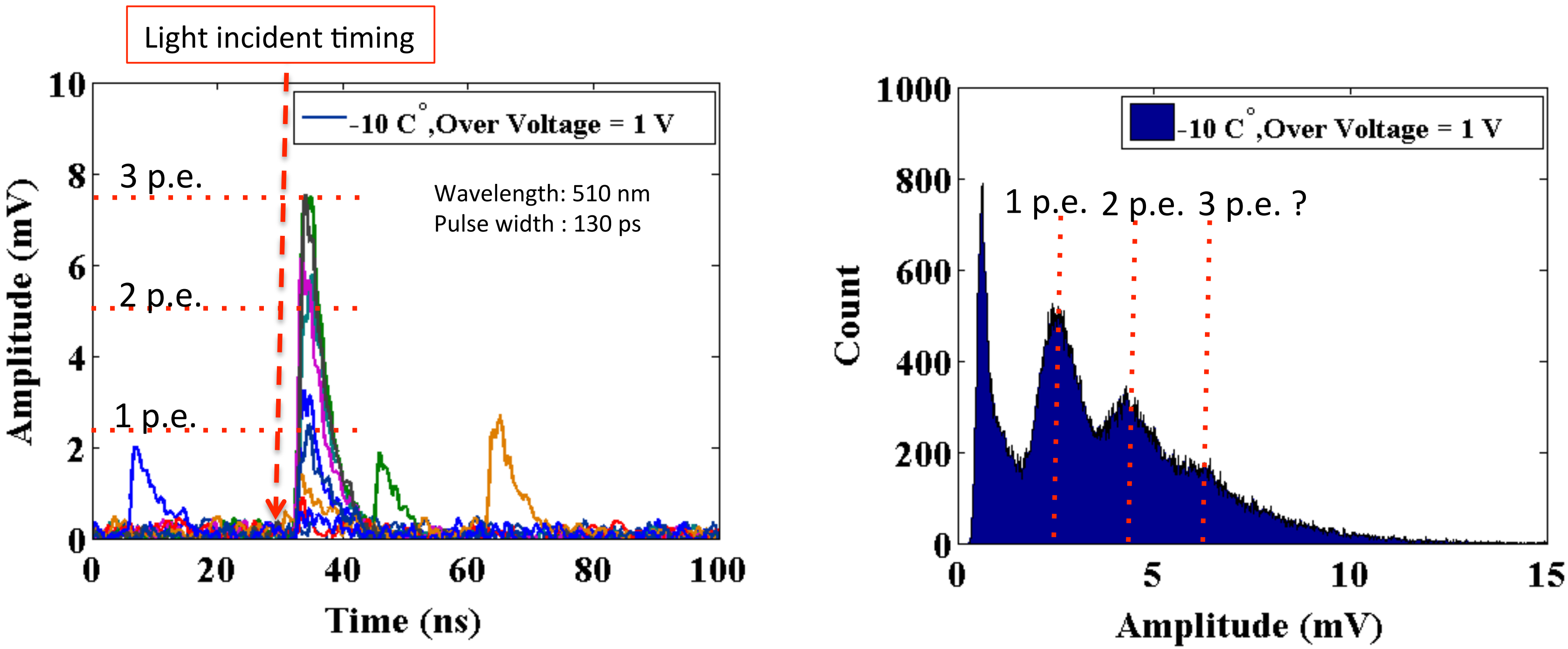


Single photon level was roughly discriminated

Conclusion

- In order to develop Photon Counting CT (PCCT),
  Sub-mm silicon photo-multiplier was designed by using SOI wafer
- Fast recovery time of less than 20 ns and
  avalanche multiplication gain of 10^5 was acquired
  by operating over breakdown voltage of 1~2 V

→ Sufficient levels to use for PCCT

Future works

- High dark count rate (>1 Mcps) needs to be reduced

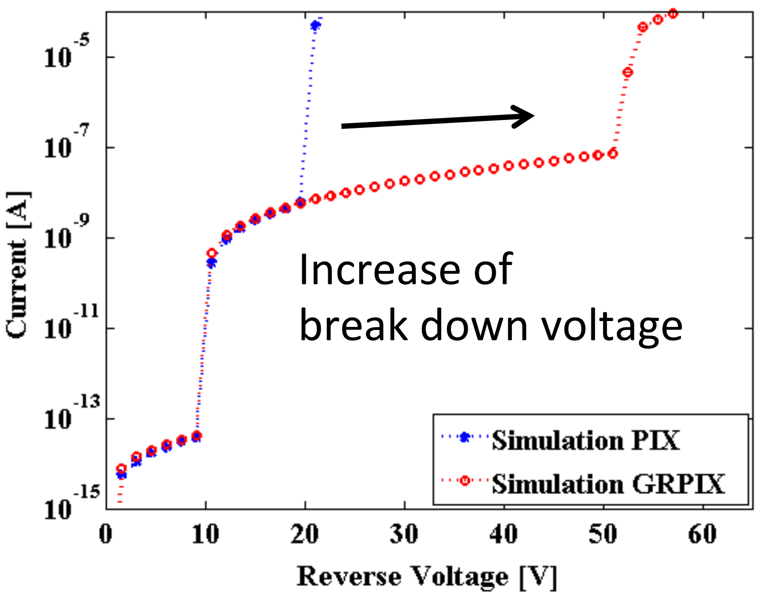
→ Optimization of sensor structure or changing wafer profile
Threshold adjustable readout circuit design is desirable
for dark count elimination

Supplemental slide

Device simulation

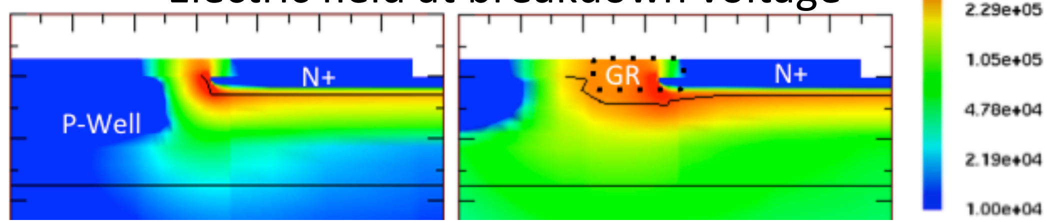
- Guard ring structure contributed to enlarge high electric field area, and increase breakdown voltage

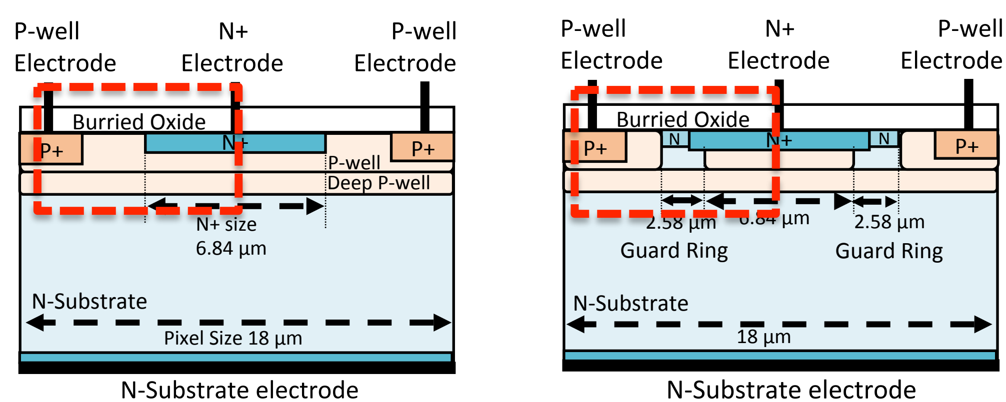
Without guard ring Guard ring



Without guard ring Guard ring

Electric field at breakdown voltage





Comparison between simulation and measurement results

- Guard ring effect was inspected using test chip
- Measurement results also showed high break down voltage at guard ring type