Development of SiPM using SOI Technology

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Outline

- Introduction
  - TOF-PET, SOI
- Research
  - Purpose, Problems
- Method
  - Sensor and Circuit Design
- Results
- Conclusion

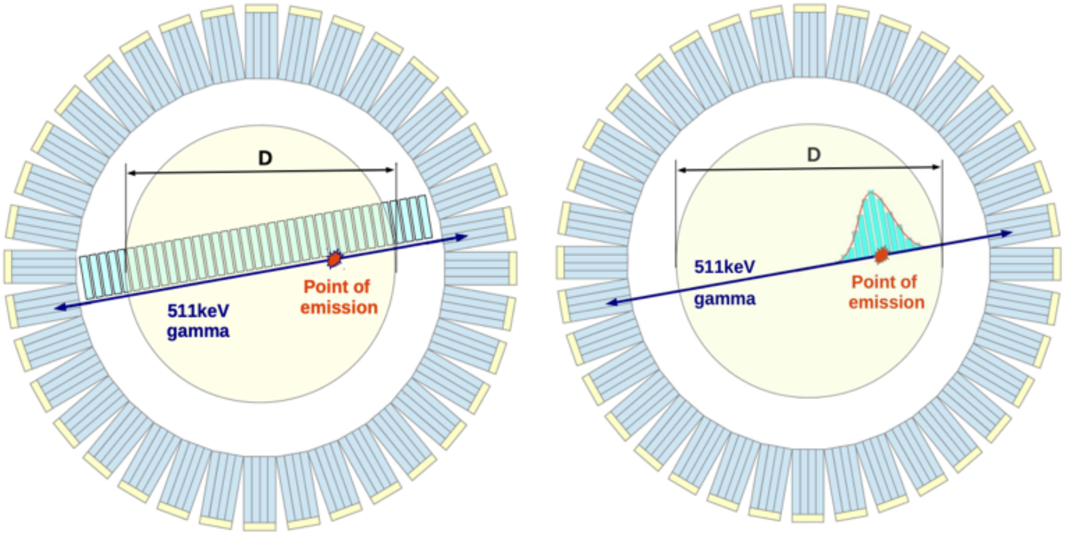
Introduction: TOF-PET

PET (Positron Emission Tomography)

- Nuclear medical imaging technique that detects two 0.511 MeV gamma rays emitting from electron-positron annihilation

TOF(time-of-flight)-PET

- Use coincidence timing information to confine the positron emission point



Normal PET   TOF-PET

[Stefan Gundacker, Routes toward 10ps in time of flight PET]

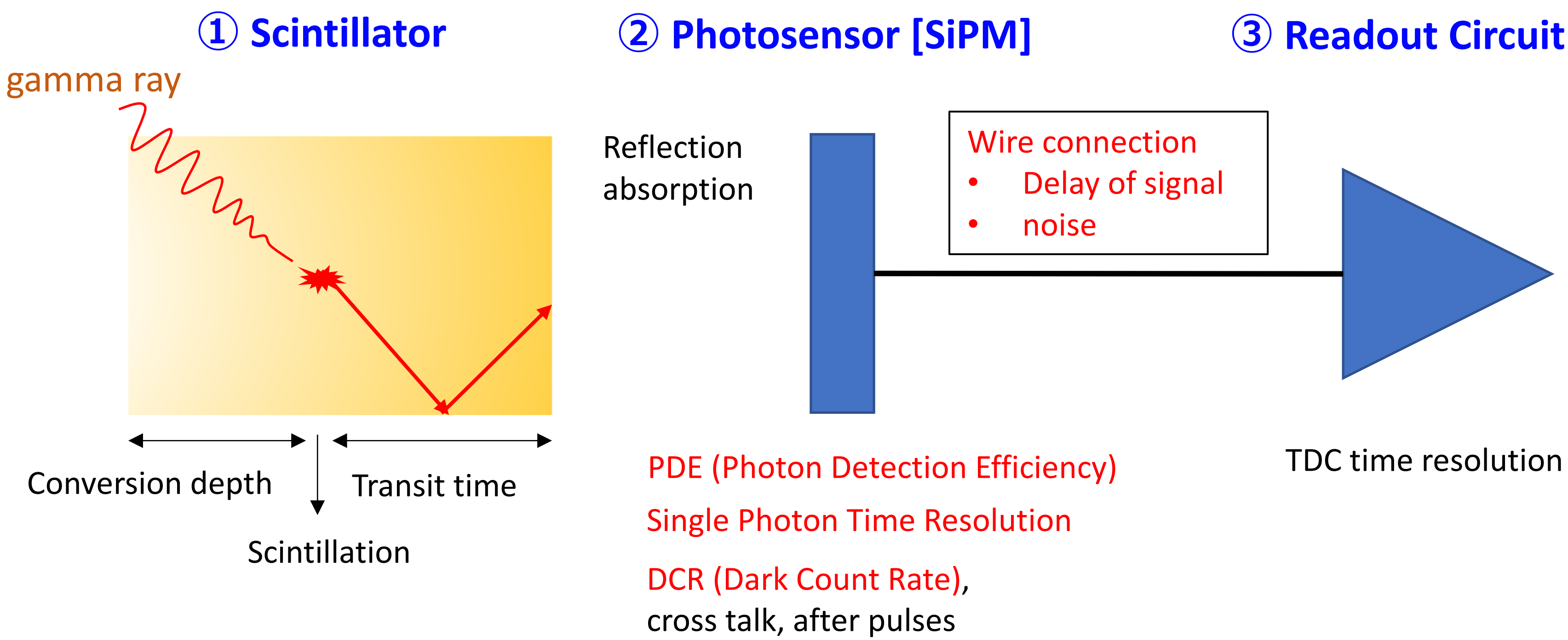
$$G = \frac{SNR_{TOF}}{SNR_{nonTOF}} = \sqrt{\frac{2D}{c * CTR}}$$

D: diameter of the field of view (FOV)
c: speed of light
CTR: coincident time resolution

CTR of 10 ps FWHM corresponds to 1.5 mm spatial resolution along line of response

➡ No need of reconstruction!!!

Introduction: Detection System

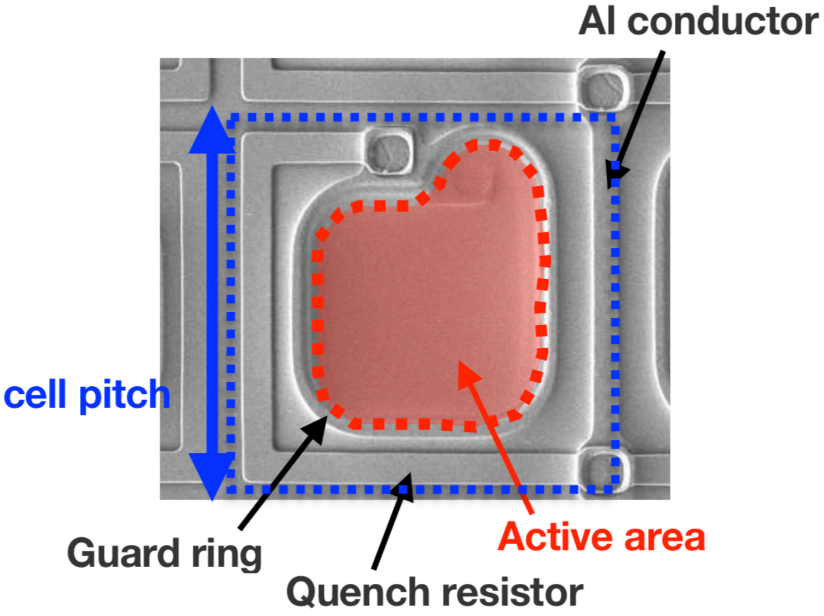


- To achieve time resolution of 10 ps as a detection system, each components [scintillator, sensor, circuit] should meet required time resolution
- Also, integration of these component without degrading the overall performance is a significant issue that should be concerned

Introduction: Integration Method

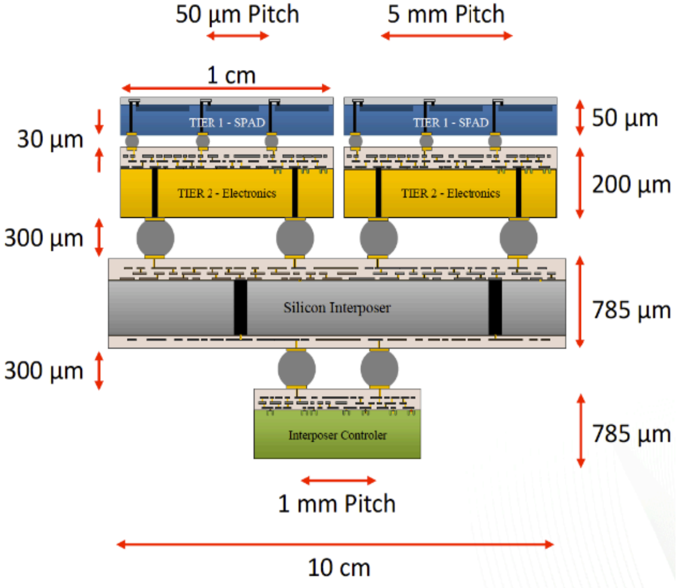
- To process SiPM signal at low noise and high speed, various methods to integrate SiPM and its readout circuit is proposed

2-dimentional integration using CMOS process



- **Accurate wiring between sensor and circuit**
- **Limited fill factor**

3-dimentional integration using bump bonding

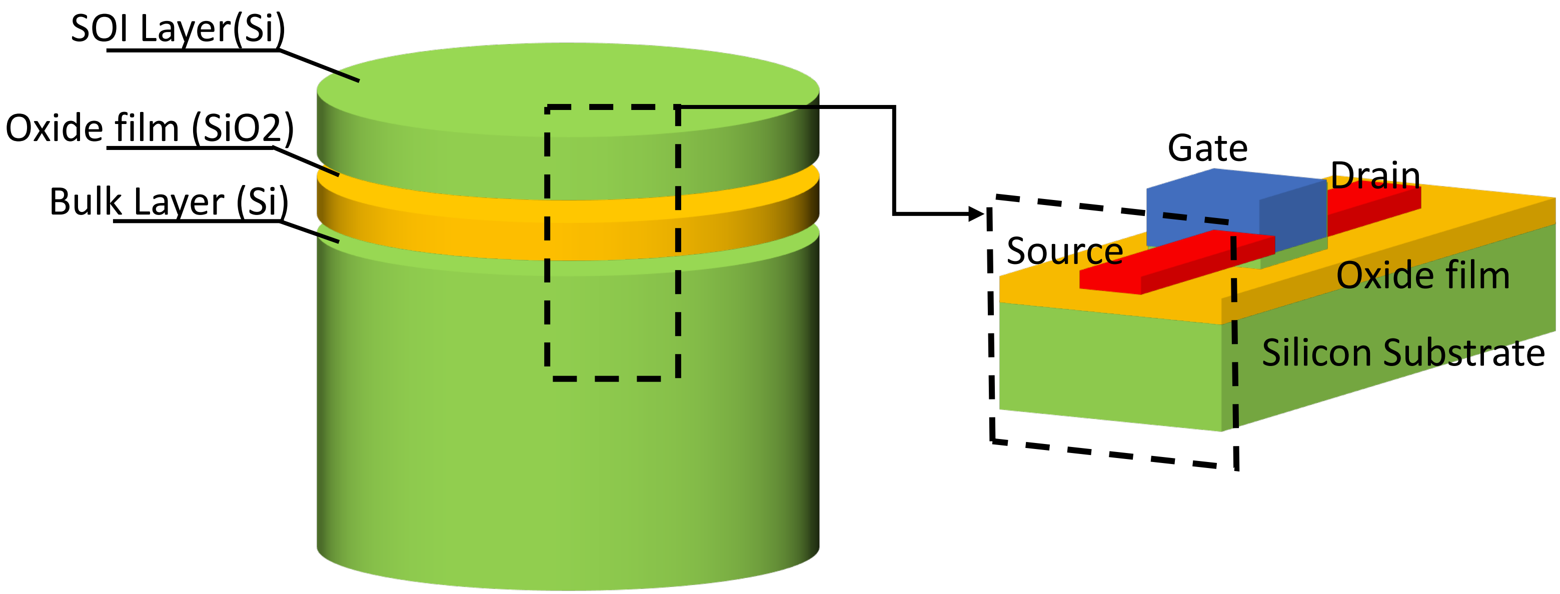


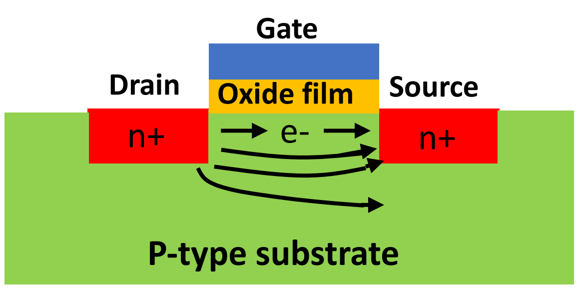
- **Sensor and circuit can be optimized separately**
- **Fill factor is not limited by circuit**
- **Limited size and accuracy**
- **Degradation due to several factors**

Introduction: SOI

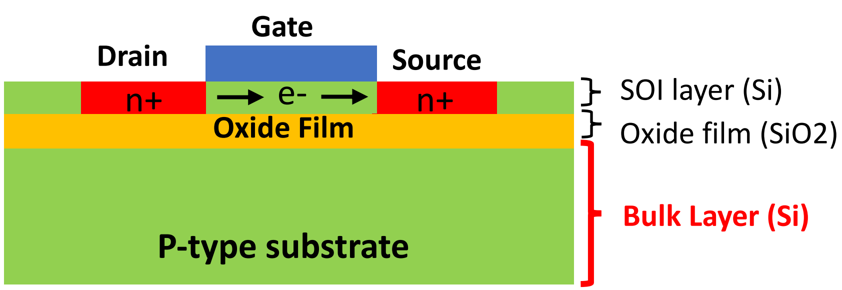
Silicon on Insulator (SOI) -CMOS process

- Semiconductor wafer technology to form thin silicon layer on top of oxide film





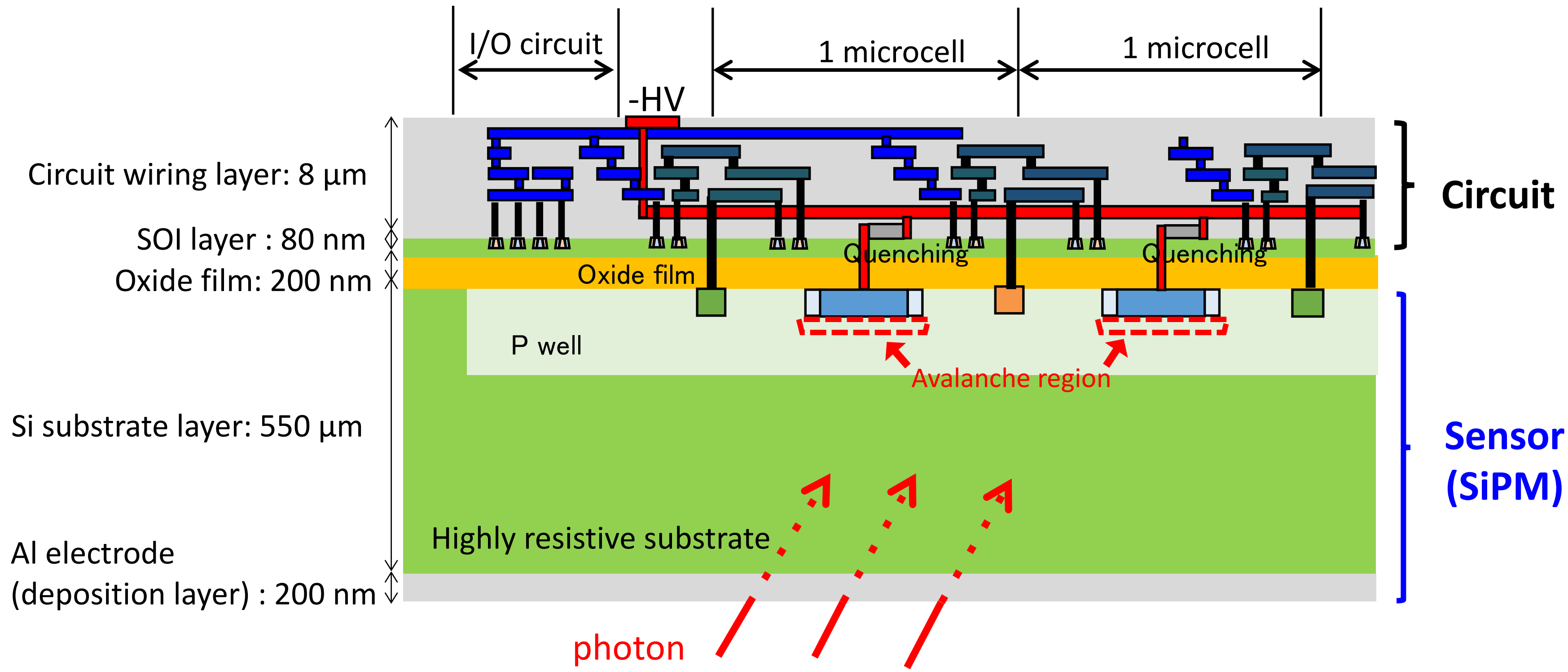
Traditional MOSFET



MOSFET using SOI technology

Research: Purpose

Development of 3-D monolithic integrated SiPM with readout circuit using SOI technology

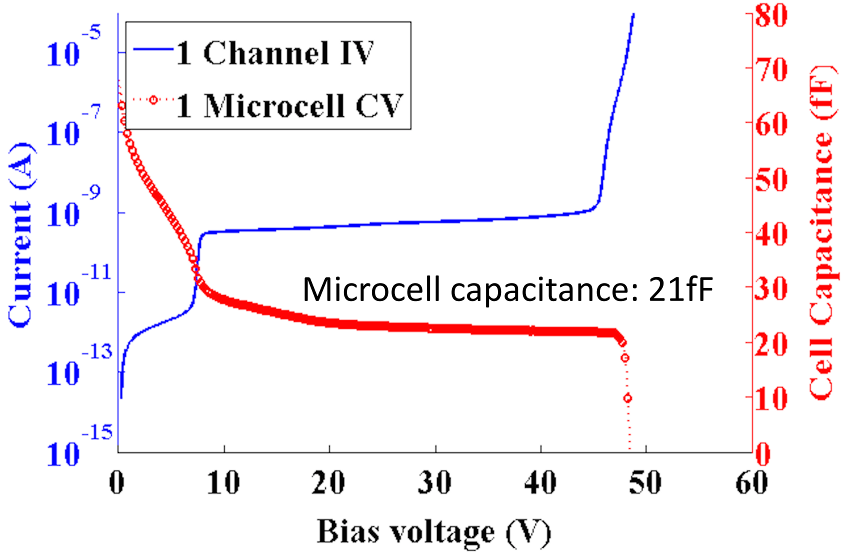


Advantage

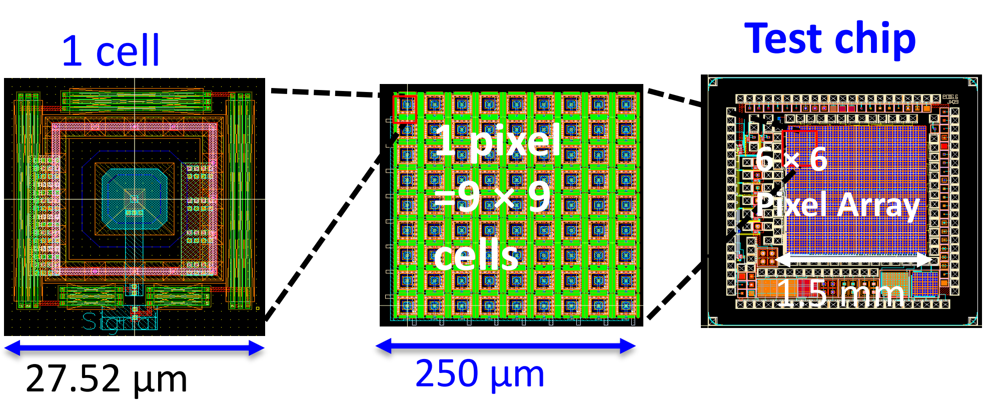
- High degree integration and fast response (10-20% faster than bulk CMOS circuit)
  [Y.Fukuda, SOI-CMOS Device Technology]
- Control power supply of circuit (30% less power than bulk CMOS circuit)
  [S.Baba, Next-generation low-power consumption SOI devices]
- Back-illumination structure availability (fill factor higher than 90%)

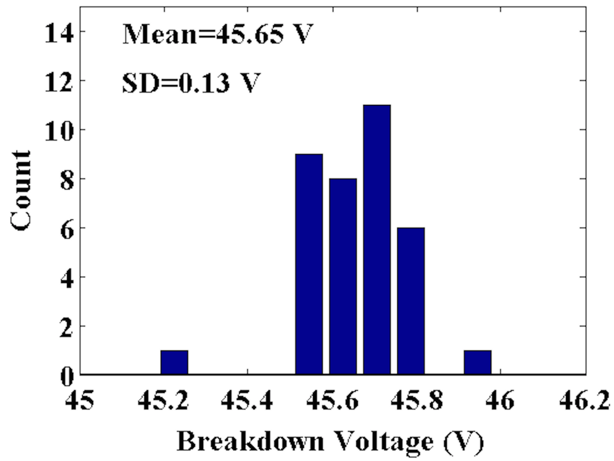
Research: so far..

- Total dimension: 6×6 pixel, 1500×1500 μm²
- 1 pixel
  - Number of microcell: 81
  - Pitch size: 250×250 μm²
- microcell
  - Size: 27.52×27.52 μm²
  - Fill factor: 25%
  - Quench Resistor: 200 kΩ



Gain at 1V of Overdrive voltage
: 20fF x 1. V /1.6e-19 = 131,250 ≈ **1.3×10⁵**

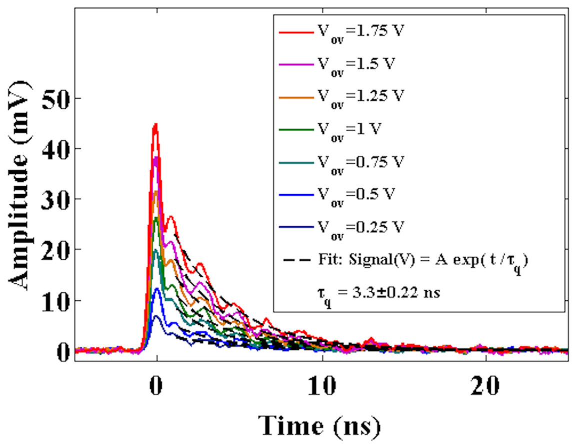


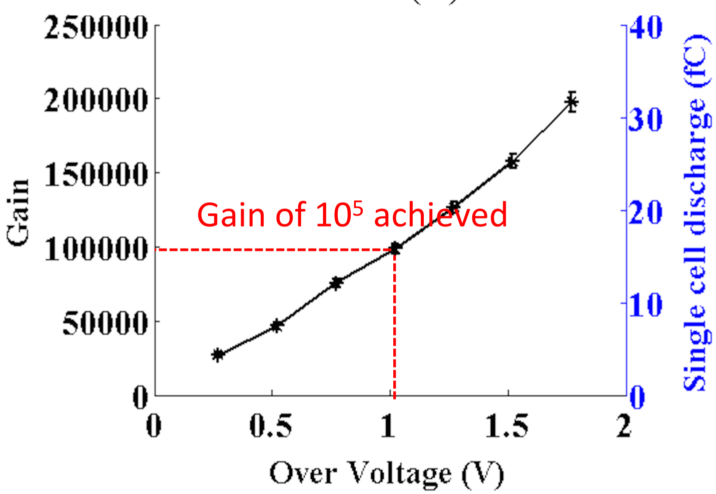


Research: so far...

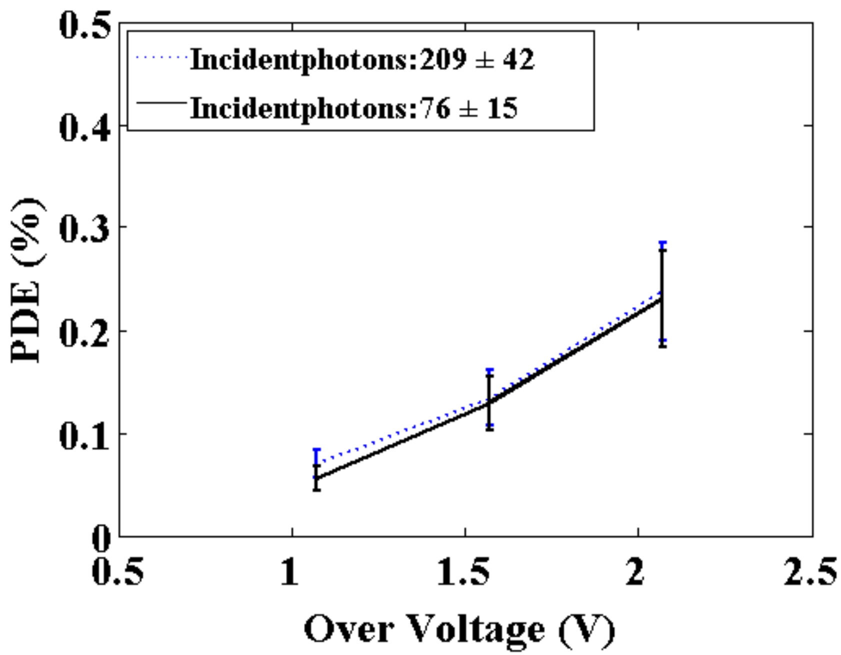
510 nm laser is irradiated

- to acquire signal waveform
- to calculate gain by total output charge of single microcell



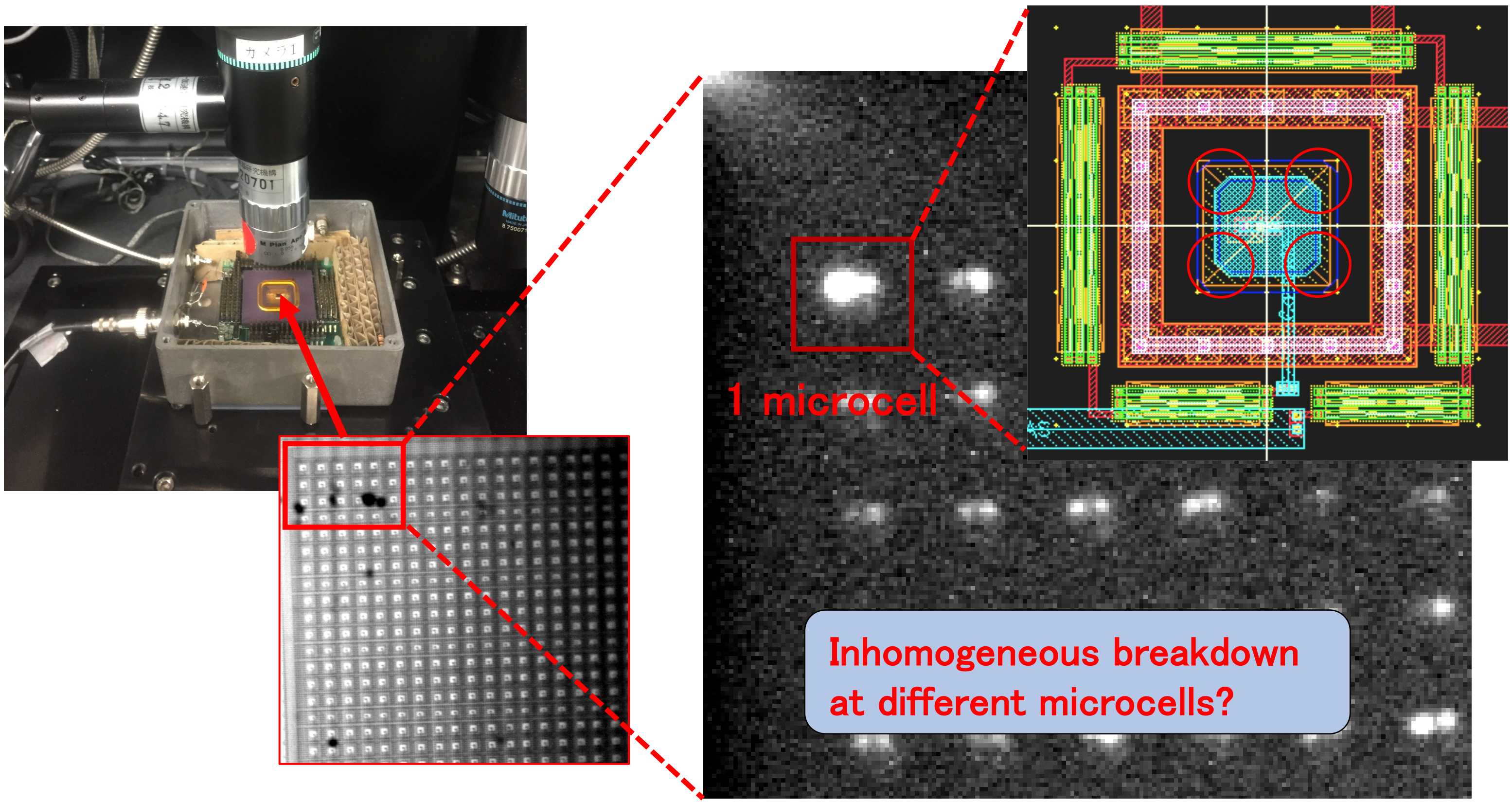


PDE: Photon Detection Efficiency



PDE (< 1 %) is limited

Method: Infrared Flash Photography



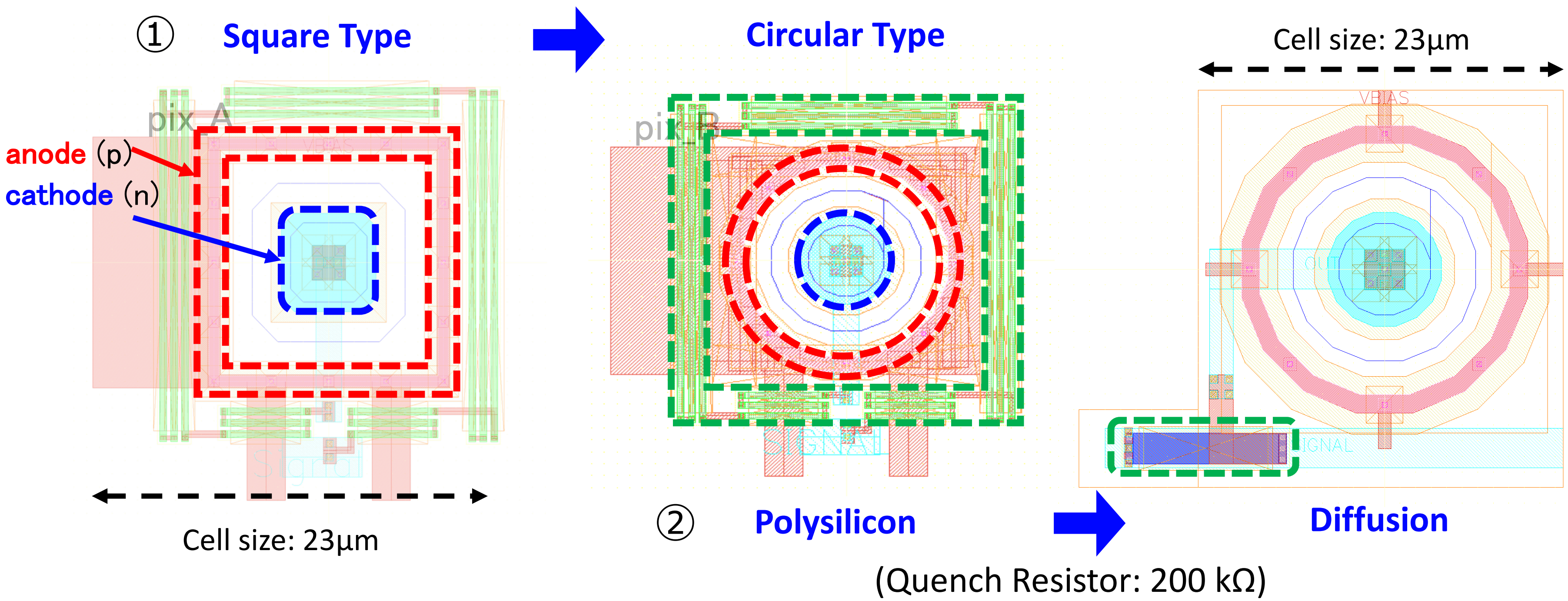
Problem

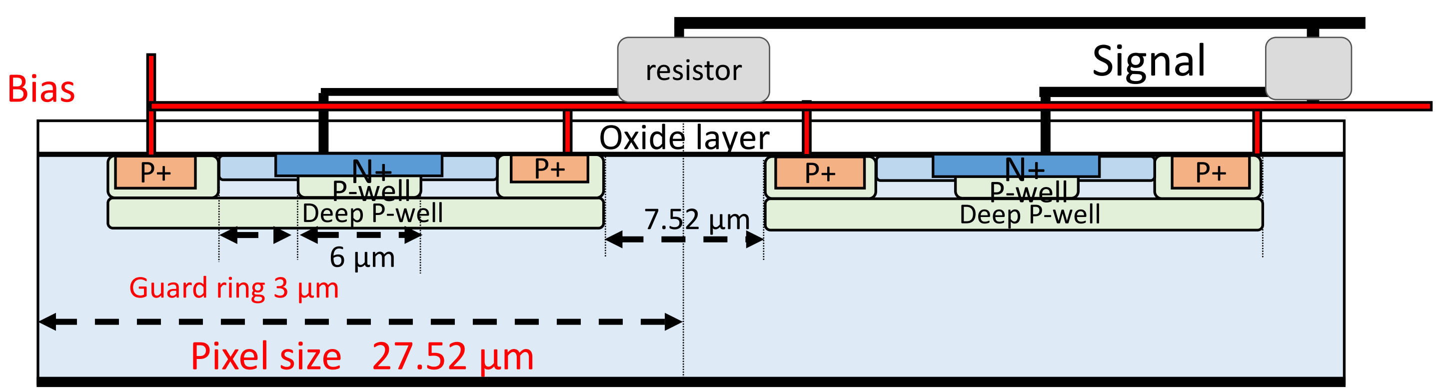
Early breakdown occurs at corner of **square** cathode
-> limited PDE (< 1 %)

Solution

To prevent electric field concentration at corner, change the shape of cathode to **circle**

Method: Sensor Modification

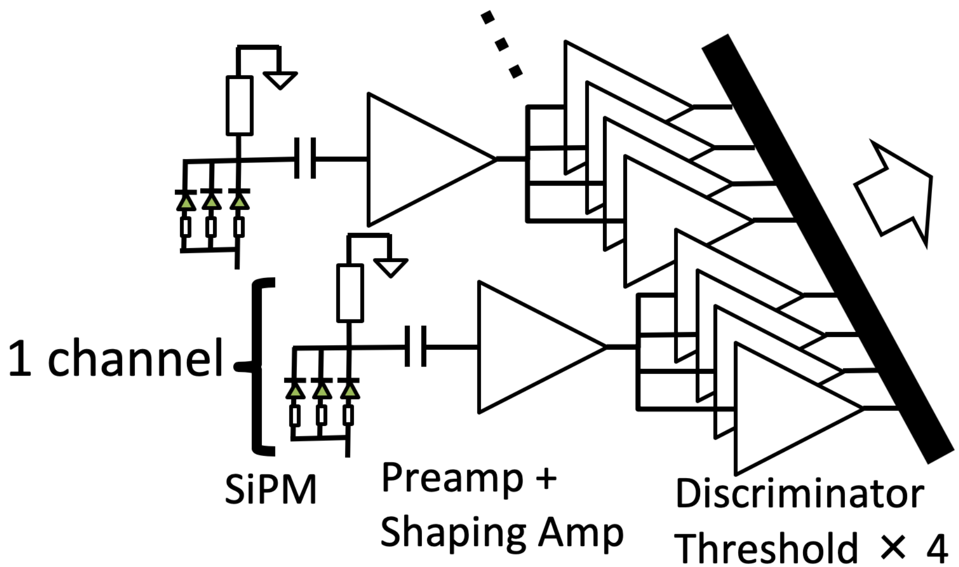




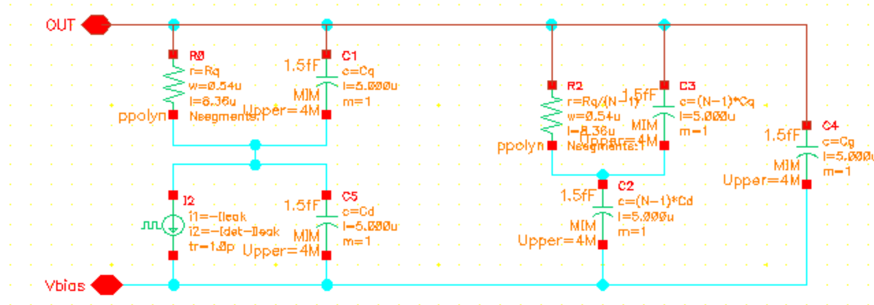
Cross Section View

Method: Circuit Design

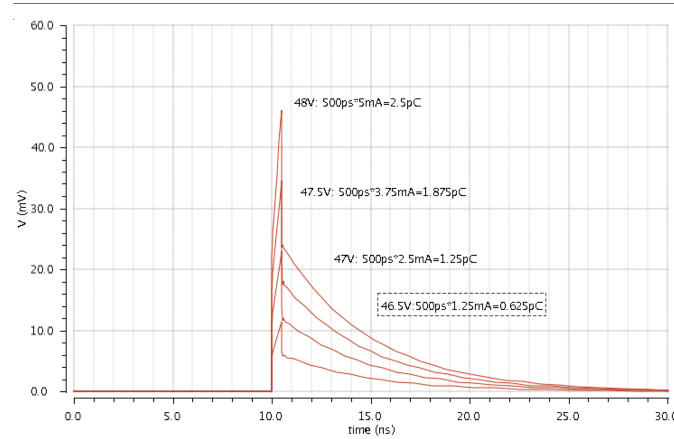
Circuit Diagram



Input Signal for simulation



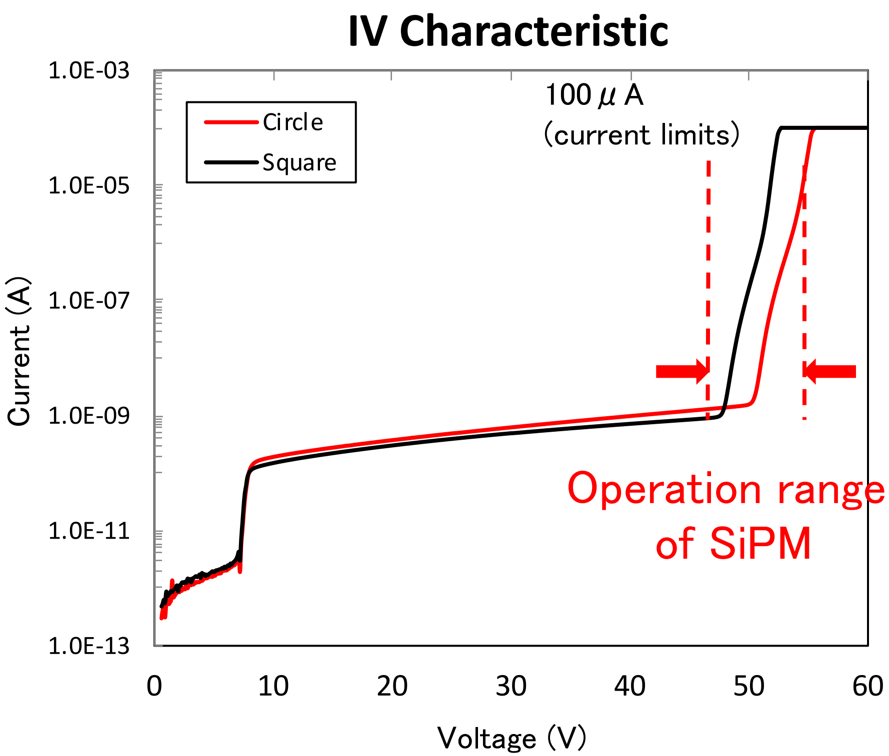
[F.Corsi, Nuclear Instrument and Methods in Physics Research A 572, 2007,416-418]



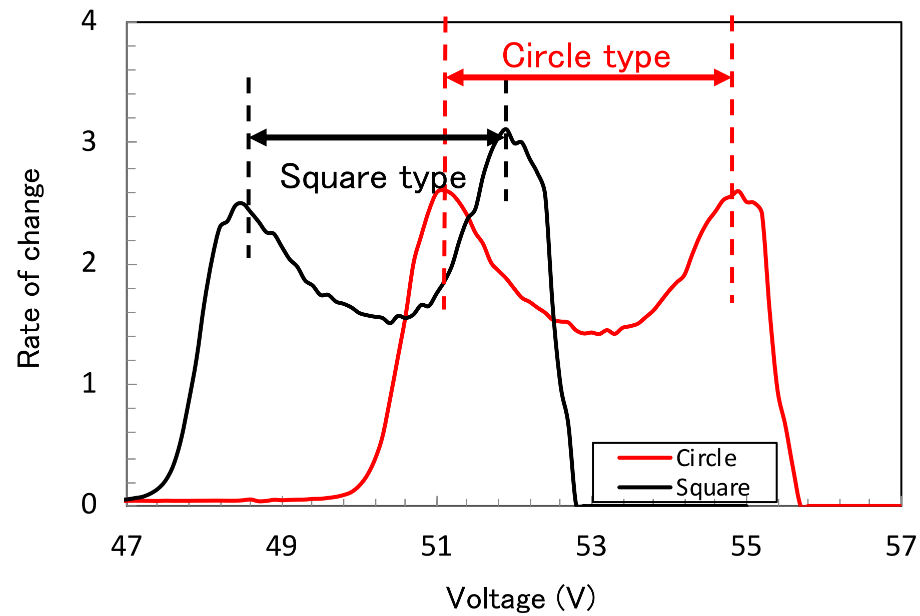
- Both simulation and measurement are performed
- In this design, discriminator is the last component of readout circuit to widen application possibility

Results 1: IV Characteristic

Semiconductor Parameter Analyzer (Keithley4200SCS)



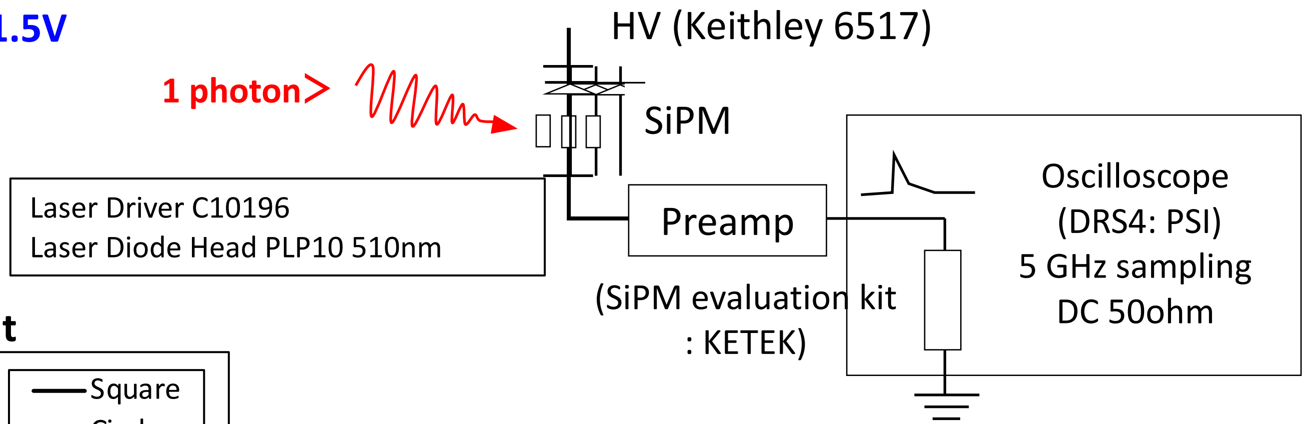
$$Rate\ of\ Change = \frac{d(logI)}{dV} = \frac{dI}{I}\frac{1}{dV} = \frac{\Delta I}{I \cdot \Delta V}$$

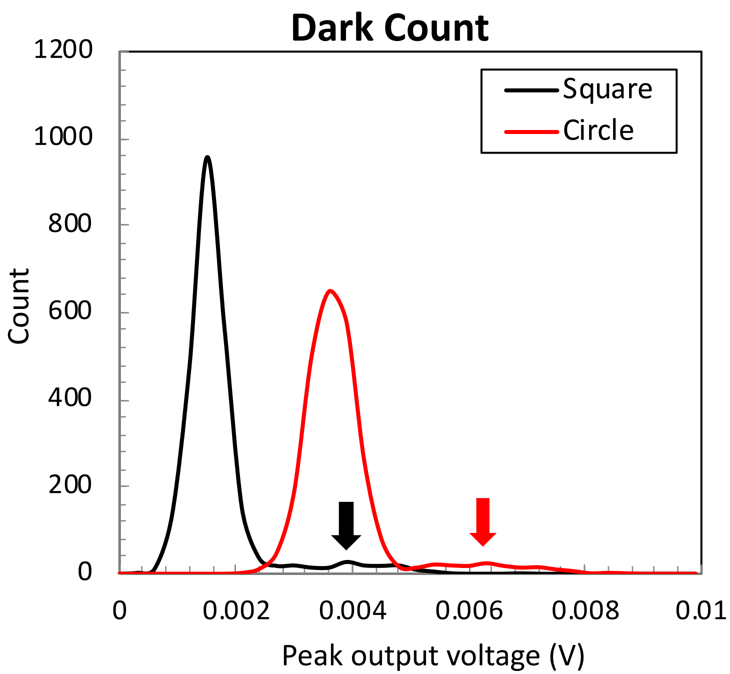


- Breakdown Voltages of Square and Circle are **48.5** and **51.1 V** respectively, an increase of **2.6 V**
- Operation ranges are 48.5 ~ 51.9 V [**3.4V**] and 51.1 ~54.9 V [**3.8V**], an increase of **0.4 V**

Results 1: Dark Count Rate (DCR)

- SiPM Bias Voltage：V_{OV}=**1.5V**
  - Square：50.0 V
  - Circle：52.6 V
- Temperature：20 °C



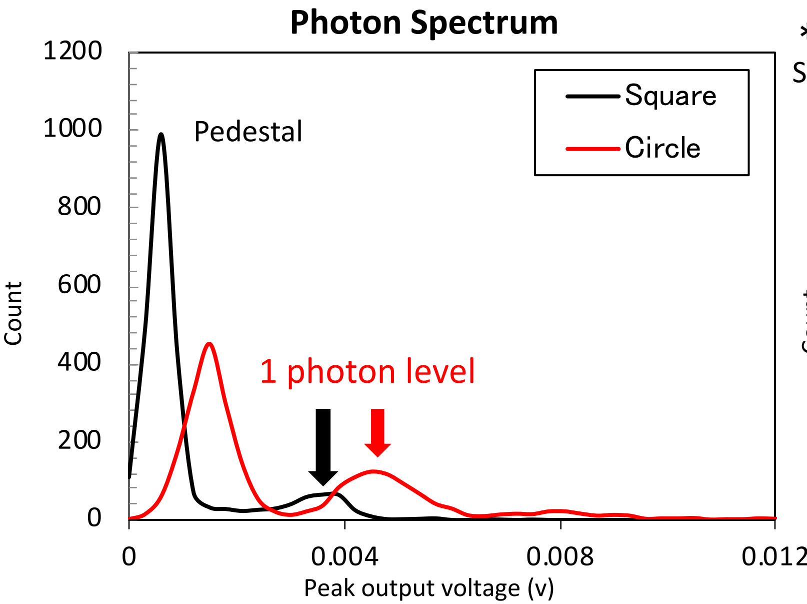


$$DCR = \frac{dark\ count}{time\ window \times all\ count} / dimension$$

- SiPM dimension: 165.12 x 247.68 μm^2
- Time window: 8ns
- Total count: 2500

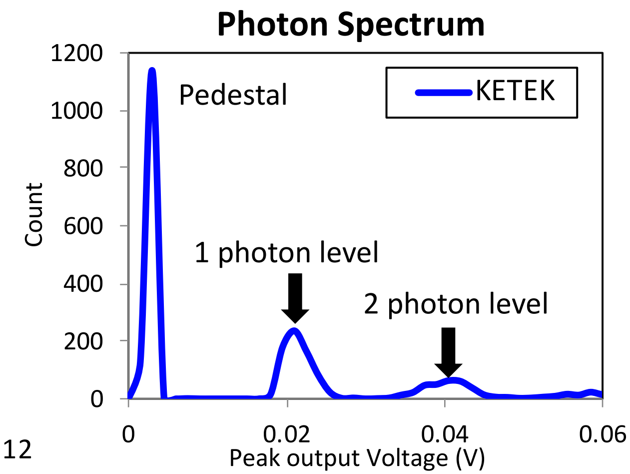
- By modifying the shape of cathode from square to circle, DCR is increased from **218.8** to **245.7** MHz/mm^2

Results 1: PDE



SOI SiPM

＊keep light intensity constant and insert ND filter until output of KETEK SiPM drops to 1 photon level in average



KETEK SiPM

$$\textit{average number of photon detection} = \mu_{photon} - \mu_{dark}$$

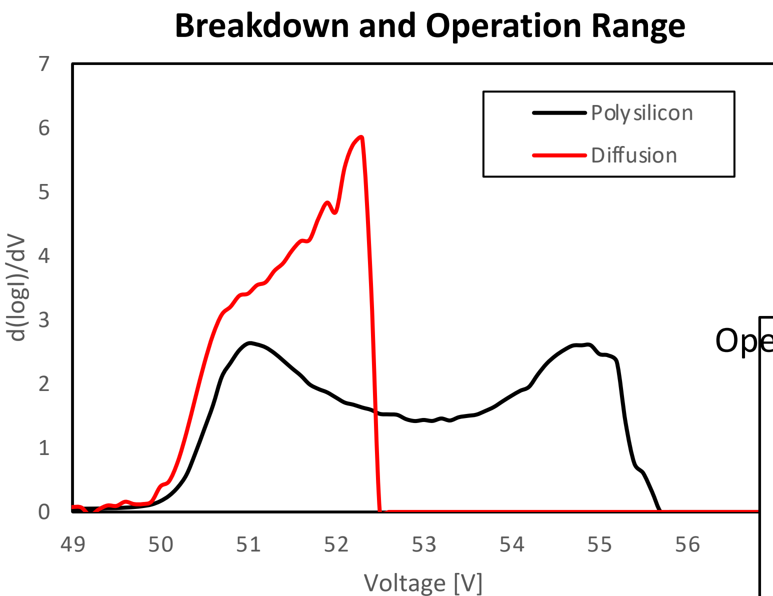
$$\mu = -ln\frac{N_{ped}}{N_{total}}$$

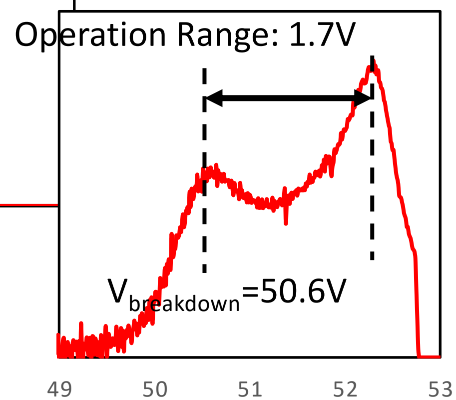
Type of SiPM	Square	Circle	KETEK
area [μm^2]	165 x 247	165 x 247	500 x 500
Average number of photon detection	0.069	0.40	0.67 (attenuated by ND filer)

*PDE is calculated by using PDE of reference (KETEK), calculated average number of photon detection, dimension ratio of SOI and KETEK SiPM, and value of ND filter

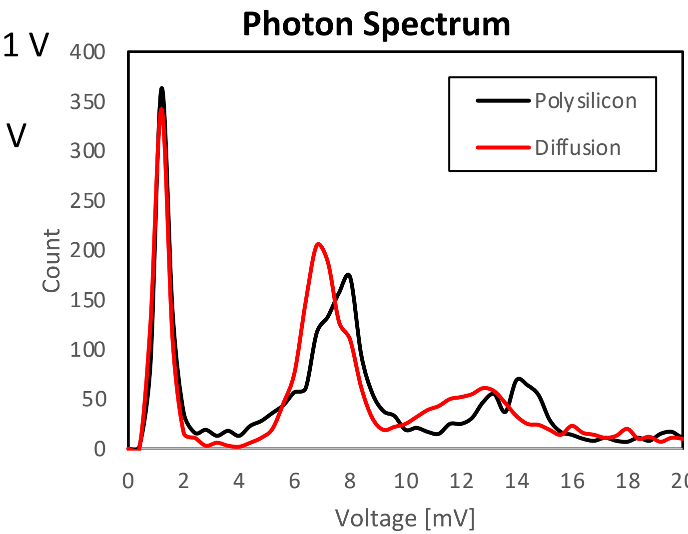
- Using PDE of KETEK SiPM (~40%) as a reference, calculated PDE of Square and Circle are **0.47** and **2.74%**, which is increased in factor of **5.8**

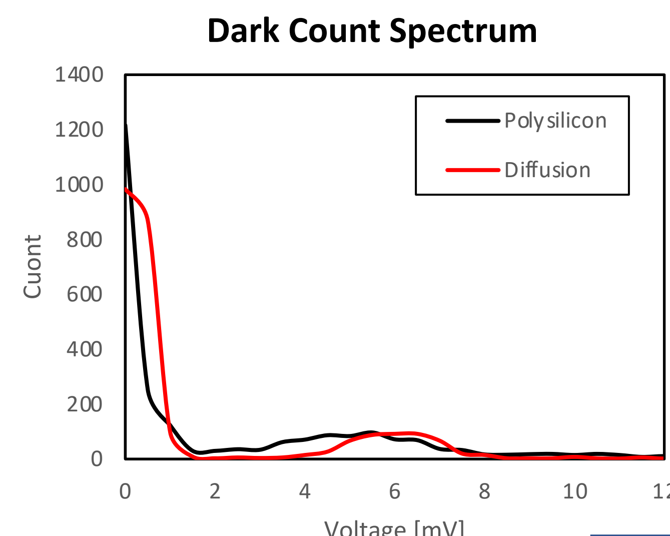
Results 2





- SiPM Bias Voltage
  - Polysilicon : 53.1 V ($V_{breakdown}$+**2V**)
  - Diffusion : 51.6 V ($V_{breakdown}$+**1V**)



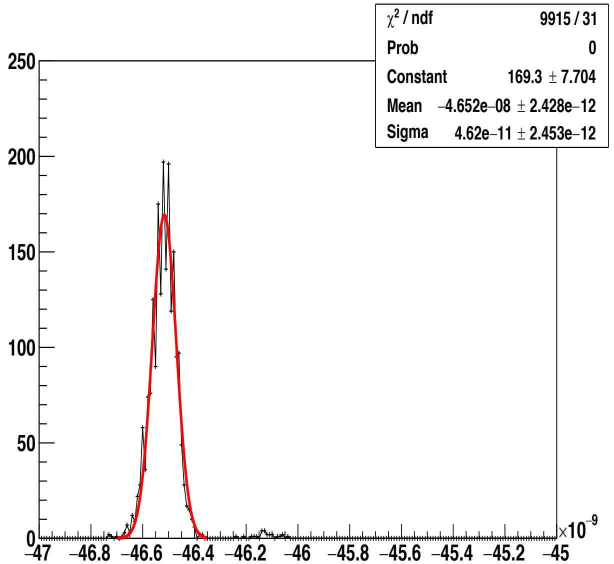


By modifying resistor type from polysilicon to diffusion

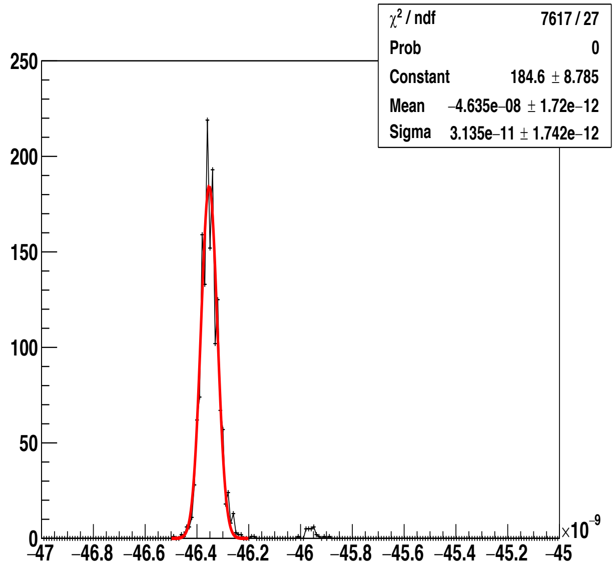
- Breakdown voltage decreases from **51.1 V** to **50.6 V**
- Operation range decreases from **3.8 V** to **1.7 V**
- Different overdrive voltage is applied, but show similar operation and sensitivity

Results 1&2: Time Resolution

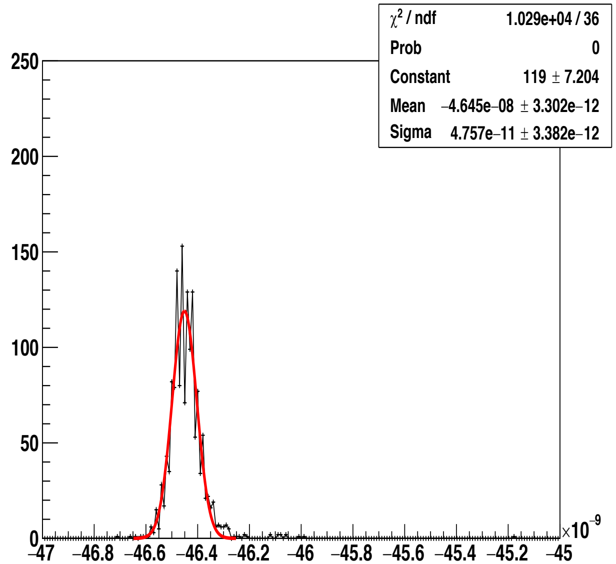
Square



Circle (polysilicon)



Circle (diffusion)

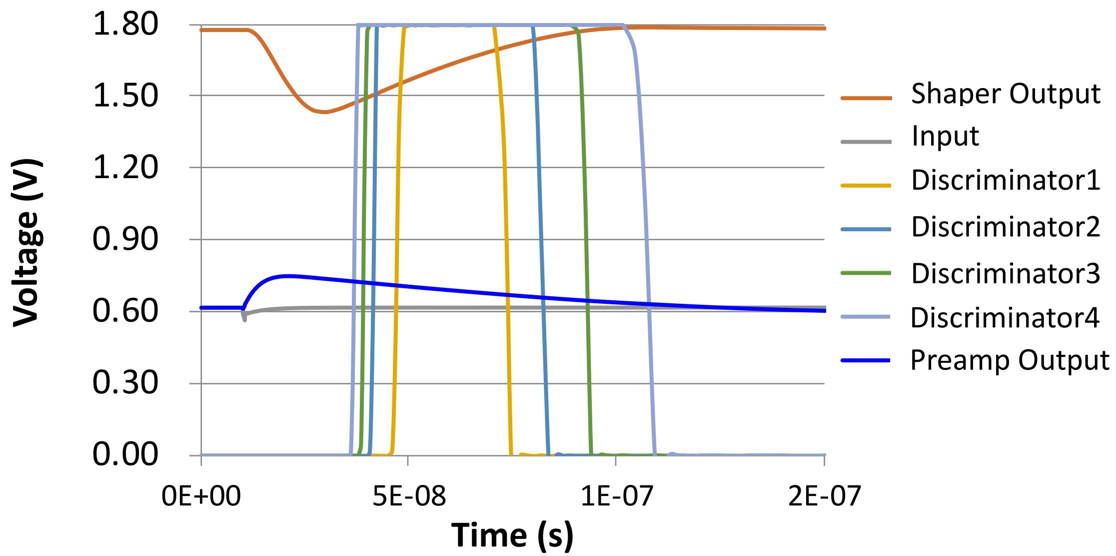


Type	Square	Circle (polysilicon)	Circle (diffusion)
Time Resolution [ps] FWHM	109	**74**	112

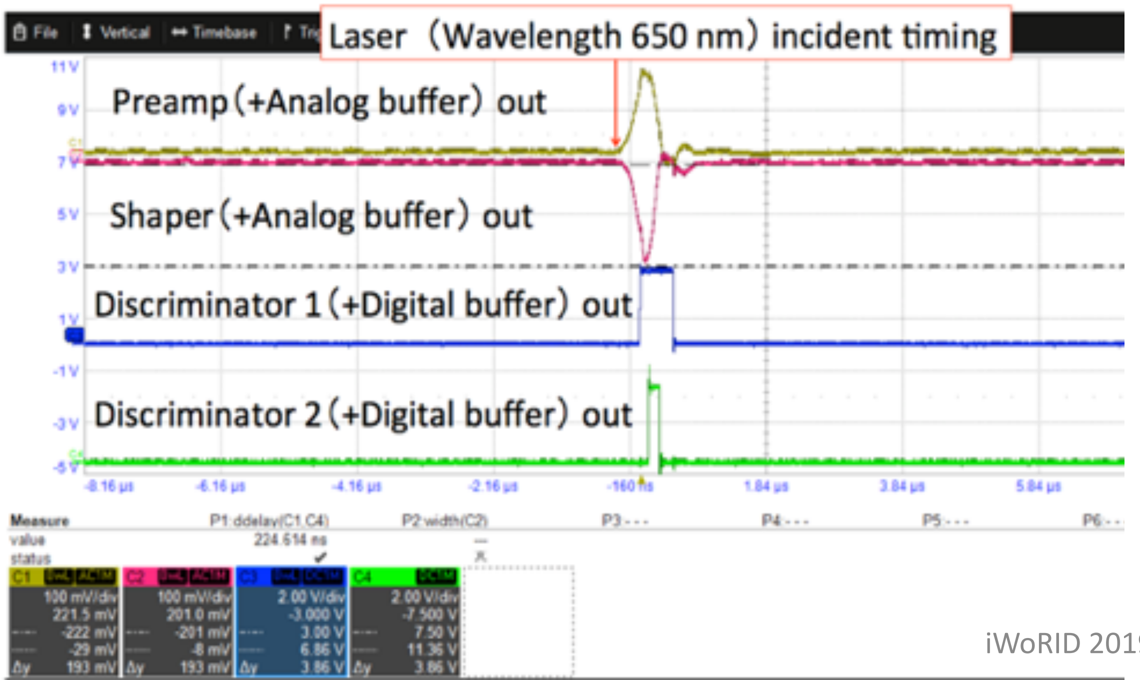
Time resolution is
- improved by modifying cathode shape from square to circle
- degraded by modifying resistor type from polysilicon to diffusion

Results 3: Readout Circuit

Simulation



Measurement



Conclusion & Future Plan

Conclusion

- SiPM and readout circuit are monolithically integrated into SOI wafer
- To improve sensor performance, the shape of cathode is modified from square to circle and the quenching resistor from polysilicon to diffusion
  - ✓ Cathode modification improves PDE and time resolution but increases DCR
  - ✓ Resistor modification degrades time resolution but other performances are kept consistent even though its operation range is halved
- Readout circuit is designed
  - ✓ Its simulation result corresponds with measurement result
  - ✓ The signal of SiPM was properly processed by our designed readout circuit that is built in same chip

Future Plan

- Continuous improvement on PDE and DCR
- Should figure out the method to do back illumination

Thank You for Your Attentions!