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

\[
G = \frac{SNR_{TOF}}{SNR_{nonTOF}} = \sqrt{\frac{2D}{c \times CTR}}
\]

- \(D\): 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!!!
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
Silicon on Insulator (SOI) - CMOS process

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

![Diagram of SOI technology]

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: \(20\text{fF} \times 1. \text{V} / 1.6 \times 10^{-19} = 131,250 \approx 1.3 \times 10^5\)
Research: so far...

510 nm laser is irradiated
- to acquire signal waveform
- to calculate gain by total output charge of single microcell

Gain of $10^5$ achieved

PDE: Photon Detection Efficiency

- **Incident photons:** 209 ± 42
- **Incident photons:** 76 ± 15

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

1. Square Type

- Cell size: 23μm
- anode (p)
- cathode (n)

2. Circular Type

- Polysilicon
- Diffusion
- Cell size: 23μm
- (Quench Resistor: 200 kΩ)

Cross Section View

- Bias
- Oxide layer
- Guard ring 3 μm
- Pixel size 27.52 μm
- Resistor
- Signal

- P+ - N+ - P-well - Deep P-well
- P+ - N+ - P-well - Deep P-well
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)

• 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**

Rate of Change: \[ \frac{d\log(I)}{dV} = \frac{dI}{I} \frac{1}{dV} = \frac{\Delta I}{I \cdot \Delta V} \]
Results 1: Dark Count Rate (DCR)

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

Dark Count

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

- 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

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

\[
\mu = -\ln \frac{N_{\text{ped}}}{N_{\text{total}}}
\]

Average number of photon detection

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

Breakdown and Operation Range

• SiPM Bias Voltage
  • Polysilicon : 53.1 V
    \((V_{\text{breakdown}} + 2\text{V})\)
  • Diffusion : 51.6 V
    \((V_{\text{breakdown}} + 1\text{V})\)

Operation Range: 1.7V

\(V_{\text{breakdown}} = 50.6\text{V}\)

Photon Spectrum

Dark Count Spectrum

By modifying resistor type from polysilicon to diffusion

• Breakdown voltage decreases from \(51.1\text{ V}\) to \(50.6\text{ V}\)
• Operation range decreases from \(3.8\text{ V}\) to \(1.7\text{ V}\)
• Different overdrive voltage is applied, but show similar operation and sensitivity
Results 1&2: Time Resolution

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

Laser (Wavelength 650 nm) incident timing
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!