A Digital Silicon Photomultiplier
The Circuit, and its Characterization

Inge Diehl, Finn Feindt, Karsten Hansen, Stephan Lachnit, Frauke Poblotzki, Daniil Rastorguev, Simon Spannagel, Tomas Vanat, and Gianpiero Vignola

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Motivation
For Digital SiPMs
Silicon Photomultipliers

Digital Devices with Analog Digital Readout

- Array of SPADs (Single-Photon Avalanche Diodes), sizes between 15 and 70 µm
- Single photon detection efficiencies reach $O(50\%)$
- Fast peaking time, reaching time resolutions of few 10 ps
- Typically with analog readout of all SPADs in parallel
- More light: number of firing SPADs approx. proportional to photon flux (within some constrains)
- BUT: The information a single SPAD provides is DIGITAL
- Add CMOS circuitry
  - No loss of information by digitizing SPAD signals
  - Profit from digital signal processing
  - E.g. resolve position of firing SPADs

[H. Kolanoski and N. Wermes]
The Circuit
A Digital Silicon Photomultiplier –
Designed in LFoundry’s 150-nm CMOS
The Readout Scheme

Key Components

- Four SPADs make a pixel
  - Variable quenching resistance ($V_{\text{quench}}$)
  - Masking (pixel not powered)
  - 2-bit hit counter (2 readout modes)
  - Wired-or connection to quadrant TDC
- 16x16 pixels form quadrant unit with
  - 12-bit TDC, time stamps of 1st firing pixel per frame; configurable validation logic
  - Per-frame hit-matrix readout

- This looks like a pixel detector! Can we operate it like a pixel detector?
- What are its MIP detection properties? Efficiency? Spatial and temporal resolution?
- Are 4D tracking applications feasible?
The Pixel

Four SPADs Make a Pixel

- Four library p+/n-well SPADs, 20 x 20 um², in parallel
- Surrounded by cathode and p-well ring for cross-talk minimization
- Pixel area 69.6 x 76 um², fill factor 30%
- Shared front-end below SPAD group

Example of a p+/n-well SPAD in a CMOS process
[F. Acerbi and S. Gundacker]
Caribou

A Versatile Readout System

- Developed by CERN, BNL, and DESY
- Fast, simple and low-cost implementation & tests of sensors, already 16 devices e.g. ATLASPix, CLICTD, ...
- System on Chip (SoC) Board – CPU and FPGA on same die
  - A CPU runs DAQ and control software
  - An FPGA runs custom hardware for data handling and detector control
- Control and Readout (CaR) Interface Board
  - Physical interface from the SoC to the sensor
  - Peripherals needed to interface and run the chip: power supplies, ADCs, voltage/current references, LVDS links, etc.
- Chip Board – passive & detector-specific components
Characterization
Lab – IV and Breakdown Voltage

Because Breakdown is what we Need

- Scanning the bias voltage in the breakdown region
- Different temperatures (climate chamber, humidity ~ 0%)
- Shift of breakdown voltage with temperature visible
- Avoid secondary breakdown for operation

Various definitions of breakdown voltage around
- We used the “relative derivative“
- Measured breakdown as a function of temperature
- 18.9 V at 20°C and about 20 mV/K

Reaching Geiger mode
Lab – DCR

Dark Count Rate

- Reading frames in dark environment
- Strong dependence on temperature and over voltage
  - Cooling helps!
- $10^4$ Hz per pixel corresponds to 6.25 Hz/um$^2$

- Pixel masking helps!
- Masking noisiest 10 % reduces noise by about 40 %
- Observed also an impact on leakage current
- Interesting case: single pixel determines breakdown

 Thermal excitation $\rightarrow$ carriers $\rightarrow$ discharge
TDC Characterization

Measuring TDC Bin-Width Variations

- Studying the fine TDC with nominal binning of 77 ps
- Expecting constant occupancy (on short time scale)
- Variations are due to delay variations
- Not exploiting full dynamic range of 32 bins!

- Find corrections statistical code density analysis
- The width of a bin corresponds to its fraction of the total entries times the clock period (~2.5 ns)
- Mean bin width 93.1 ps
Laser Measurements

Measuring Propagation Delays

Setup

- DUT placed on an x-y stage; laser optical system on a z-stage
- 1054 nm pulsed laser; focus width < 10 um in beam waist
- Laser in sync. with the DAQ clock
- Scan chip pixel-by-pixel, measure Time of Arrival (ToA)

• Clear function of distance to TDC
• Different offsets for each quadrant
Characterization

Beam Tests
Our Setup

Setup in March 2023

• Main goal: measure time resolution
• Triggering using 3 scintillators in coincidence
  • 4th scintillator with hole vetoes tracks out of acceptance
• For the time resolution measurement we take 2 dSiPMs
  • Not easy to find time reference better than 100 ps
• Assume 2 DUTs have similar resolution
  • Derive residual $\Delta t = t_{\text{DUT1}} - t_{\text{DUT2}}$
  • DUT resolution $\sigma_{\text{DUT}} = \frac{\sigma_{\Delta t}}{\sqrt{2}}$
• Custom cold box to allow for temperatures down to -5°C
• Estimated track resolution around 4 um

DSiPM | HSTD13 – Vancouver | Finn Feindt | 08.12.2023
Hit Detection Efficiency

Fill Factor Limited

- Analysis using Corryvreckan
  - Reconstruct tracks using the beam telescope
  - Associate hits on DUT using spatial cuts
  - \( E = \frac{N_{\text{assoc}}}{N_{\text{reco}}} \)
- In-pixel efficiency
  - Inefficient outside of SPAD region
  - Smearing due to track resolution (larger than expected)
- Over all efficiency – determined by fill factor
  - About 30 %, corrected for dead time and fake hit contributions
  - Small voltage dependence above breakdown observed
Spatial Resolution

Determined by Pixel Size

- Difference between reconstructed hit and interpolated track position \( \Delta x = x_{\text{track}} - x_{\text{hit}} \)

- Double peak feature due to in-efficient region between SPADs (remember previous slide!)
  - Added Corryvreackan feature: Define arbitrary fit function for DUT alignment MR

- Unavoidable contribution from dark counts (circular background distribution)

- Signal described by double box convolved with Gaussian

- Does the track resolution explain the width of the Gaussian?

- Achieve spatial resolution on the order of 20 um
Time Residuals

Measuring the Time Resolution

Time residual between two dSiPMs $\Delta t = t_{\text{DUT1}} - t_{\text{DUT2}}$

- Each of them contributes 3 cases
  - Fast signal; Gaussian with width between 35 and 55 ps
  - Slow signal; exponential tail (about 15 %)
  - Noise; flat background

Origin of the tails
- Left: Intercepts of tracks with associated hits
- Right: same, but excluding fast component
- Slow response associated to SPAD edges
Also visible in laser measurements
**Time Residuals**

Measuring the Time Resolution

Time residual between dSiPM and ref. \( \Delta t = t_{\text{DUT0}} - t_{\text{TLU}} \)

- Fast signal; dominated by time reference
  - Trigger scintillator + TDC in AIDA TLU
- Slow signal; slow DUT response

Origin of the tails

- Left: Intercepts of tracks with associated hits
- Right: same, but only for slow component
- Slow response associated to SPAD edges
- Also visible in laser measurements
MIP Timing

Timing Plane Application

• Spatial and temporal resolution are promising

• Hit detection efficiency too low
  • 30 % fill factor probably not practical

• Fill factor can be optimized but will always be limited

• F. Carnesecchi, et al. increased MIP detection efficiency of SiPMs due to Cherenkov effect in encapsulation
  • We started studies in that direction!
    • Keep spatial resolution on the order of pitch
    • First photon counts → suppress tails in timing

• How much will the efficiency increase?

• How much will it cost in material budget?

Example: encapsulated Hamamatsu SiPMs
Summary

Yes, like a pixel detector!

Introduced a digital silicon photomultiplier produced in an LFoundry’s 150-nm CMOS process

Test-beam characterization

• Hit detection efficiency (MIPs): > 30 %
• Spatial hit resolution (MIPs): ~ 20 um
• Temporal resolution (MIPs): ~ 50 ps

Submitted first paper on circuit design and laboratory characterization (already available on ArXiv)

We are eager to test dSiPM + radiator in the beam!
A Single Photon Avalanche Diode
Basic Building Block of a SiPM

- Strong doping gradient generates strong field → Geiger mode amplification
- Quenching of discharge by lowering the bias voltage (quenching resistor)
- Gain on the order of $10^5$ to $10^6$ → counting device sensitive to single photons
- Photon interactions (optical energy range)
  - Exciting single electron from to conduction band
  - Penetration depth between 0.1 μm (blue) and 10 (red) μm
- Photon detection efficiency: fill factor $\times$ quantum efficiency $\times$ breakdown probability
- Electron interactions (GeV energy range, close to minimum)
  - 50 to 100 electron-hole pairs per micrometer
  - Deposition along electron trajectory

[F. Acerbi and S. Gundacker]
Charged Particles

And Their Interaction with Matter - Silicon

- Electrons (GeV energy range, close to minimum)
- Energy loss dominated by ionization and excitation
- Radiative losses below 1%, limited contribution to signal in thin Silicon detectors
- Straggling functions are highly skewed due to rare large energy depositions
- Mean ionization energy 3.67 eV per electron-hole pair
- Signal on the order of 50 to 100 electron-hole pairs micrometer (depends on material thickens)
- Deposition along electron trajectory
- Similar for other charged particles around energy loss minimum (MIPs)
Optical Photons
And Their Interaction with Matter - Silicon

- Photons (optical energy range)
  - Internal photo effect: dominant contribution from 1 eV to several 10 keV [cw]
  - Exciting 1 electron from valance to conduction band
  - Minimal energy (band-gap) 1.12 eV, corresponding wavelength 1100 nm (UV)
  - Indirect band-gap transition requires phonon interaction
    - Strong rise in absorption probability to 3.4 eV
    - Temperature dependence
  - Penetration depth between 0.1 and 10 um
Validation Logic

Suppressing Noise

• Implemented for each quadrant separately
• Hit within a row generates „true“ for said row
• Cascade of AND/ OR operations between rows
• Allows to select certain hit patterns
  • E.g. at least 1 hit in each row
  • Or at least 1 hit per row in a pair of rows
• Helps to discard noise hits if certain signal patterns are expected
TDCs

Time Digital Converters

- Fine TDC – taped delay line with delay locked loop
  - 32 delay elements
  - 5 bit, nominal binning of 77 ps
  - 32 to 5 bit encoding

- Frame clock 3 MHz defines readout frames 333 ns
- System clock 408 MHz used in coarse and fine TDC

- Coarse TDC – ripple counter
  - 7 bit, covers 313.7 ns acquisition window
First Timing studies with LED

Preliminary Results

Timing performance

- From Preliminary LED studies
- TR of the whole system reported
- Quadrant TOA: $\sigma \sim 120$ ps
- Time differences bw Quadrants: $\sigma \sim 160$ ps
- No correction for propagation delays

![Diagram of TDCs and Quadrants]

TOA Noise < ToA LED

High light effect
Our Setup

The First Shot

Setup in May 2022 – proof of concept, integration test

- Triggering using 3 scintillators in coincidence
- 4th scintillator with hole vetoes tracks out of acceptance
- Track time resolution $O(1\text{ns})$ (scintillator + TLU TDC)
- Estimated track resolution around 5 $\mu$m
- Temperature stabilization $\sim 25^\circ \text{C}$ (no cold box)
Beam Test – Introduction

Test Bench for Particle Detectors – The Tracking Detector Case

Components

- Beam (DESY II 5 GeV, SPS, MAMI;)
- Tracking system, 6 planes of pixel detectors
- E.g. scintillators for timing and triggering
- Device Under Test

Goals

- Prove/ test integration of prototypes
- Performance characterization
- Detection efficiency
- Resolution in space, time, (energy)

Reconstruct individual charged particles – time and position information
Alignment

Material Budget Imaging

DUT- Trigger Alignment With High Dark Count Rate

- DCR/MIP event distinction impossible before alignment
- dSiPM too noisy to use self trigger

Material Budget Imaging (MBI)

- Amount of scattering is proportional to the thickness of the scattering medium in radiation lengths
- Plot width of scattering angle distribution in DUT-plane

Evaluation of MB using Corryvreckan

- Maximize multiple Coulomb scattering
- Use the straight line approximation for tracks in the two arms of the beam telescope (TrackingMultiplet)
- Material budget image obtained in global coordinates
Contact

DESY. Deutsches Elektronen-Synchrotron
Finn Feindt
Tangerine

www.desy.de
finn.feindt@desy.de