Outline

• Photo-detection with silicon: Basic principle

• Multi-pixel avalanche photo-diodes in Geiger mode (SiPM)

• Characterization of Silicon Photo-Multipliers
  – Static measurements
  – Dynamic measurements

• Analogue and Digital SiPMs

• Discussion: application to HEP and medicine
Light absorption in Silicon

E\textsubscript{\gamma} \sim 1.7-3 \text{ eV} \text{ penetrates} 
\sim 1-5 \text{ \textmu m} \text{ in Si}

Absorption length (\textmu m)

Wavelength (nm)

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Absorption length (\textmu m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue (470 nm)</td>
<td>0.6 \textmu m</td>
</tr>
<tr>
<td>Green (525 nm)</td>
<td>1.2 \textmu m</td>
</tr>
<tr>
<td>Yellow (590 nm)</td>
<td>2.2 \textmu m</td>
</tr>
<tr>
<td>Red (625 nm)</td>
<td>2.9 \textmu m</td>
</tr>
</tbody>
</table>
Photon detection in Silicon

Avalanche Photo-Diode operated in linear mode ~ AMPLIFIER (Gain ~ 50-500)
!! signal proportional to number of photons deposited
⇒ used in CMS ECAL

Geiger mode Avalanche Photo-Diode
operate above breakdown voltage (Gain ~1*10^6)
!! It’s a BINARY device
⇒ for practical application use ARRAY of single Geiger mode Avalanche Photo-Diodes:
the Silicon Photo-Multiplier
Issues with Geiger mode operation

Non-linear response:
due to Geiger mode operation 2 or more photons simultaneously hitting 1 pixel give the same response as 1 photon

Quenching of avalanche:
~ Infinite gain = infinite current

Self-supporting avalanche will continue “forever” ➔ need to stop the avalanche
SiPM schematic (simplified)

- all pixels connected in parallel
  - only one signal line
  - output = \( \Sigma \) pixel signals

- typical Bias voltage \( \sim 1-5 \) V above breakdown

- Poly-silicon resistor \( R_q \sim 1-10 \) M\( \Omega \)

- Pixel:
  - size \( \sim 20-100 \) \( \mu \)m
  - \( C_{\text{pixel}} \sim 10-100 \) fF
The Silicon Photo-Multiplier

small multiplication region \( \sim 2 \mu m \)
strong electric field \( (2-3) \times 10^5 \) V/cm
gain \( \sim 10^6 \)
carrier drift velocity \( \sim 10^7 \) cm/s
very short Geiger discharge

Si: \( \sim 5 \times 10^{22} \) atoms/cm\(^3\)
n++: \( \sim 10^{19} \) /cm\(^3\)
p+: \( \sim 10^{16} \) /cm\(^3\)
Signal shape

Often two time components visible:

Geiger discharge formation (fast)

Recovery time (slow): Time needed to recharge a cell after a breakdown mostly depending on the cell size ($C_{\text{pix}}$) and the quenching resistor ($R_q$).
Signal timing

Avalanche breakdown process is fast and the signal amplitude is big. ⇒ very good timing properties even for single photons.

Fluctuations in the avalanche are mainly due to a lateral spreading (~10 ps) by diffusion and by the photons emitted in the avalanche.

SiPM characterization

Static characteristics
• Current-voltage
• Capacitance-voltage

Dynamic characteristics
• Photo-detection efficiency
• Gain
• Dark count rate
• Cross-talk and after-pulse
Current-voltage characteristics

qualitative IV diagram (currents are not in scale)

reversal region

forward region

\[ I = \frac{U}{R} + I_0 = \frac{U}{R_q/N_{pix}} + I_0 \]

leakage current

\( O(10pA) \)

Firing pixel

Non-firing pixels

RC model of a reverse-biased SiPM

Partial Depletion

Fully Depleted

Breakdown

Reverse Bias Voltage [V]

Current [A]
Photon Detection Efficiency (PDE)

PDE is the product of mainly three components:

PDE = QE \cdot \varepsilon \cdot P_{\text{Geiger}}

- intrinsic Quantum Efficiency (~80% for Si)
- fraction of sensitive area (20-80%)
- probability of Geiger breakdown (~100%)

But more factors contribute:
- surface reflection losses
- pixel recovery time ($R_{\text{pixel}}$)

Note: semiconductor detectors offer better PDE than vacuum tubes (no electron emission needed)
Photon Detection Efficiency (PDE)

PDE is the product of mainly three components:

\[
PDE = QE \cdot \varepsilon \cdot P_{\text{Geiger}}
\]

- fraction of sensitive area (20-80%) → technology

Photoemission spectra* for SiPMs from different producers. Form left MEPhi/PULSAR, SensL and MPPC (Hamamatsu).
Color scale: red = high / blue = low emission rate (*different from absorption)
The dopant implanted in the silicon is responsible for the shape of emission.
Photon Detection Efficiency (PDE)

PDE is the product of mainly three components:

\[ \text{PDE} = \text{QE} \cdot \varepsilon \cdot P_{\text{Geiger}} \]

- fraction of sensitive area (20-80%) ➔ technology

influence of sensitive area

=400nm, including the cross-talk and after pulse
Photon Detection Efficiency (PDE)

PDE is the product of mainly three components:

\[ \text{PDE} = \text{QE} \cdot \varepsilon \cdot P_{\text{Geiger}} \]

- intrinsic Quantum Efficiency (\(~80\% \text{ for Si}\) \(\Rightarrow\) \(\lambda\) dependent

influence of quantum efficiency

![Graph showing PDE vs. wavelength with markers for different detectors: XP2020 PMT, INR/JINR APD, CPTA APD.](image)
Photon Detection Efficiency (PDE)

PDE is the product of mainly three components:

\[ \text{PDE} = \text{QE} \cdot \varepsilon \cdot P_{\text{Geiger}} \]

Geiger probability

Electrons have a higher probability to trigger an avalanche breakdown than holes.
SiPM gain

SiPM signal output = analogue sum of all pixel signals

Gain vs. over-voltage

Fit function:

\[ G = \frac{Q_{out}}{q_0} = C_{pix} \cdot \frac{(V_{bias} - V_{bd})}{q_0} \]
Dark count rate

Only the very basics:

A geiger discharge in a SiPM pixel can be initiated by an incoming photon or by free carries generated by thermal effects or tunneling (field-assisted generation)

→ dark count rate of 100 kHz – 10 MHz / mm² (@25°C) with threshold at half of one photo-electron amplitude

Free carrier generation by thermal effects

- Depends on temperature (can be cooled away)
- ... charged impurities assist the emission of free carriers (Poole-Frenkel effect)
- ... depends on silicon quality

Note: Vacuum tubes inherently lower dark current per unit of sensitive area
Correlated noise: inter-pixel cross-talk

Optical inter-pixel cross talk:

during Geiger avalanche
~3 emitted $\gamma / 10^5$ carriers
with $E_\gamma > 1.14 \text{ eV}$

*A. Lacaita et al, IEEE TED (1993)*

Absorption coefficient $\sim 2\mu\text{m}$

Emission microscopy picture, MPI

→ Leads to artificial increase of signal

A. G. Chynoweth and K. G. McKey (1956)
Correlated noise: after-pulse

In the silicon volume, where a breakdown happened, a plasma with high temperatures (few thousand degree C) is formed and deep lying traps in the silicon are filled. Carrier trapping and delayed release causes after-pulses during a period of several 100 ns after a breakdown.

The probability for after-pulses increases with higher overvoltage (higher gain).

The amplitude of the after-pulse signals depends on the recovery stage of the pixel ➔ Use to determine recovery time
Effective noise spectrum

- **Single photon (DCR)**
- **Cross-talk**
- **After-pulse**

Electronic noise
Dark rate
Cross-talk
After-pulse

Integration gate

Counts

QDC channel

Electron
Hole

SiPM Z-type. U-Ubd = 8V. \( k_{opt} = 1.85 \).
\( t_{gate} = 80 \text{ns}. \)

QDC LeCroy 2249A. Noise.

This is what you observe (3 pixels)
Analogue and Digital SiPMs

\[ i = i_1 + i_2 + i_3 + i_4 + \ldots + i_n \]

SiPM with localized signal digitization: detector + integrated circuit on same silicon substrate

- Utilize the industrial CMOS process
- Lower overall power consumption
- Reduce noise, time jitter
- “Smart” pixels (on-chip logic)
dSiPM implementation

CMOS fabrication process for SPAD
- Standard process for CMOS transistors
- Reliable, reproducible, low cost, huge library of digital circuit

But: need to comply to design rules → severe constrains (especially on guard ring)
- Create high-field multiplication region
- Keep it uniform
  - Avoid premature edge breakdown

E-field simulation

Heat image

No guard ring

with guard ring

S. Sze et al. 1966

E. Kamarani et al. 2012
dSiPM implementation

CMOS fabrication process for SPAD
- Standard process for CMOS transistors
- Reliable, reproducible, low cost, huge library of digital circuit

But: need to comply to design rules → severe constrains (especially on guard ring)
  - Create high-field multiplication region
  - Keep it uniform
    - Avoid premature edge breakdown (high DCR)

E-field simulation

Heat image

No guard ring

with guard ring

E. Kamarani et al. 2012

Many different solutions:
dSiPM implementation

CMOS fabrication process for SPAD

• Standard process for CMOS transistors
• Reliable, reproducible, low cost, huge library of digital circuit

But: need to comply to design rules $\rightarrow$ severe constrains (especially on guard ring)

- Create high-field multiplication region
- Keep it uniform
  - Avoid premature edge breakdown
- Many limiting factors effect the shape of the SPAD: scalability, feature size limit, noise induction etc.

Many different solutions:

- High E-field at corner $\Rightarrow$ high Dark Count Rate
- Low fill factor $\Rightarrow$ low PDE
Benefits of dSiPM

- Localized digitization
  - resume the binary nature of the SPAD → Gain measurement not needed
  - Overall reduced power consumption and temperature sensitivity
- Active Pixel Quenching and Recharging
  - controllable dead time → high count rate with very short dead time
- Dark Count Rate suppression – Pixel masking
  - DCR in a SiPM is skewed → lattice defect, contamination, local high field
- High precision timing measurement
  - Timing deteriorated by jitter in avalanche build up time & routing → TDC integrated on chip minimizes routing jitter
- Photon – time correlation measurement
  - Multiple TDCs provide multiple time measurement → Use order statistic for the optimum time resolution (Cramer-Rao limit)
Photon – time correlation measurement

- Multiple TDCs provide multiple time measurement → Use order statistic for the optimum time resolution (Cramer-Rao limit)
Example of dSiPM: MD-SiPM from TU Delft

- TU Delft's MD-SiPM prototype specification:
  - 30x50 μm² pixel size with 57% fill factor
  - 416 SPAD pixels (26x16) per cluster
  - 780x800 μm² cluster size
  - Photon Detection Efficiency (PDE) up to 17%
  - 48 column-wise shared TDC
  - 45 ps per TDC bin

Note: several inputs instead of 2-pins connection (LV, bias, clock, reset, data in, data out, ...)

27/34
Dark Count Rate (DCR)

- Rate of randomly discharged pixels due to thermal excitation, tunneling effect
  - Occurrence of dark counts follow Poisson statistic
  - Using zero counts to calculate the rate

DCR has non-linear dependence on:
- Excess bias voltage over break down
- Temperature

- Room temperature
- 1.4 V excess bias
- Charge integration time: 100 ns

- Room temperature
- 2.5 V excess bias
- Readout frame of 100 ns
Dark Count Rate (DCR)

- Compare to MPPC
  - Sensor DCR Comparison

- DCR per $\mu m^2$ of the two sensors at nominal operating voltage, room temperature

<table>
<thead>
<tr>
<th>MPPC</th>
<th>MD-SiPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sim 1$ Hz/$\mu m^2$</td>
<td>$\sim 50$ Hz/$\mu m^2$</td>
</tr>
</tbody>
</table>

- DCR Suppression:
  - Cool the sensor
  - Turn noisy pixel off (lost in efficiency)

- Cumulative Pixel DCR

  - Room temperature
  - 2.5 V excess bias
  - Readout frame of 100 ns
Trigger validation in dSiPM

- "Smart Reset" (SR): Reset pixels and TDCs if there is no TDC activation burst
  - Comparing to pixel memory, number of activated TDCs can be faster read out
  - Threshold on number of activated TDCs is "energy-like"

![Diagram of 2x16 pixel array with SR indicator and pixel occupancy graph showing number of pixels occupied by dark counts vs. frame acquisition time.](image)
Applications of SiPMs

- Photo-detectors + scintillators (organic or inorganic)
  standard solution for particles and photon detection in medical and high energy physics
SiPM applications: PET

SiPM matrix

High granular Positron Emission Tomography detectors with Time-of-Flight information

4x4 LYSO 3x3x15mm³

PET module with ~4000 channels

Higher granularity (0.75 mm) best with dSiPM

2013: Philips Vereos digital PET/CT
Detector response

$^{22}$Na source + 1x1x15 mm$^3$ LYSO crystal, dry contact, without wrapping

$^{22}$Na spectrum by MPPC (calibrated to number of fired pixels)

- 1x1 mm$^2$ device
- Gain measurement uses blue LED light
- Energy spectrum of $^{22}$Na is calibrated to number of fired pixels:
  \[ \text{Number of pixels} = \frac{\text{Charge}}{\text{Gain}} \]

$^{22}$Na spectrum by MD-SiPM

- 0.78x0.8 mm$^2$ device
- No need of gain calibration
SiPM applications: HEP

High granular calorimeter for future HEP experiments
Discussion

• **SiPM well established photo-detector**
  – Can it replace PMTs?
  – Limitations / advantages

• **dSiPM being established for medical application**
  – Can it be used also in HEP detectors?
  – Limitations / advantages
Advantages of semiconductor technique:

- reduced size
- low operation voltage ~ 100 V
- magnetic field insensitive !!!
- robust
- “cheap”
Capacitance-voltage characteristics

\[ C = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A}{d} \]

\[ \frac{1}{C^2} \text{ reaches a plateau at full depletion} \]
\[ Y = G_P + i\omega C_P, \]

\( G_P \) is the parallel conductance of the device, \( C_P \) its parallel capacitance
\( \omega = 2\pi \nu \), frequency of the alternating current
\[
C_P = \frac{Im\{Y\}}{\omega} \rightarrow N_{pix} \times (C_{pix} + C_q) \quad \text{high frequency values;}
\]
\[
R_P = Re\{Y\}^{-1} \rightarrow R_{par} \quad \text{for low frequency values;}
\]
\[
R_S = Re\{Y^{-1}\} \rightarrow R_q/N_{pix} \quad \text{for high frequency values;}
\]
Suppress optical cross talk

Possible counter measures:

• lower $V_{\text{Bias}}$ $\rightarrow$ lower breakdown probability (lower PDE)

• optical insulation between pixels $\rightarrow$

• technological modifications: i.e. smaller $C_{\text{pixel}}$

Before

SiPM $Z$-type. $U_{\text{opt}}=8V$. $k_{\text{opt}}=1.85$. $t_{\text{gate}}=80\text{ns}$. QDC LeCroy 2249A. Noise.

G=3*10^6

Counts

SiPM, MEPHI/Pulsar, PRELIMINARY

After

G=3*10^7

Counts

QDC channel

events
SiPM applications

High granular cameras for gamma-ray astronomy

which photo-detector to use?!
Applications for fast timing photo-detectors

- High energy physics – Calorimeter, PID, tracking
- Nuclear medicine – TOF-PET
- Astro-physics – Cherenkov telescope

- Photon correlation spectroscopy (use Brownian motion to determine the size of protein, molecule etc.)
- Fluorescence lifetime imaging (biology, neurobiology)
- Luminescent imaging (protein structure, chemical compound)
- Reflectometry (characterize optical fiber by photon-counting)
- Satellite laser ranging (Geodesy, material science)
- 3D imaging