Silicon-photomultiplier technology and their application in high energy physics detectors

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Outline

• Photo-detection in semiconductors: Basic principle

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

• Characterization of Silicon Photo-Multipliers

• Application of SiPM in detector development

• Conclusions: a bright future for photon detection
Photon detection in Semiconductors

Avalanche Photo-Diode

- operated in linear mode ~ AMPLIFIER (Gain ~ 50-500)
- !! signal proportional to energy deposited
- used in CMS ECAL

Geiger mode Avalanche Photo-Diode
- operate above breakdown voltage (Gain ~ $1 \times 10^6$)
- !! It's a BINARY device
- for practical application use ARRAY of single Geiger mode Avalanche Photo-Diodes:
  - the Silicon Photo-Multiplier
A brief history of SiPM development


The first 2 silicon single photon detectors fabricated by Haitz and by McIntyre. Both had to be operated in Geiger-mode, with a bias voltage several volts higher than the breakdown voltage.

after this single “photon counter” the playground for development of Geiger mode silicon-based photo-detectors moves to Russia … “where the SiPM is born”

Main players: Center of Perspective Technology and Apparatus, CPTA, Moscow
MEPhI/Pulsar Enterprise, Moscow & DESY (R. Klanner)
JINR (Dubna)/Micron Enterprise

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Array of Single Photon Avalanche Diodes

I will refer to one SPAD as pixel in the following

- typically 100-1000 pixels / mm²
- Some typical pixel parameter:
  - pixel size ~20-30μm
  - pixel capacitance $C_{\text{pixel}} \sim 50\text{fF}$
  - quenching resistor $R_{\text{pixel}} \sim 1-10\text{ MΩ}$

all pixels connected in parallel
only one signal line

- output = Σ pixel signals

typical Bias voltage ~ 2 V above breakdown
The Silicon Photo-Multiplier

Typical sensor area 1x1 mm² → new developments 3x3, 5x5 mm²

- small depletion region ~ 2 μm
- strong electric field (2-3) x 10^5 V/cm
- gain ~ 10^6
- carrier drift velocity ~ 10^7 cm/s
- very short Geiger discharge development < 500 ps
Semiconductor detector scale

Advantages of semiconductor technique:

- reduced size
- low operation voltage ~ 100 V
- magnetic field insensitive !!!
- robust
- “cheap”
Many different names / and different products

MPPC from Hamamatsu, Japan

Available on Hamamatsu catalogue

Short disclaim:
using the name SiPM I will refer to multi-pixel avalanche photo-diodes operated in Geiger mode

SiPM from MEPHI / PULSAR, Moskow

SiPM-CPTA from Photonique, Switzerland

AMPD from Z. Sadygov, Moskow

GMPD from INR/JINR, Moskow

“SiPM” from SENSL, Irland is coming...
... and many others

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SiPM properties: single pixel resolution

SiPM output is the analog sum of all pixel signals

- High gain   pixel signal visible on scope
- Signal rise time < 1 ns
- Fast fall ~ 5-10 ns
- Recovery time tunable by choice of quenching R
  \[ \tau \sim R_{\text{pixel}} C_{\text{pixel}} \sim 20 – 500 \text{ ns} \]
Single photoelectron spectrum recorded with silicon photodetector

— Albert Einstein, letter to Michel Besso, 1951.
Dynamic range naturally limited by number of pixels

Optimal working condition: number of photo-electrons $< N$ pixels

from probability considerations:

$$N_{\text{pixels}} = N_{\text{available}} \cdot \left[ 1 - e^{\frac{N_{\text{photo-electrons}}}{N_{\text{available}}}} \right]$$

~20% deviation from linearity if 50% of pixels are fired
Electron
Hole
Photon Detection Efficiency (PDE)

Most important parameter of a photo-detector !!!

Limiting factors:
• intrinsic Quantum Efficiency (~80% for Si) \(\rightarrow\) \(\lambda\) dependent
• fraction of sensitive area (20-80%) \(\rightarrow\) technology
• surface reflection losses
• probability of Geiger breakdown (~100%) \(\rightarrow\) \(V_{\text{Bias}}\) (or \(E\)) dep.
• pixel recovery time \((R_{\text{pixel}})\)

influence of quantum efficiency

influence of sensitive area

=400nm, including the cross-talk and after pulse
Dark count rate

Only the very basics:

- a SiPM pixel can be fired by an incoming photon but free carries can be generated also by thermal effects or tunneling (field-assisted generation)

- these lead to a dark count rate of 100 kHz – 10 MHz / mm² (@25°C) with threshold at half of one photo-electron amplitude (~0.5x10⁶)

Free carrier generation by thermal effects

- Depends on temperature (can be cooled away)

Tunneling

- Depends on operation voltage (E field)
- Influenced by technological design
Dark count rate

Dark Count vs Pixel Threshold (T=22°C)

dark count rate > 0.5 pixel ~ MHz decrease rapidly with threshold

what is the relevant threshold for physics?

β-source $^{90}$Sr

noise only

400 pixels, Hamamatsu

Blue sensitive SiPM directly coupled on 3x3x0.5 cm$^3$ scintillator tile
Pixel: a closer look

Optical inter-pixel cross talk:

during Geiger avalanche
~3 emitted $\gamma / 10^6$ carriers
with $E_\gamma > 1.14$ eV


 Leads to artificial increase of signal

Emission microscopy picture, MPI
How to suppress optical cross talk

Possible counter measures:

- lower $V_{\text{Bias}} \rightarrow$ lower breakdown probability (lower PDE)
- optical insulation between pixels
- technological modifications: i.e. smaller $C_{\text{pixel}}$

Before

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

Counts

G = $3 \times 10^6$

After

G = $3 \times 10^7$

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SiPM, MEPHI/Pulsar, PRELIMINARY
SiPM voltage dependence

characterization of 4000 SiPM MEPHI/Pulsar, from E. Tarkovski, ITEP
SiPM temperature dependence

Voltage and gain depend on temperature

\[ \Delta V_0 / \Delta T = (57.3 \pm 0.1) \text{ (mV/°C)} \]

\[ \text{Gain} = C \left( V_{\text{bias}} - V_0 \right) / e \]

\[ \text{C} : \text{Pixel capacity} \]

\[ V_0 : \text{Breakdown voltage} \]

\[ \text{Total Charge (Q)} = G \times \text{PDE} \]

\[ \frac{dG}{dT} \sim -1.7 \% / \text{K} \]

\[ \frac{dQ}{dT} \sim -4.5 \% / \text{K} \]

\( V_0 \) is linear to temperature.

\( \Rightarrow \) temperature changes affect the over-voltage \( V_{\text{bias}} - V_0(T) \)

\( \Rightarrow \) therefore all SiPM properties

\( \leftarrow \) 1200 pixels, MEPHI/Pulsar
Summary of SiPM features

- High gain (∼10^6) ➔ simplest r/o electronics
- Low electronics noise
- Low bias voltage (∼50 V)
- Low power consumption (≤50 μW/mm²)
- Insensitivity to magnetic field ➔ next generation of HEP detectors
- Compact and light ➔ direct couple to active material / space mission
- Excellent photon counting capability ➔ astro-particle physics
- Very low charge particle sensitivity (negligible nuclear counting effect)
- Very good timing (≤100 ps) ➔ medical applications
- Small recovery time
- Good temperature and voltage stability
- Room temperature operation
- Relatively low cost ➔ high number of channels possible

draw backs and limitations in the outlook ➔
SiPM application in detector development

• High energy physics
  - low light level detection
  - scintillation light readout

• astrophysics / “space” experiments
  - Cherenkov and Fluorescence light detection
  - Liquid Xenon detector

• medical applications
  - time resolution
The first detector with SiPM r/o operated in a beam

**H1 Radiation Monitor and FST Trigger**

(disk diameter ~30 cm)

Silicon Photomultiplier (x32)

Operating conditions:
- $U - U_{\text{breakdown}} \approx 1.5$ V
- Discriminator Threshold $\approx 1$ MIP

H1 shift tool (java applet):
- Single SiPM count rate/bunch X-ng
- Count rate of whole detector / bunch X-ng

- On-line Measurement of the Dose rate and Total Ionization Dose
- Automatic Beam Dump by either Detector for too high Dose Rate
R&D for Calorimeters for the ILC

Key requirements for photo-detectors:

- couple to scintillator material
  - high sensitivity to blue or green (+WLF)
- operate in high magnetic field (~5T)
- high granularity = compact detector
First prototype calorimeter with SiPM

Electron

Hole

First prototype calorimeter with SiPM

5x5cm² cells

Energy deposition, MIP's

Energy, GeV

Exp data

MC data

Energy resolution, %

Energy deposition [MIP]

Energy resolution [%]

100 channels technical prototype

tested with EM showers at DESY

test-beam in 2004

Excellent results obtained!

Beam energy [GeV]

1 (out of 13) layer from MiniCAL prototype

sandwich calorimeter 0.5:2 cm Scint. : Steel

Lateral shower shape

Longitudinal shower shape
High granularity hadronic calorimeter

A crucial technology improvement to calorimetry

Single tile readout with SiPM

1 mm²

3x3 cm²

1x1m² prototype calorimeter with 8000 channels readout with SiPM (MePHI/Pulsar)

100x100 cm²

Light Yield = 15 pixels / MIP
Dynamic range ~ 100 MIPs

!! auto-calibration of SiPM gain from single-pixel spectra

38 layers (~4.5 λ)
Scintillator – Steel sandwich structure (0.5:2cm)

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SiPM r/o for scint. strip: muon detector

16 layers (~5.5 $\lambda$)
2 Scint. – Steel sandwich structure
8x(0.5:2)cm+8x(0.5:10)cm
tested at DESY electron test beam

Test on 2m scint. strip with double SiPM r/o

Strip Responses to Beam

Coordinate along Scint. strip [cm]
The prototype calorimeter system for ILC

Establish the technology

Collect hadronic showers data with unprecedented granularity to
- tune clustering algorithms
- validate existing MC models

The final goal of CALICE:
A high granularity calorimeter optimised for the Particle Flow measurement of multi-jets final state at the International Linear Collider
High granularity EM Calorimeter for ILC

Scintillator – Tungsten sandwich structure
Scint. : W = 3mm:3.5mm

Fist prototype ready for test beam at DESY in Feb. 2007

Wave-Length Shifter Fibre

MPPC R/O

Electron

Hole

Pion

Multi-Pixel Photon Counter from Hamamatsu
R&D for Astro-particle and space physics

Key requirements for photo-detectors:

- detection of Cherenkov or fluorescent light
  - high sensitivity to UV (deep UV)
- good photon-counting capability
- rare events
  - highest possible Photo Detection Efficiency
- large detectors with small number of channels
  - larger area SiPM
- light and robust device
- time resolution
Ground based Gamma Ray Astronomy

Gamma Ray induces electromagnetic cascade

- Relativistic particle shower in atmosphere
  - Cherenkov light
    - fast light flash (~ns)
    - $100 \gamma / m^2$ (1 TeV Gamma Ray)

- MAGIC: world largest air Cherenkov telescope

which photo-detector to use?!
Space-based High Energy Neutrino Astronomy

The Extreme Universe Space Observatory

The detector requirements:
- compact and light-weight (solid state?)
- high efficiency (>30-40%) photo-detectors ($\lambda \sim 300-400$ nm)
- good single photon counting capability
- timing at the level of $\leq 10$ ns (~few meters space resolution)
- low single photoelectron dark rate (less than night sky rate)
SiPM development for single photon counting
(MAGIC/EUSO)

The requirements:
PDE > 40% → lowers E threshold, allows overlap with other experiments
Larger size (up to 10x10mm², 3x3 and 5x5 mm² under test) → to cover large area detector
Alternative development: back-illuminated SiPM

100μm Geiger drift cell:
- small $C_{cell}$
- full area efficiency

• Jitter of arrival of photo-electrons in the drift region < 3ns
• Dark rate (large drift volume ~ large noise?)
• Crosstalk should be kept one order of magnitude below physics

increase of PDE up to 70% possible

Semiconductor laboratory (HLL), MPI and MEPHI, Moscow
SiPM application for fast single photon timing

new generation of Cherenkov DIRC (Detector of Internal Reflected Cherenkov light) detectors for future High Luminosity B-factories:
- DIRC upgrade for BaBar
- Time of Propagation (TOP) detector for BELLE

The detector requirements:

time resolution <100 ps
dark rate <300 kHz/few mm² size
photon detection efficiency > 30%

Light Yield of Cherenkov light compared to Scint.

\begin{itemize}
\item \textbf{Lead glass:} \(2.4 \pm 0.5\) p.e. / \textbf{Bicron 408:} \(27 \pm 4\) p.e.
\end{itemize}

(from cosmic ray measurement)
Deep UV detection: Liquid Xenon detectors

E. Aprile, P. Cushman, K. Ni, P. Shagin

Liquid Xenon: T = -95°C
\( \lambda = 178 \text{ nm} \)

576 pixels SiPM, MePHI/Pulsar

→ Attractive alternative to PMT for UV photon detection at low energy detection threshold (i.e. neutralino dark matter searches)

typical PMT applied in TPC for WIMP searches PDE ~20%

\( ^{241}\text{Am} \) source
R&D for medical field applications

Key requirements for photo-detectors:
- ✓ coupling to LSO, LYSO crystals
  - ➔ sensitivity to blue light
- ✓ high number of photons
  - ➔ dark rate and crosstalk are not an issue
- ✓ insensitivity to B field (inside NMR magnet)
- ✓ time resolution (TOF+PET)
Time Of Flight Positron Emission Tomography

PET + time information ➔ key for noise suppression

3x3mm² SiPM (Z. Sadigov) + LSO crystal (2x2x10mm³)
test with $^{22}$Na

$\Rightarrow$ time resolution: 540 ps

5625 pixels, MEPHI/Pulsar, B. Dolgoshein, Beaune 2005

large area 3x3mm² SiPM directly coupled to
3x3x40 mm³ scintillator BC418
test with 3 GeV e- from DESY test beam
$\Rightarrow$ signal A ~ 2700 pixels
$\Rightarrow$ time resolution: $\sigma$(SiPM+BC418) = 33ps
SiPM summary

Advantages:

- High gain ($\sim 10^6$) $\Rightarrow$ simplest r/o electronics
- Low electronics noise
- Low bias voltage ($\sim 50$ V)
- Low power consumption ($\leq 50 \, \mu$W/mm2)
- Insensitivity to magnetic field
- Compact and light
- Excellent photon counting capability
- Very low charge particle sensitivity
- Very good timing ($\leq 100$ ps)
- Small recovery time
- Good temperature and voltage stability
- Room temperature operation
- Relatively low cost

Drawbacks and limitations:

- Small size (established only 1x1mm²)
- Not enough PDE ($\sim 20\%$)
- High dark rate
- Limited dynamic range
- Optical crosstalk being reduced ($< 10\%$)
- Sensitivity to blue being established

Fast developing technology
Solutions to the remaining open issues are coming
The future of photo-detectors

The SiPM field is fascinating and full of potentiality

The future is *bright* and efficient

Stay tuned on the developments !!!