Innovative technology for SiPM-like detectors

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## Low Light Level photon detector

### Silicon Photomultiplier (SiPM)
- Compactness
- Low weight
- Low power consumption (~50μW)
- Low voltage supply (20-100V)
- Fast signal (~1 ns front)
- Simple FE electronics
- Room temperature operation
  - Sensitivity to single photons
  - Possibility to measure light intensity
  - Excellent amplitude resolution
  - Negligible nuclear counting effect
  - Immunity to magnetic fields up to 7 T

### Vacuum photomultiplier (PMT)

E.Popova MEPhI
Outline:

1. Silicon Photomultiplier (SiPM)
2. SiPM main parameters
3. Advanced SiPMs (Innovative technology)
4. Digital and Multidigital SiPMs
5. Packaging and Matrixes
6. SiPM applications
7. Summary
Around 1990 the initial prototypes of SiPM (MRS Metal-Resistor Semiconductor APD’s) were invented in Russia (V.Golovin, Z.Sadygov, N.Yusipov (Russian patent #1702831, from 10/11/1989)).

They had:
- Too difficult and unreproducible technology
- Too low light detection efficiency (of about 1%)
- Unclear operational principle

But nevertheless they look very promising detectors for Experimental Physics!

What is available:

- MEPhI/Pulsar (Moscow) - Dolgoshein
- CPTA (Moscow) - Golovin
- Zecotek (Singapore) - Sadygov
- Amplification Technologies (Orlando, USA)
- Hamamatsu Photonics (Hamamatsu, Japan)
- SensL (Cork, Ireland)
- AdvanSiD (former FBK-irst Trento, Italy)
- STMicroelectronics (Italy)
- KETEK (Munich)
- RMD (Boston, USA)
- Excelitas Technologies (former PerkinElmer)
- MPI Semiconductor Laboratory (Munich)
- Novel Device Laboratory (Beijing, China)
- Philips (Netherlands)

...Every producer uses its own name for this type of device: MRS APD, MAPD, SiPM, SSPM, MPPC, SPm, DAPD, PPD, SiMPI, dSiPM...
Homage of Boris Dolgoshein (1930-2010)

Professor MEPHI
Head of the particle-physics department of MEPHI

Inventor of streamer chamber (1962)
Developer and pioneer of Transition Radiation Detector (TRD)

prof. Dolgoshein started to develop novel photodetectors which he called Silicon Photomultipliers (SiPM) since 1993

Now we have at MEPHI the new organized and well equipped in framework of the Russian Megagrant Program the Silicon Photomultipliers laboratory with ~ 50 employees
• Each cell – p-n-junction in selfquenching Geiger mode
• cell numbers: ~ 100÷10000/mm²
• All cells are equal
• Cells are independent from each other
• Signal – is a sum of all fired cells

Cell signal - 0 or 1
But SiPM is analogue device
**Silicon Photomultiplier (SiPM)**

**p-n-junction based detectors**

- Impact Ionization
- Avalanche multiplication
- Geiger discharge

**Geiger mode features**

Output signal doesn’t depend from input

Output signal value $Q$ is determined by charge accumulated on a cell capacitance

$$Q = C_{cell} \cdot (V - V_{breakdown})$$

**Microcell gain**

$$M = \frac{Q}{e}$$

$M = 10^5 - 10^7$

Discharge duration – of about 1 ns

(selfquenching due to resistor)
Silicon Photomultiplier (SiPM)

Response function for SiPMs with different microcells numbers

- "light" and "dark" signals are identical
- more intensive light

\[ N_{\text{fired cells}} = N_{\text{total}} \cdot \left[ 1 - e^{-\frac{N_{\text{photon}} \cdot \text{PDE}}{N_{\text{total}}}} \right] \]

- Response function depends on total number of microcells inside SiPM
- Saturation correction is possible
SiPM main parameters

- **Photon Detection Efficiency (PDE)**

\[
PDE = \frac{<N_{\text{fired cell}} >}{< N_{\text{photons}} >} \quad P(n, \lambda) = \frac{\lambda^n e^{-\lambda}}{n!} \quad < N_{\text{cell}} > = -\ln P(0, < N_{\text{cell}} >)
\]

- **Crosstalk (xt)** (afterpulsing (ap))

- **Gain (G)**

**Dark rate** \( f = < n_{\text{dark}} > / T \),

where \( T \) – integration time

- **Intrinsic jitter (\( \sigma_t \))**

SiPM’s single pixel spectrum is very useful thing for precise measurements! There are allow us to determine all main SiPM parameters.

Quite important – **PDE**, **gain** and **xt** are measured independently.
Crosstalk (XT)

**Xt and light signal**

MEPhI/MPI SiPMs

- **no xt suppression**
  - $U=64.7V$  $U_{bd}=60.74$
  - Gain = $0.8\times10^7$
  - $N_{\text{pixel}} = 4.29$

- **with xt suppression**
  - $U=35.5V$  $U_{bd}=31.5$
  - Gain = $1.62\times10^7$
  - $N_{\text{pixel}} = 4.32$

(IMAGING2010 Stockholm, Sweden June 8 – 11, 2010
B.Dolgoshein “Silicon Photomultiplier”)

**Main protection from crosstalk – optical trenches between the SiPM cells**

Geiger discharge emits secondary photons

**Xt and dark rate**

- $T = -61 ^\circ C$
- **no OC suppression**
- **with OC suppression**
- *Poisson*

MEPhI/MPI SiPMs

P. Buzhan et al. / NIM A 610 (2009) 131–134
PDE vs. XT

What is better –

- High PDE and high XT?
- Low XT and low PDE?

Of course **High PDE and low XT!**

But you can find quantitative answer in Sergey Vinogradov’s SiPM statistical analysis:


Crosstalk

$$ENF_{xt} = \frac{1}{1 - \ln(1 - xt)} \approx 1 + xt + \frac{3}{2} xt^2 + ...$$

- **Multiplication**
  
  $$ENF_{gain} = 1 + \frac{\sigma_{gain}^2}{Gain^2}$$

- **Photon detection**
  
  $$ENF_{pde} = 1 + \frac{PDE \cdot (1 - PDE)}{PDE^2} = \frac{1}{PDE}$$

- **Dark counts**
  
  $$ENF_{dcr} = 1 + \frac{DCR \cdot t}{N_{pe}}$$
SiPM main parameters

PDE & XT overvoltage trade-off

Total ENF based on PDE and P_dup relation (6) in detection of 60 ps 700 photon pulses in 100 ns gate by 1 mm MPPC 1600 pixels (vendor spec. bias 71.2 V). S. Vinogradov et al., IEEE NSS/MIC 2009.

Total ENF for a sequence of specific processes is

\[ RES(Y_{out}) = RES(X_{in}) \cdot \sqrt{ENF_{total}} = RES(X_{in}) \cdot \sqrt{ENF_{process\;1} \cdot ENF_{process\;2} \cdot \ldots} \]
Requests from HEP experiments

- Higher Photo-detection Efficiency (or Probability)
  - Currently standard 15-20% (green), 30% (blue)
  - Limiting factor = fill factor (fraction of active to total area)

- Larger dynamic range
  - Currently standard ~1000-1500 pixels / mm^2 (25 μm)
  - Drawback for larger dynamic range = reduction of fill factor

- Single photon counting = lower dark rate (DR) and cross-talk (XT)
  - Currently standard DR ~0.5-1 MHz/mm^2 (dependent on U_{ex})
  - Currently standard XT ~10-15% (dependent on U_{ex})

- Large surface photo-detectors (or photo-detector array)
  - Strong interest also for medical applications
Photon Detection Efficiency (PDE)

KETEK-W11-PM1150NT SiPM, 50 μm cell pitch, T=24 C

PDE is higher than 60%!

2nd advanced SiPM CTA workshop (March 2014)

Y. Musienko (louri.Musienko@cern.ch)

PDE is higher than 60%!
PDE&Crosstalk

MEPHI/MPI
NDIP2011

Hamamatsu
2014

PDEmax=50%

2nd advanced SiPM CTA workshop 2014

E.Popova MEPhi
FAIR 2014

Elena Popova, MEPhi (NDIP 2011)

Hamamatsu MPPC 2013, 50 μm cell, U=61 V

New 50 μm cell pitch MPPC, T=23 C

10% 0 5 10 Bias [V]

Y. Musienko (louri.Musienko@cern.ch)
Second generation of optical trenches developed by KETEK

(a) Micro Pixel with 62.5 µm x 62.5 µm

2nd Trench Generation

(b) KETEK SiPM device with 82.5 µm x 62.5 µm cell pitch

(c) Cross Talk Probability [%]

XT = 2.5%

F. Wiest NDIP2014
Excelitas Technologies

Effect of potting epoxy and pixel size on XT

- 3mm 50C Potted
- 3mm 50C Not Potted
- 6mm 50C Potted
- 6mm 50C Not Potted

Over-Voltage (V)

Crosstalk

5%
Dark Count - 30035 Engineering Samples

- B Series 30035
- Next Generation 30035

Current B Series

NEXT GENERATION

60kHz/mm²
NUV: new developments

Fine technology tuning is ongoing. New prototypes with:
- Breakdown voltage shifted from 26.5 to 32V.
- lower noise.

March 25, 2014  CTA meeting
New S12651-050C(X) MPPCs, 1mm², 50 μm cell pitch

T=22 C

Dark Count [kHz]

0  50  100  150  200  250

V-VB [V]

90kHz/mm²

Y. Musienko (louri.Musienko@cern.ch)
**KETEK SiPM, 2.8 mm dia., 15 µm cell pitch**

**KETEK SiPM, T=24.5 C**

- **PDE (515 nm) [%]**
  - Bias [V]: 29, 30, 31, 32, 33, 34, 35
  - Values range from 45% to 0%

- **Dark Count [MHz]**
  - Bias [V]: 29, 30, 31, 32, 33, 34, 35
  - Values range from 6 MHz to 0 MHz

**KETEK-W3_V11_D28 SiPM, T=24 C**

- **PDE [%]**
  - Wavelength [nm]: 350, 400, 450, 500, 550, 600, 650, 700, 750, 800
  - Values range from 60% to 0%

- **ENF**
  - V-VB [V]: 29, 30, 31, 32, 33, 34, 35
  - Values range from 1.5 to 0.8

46%
High density FBK SiPMs

T=24 °C

PDE[%] vs V-VB [V]

12 micron, PDE=35%

SiPM, T=22 C

Gain vs Bias [V]

FBK SiPM, T=24.5 C

ENF vs V-VB [V]

Y. Musienko (louri.Musienko@cern.ch)
Metal resistor is less sensitive to temperature than polysilicon one.
Fast Output Advantages

Fast Mode Improvements
- Rise times <100ps; 2ns recovery
- Short impulse response from 1-2ns FWHM
- Reduced signal output capacitance
- Higher count rate resolution ability
- Ability to clearly distinguish the first photon arrival time

SensL’s international patent application no. WO2011117309
Digital and Multidigital SiPMs

Analog SiPM
External electronics are required

Digital SiPM (Philips)

Ideal multidigital SiPM

TUI Delft MD- SiPM

OPTICS LETTERS / Vol. 39, No. 3 / February 1, 2014
E.Popova MEPhi

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Flexibility in digital SPAD design

- single pixel aspect ratio

Cell of an “Ideall” multidigital SiPM – too space and power consuming

Over 500 transistors in 50 x 50 μm² can be reduced depending on required functionalities. Typically 50/50 sensitive area to electronics.

E.Popova MEPhI

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**dSiPM - Digital SiPM (Philips)**

Signal from each pixel is digitized and the information is processed on chip:
- time of first fired pixel is measured
- number of fired pixels is counted
- active control is used to recharge fired cells
- 4 x 2047 micro cells
- 50% fill factor including electronics
- integrated TDC with 8ps resolution
Digital SiPM – Cell Electronics

- Cell electronics area: 120µm²
- 25 transistors including 6T SRAM
- ~6% of total cell area
- Modified 0.18µm 5M CMOS
- Foundry: NXP Nijmegen
Digital SiPM – Slow Scan Imaging Mode

- Spatial sampling of the light distribution
- Similar to dark count map measurement
- Dark count map can be used for correction
- Alternatively, use coincidence to reduce noise
- Potentially useful for light guide design
Inner PET head - Photo-detector - MD-SiPM

- 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
Detector response

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

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

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

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

- 0.78x0.8 mm$^2$ device

Erika Garutti
KETEK PM5550: 4-side buttable SiPM single channel solution

PM5550: 4-side buttable SiPM
- Cell type: 50 µm pitch
- Number of micropixels: 11164
- Active pixel area: 0.2791 cm² (5.2mm x 5.2mm)
- Chip size: 5.60 mm x 5.60 mm
- Package size: 6.0 mm x 6.0 mm

SiPM-Chip
- Based on PM5550

Array Dimensions:
- 3x3 SiPM array
- 9 output signals / 9 bias supplies
- Total PCB size: 17.8 x 17.8 mm²
- Total active area: 9 x 27.9 mm²
- SiPM to package fill factor: \( F = 79.3\% \)
- Symmetric package
2D MPPC Array with TSV

50μm pitch, 3x3mm chip, 16x16 channels with Connector type
Requests from HEP experiments

- Higher Photo-detection Efficiency (or Probability)
  - Currently standard 15-20% (green), 30% (blue) ->40% green - 50% blue
  - Limiting factor = fill factor (fraction of active to total area)

- Larger dynamic range
  - Currently standard ~1000-1500 pixels / mm²
  - Drawback for larger dynamic range = reduction of fill factor
    ->10 μm 10,000 pixels/mm²

- Single photon counting = lower dark rate (DR) and cross-talk (XT)
  - Currently standard DR ~0.5-1 MHz/mm² (dependent on $U_{ex}$) 30-100 kHz/mm²
  - Currently standard XT ~10-15% (dependent on $U_{ex}$) <10%

- Large surface photo-detectors (or photo-detector array)
  - Strong interest also for medical applications

TSV commercially available
SiPM pioneering experience

A crucial technology improvement to calorimetry

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

- 3x3 cm²
- 100x100 cm²

- Single tile readout with SiPM

- Si-based = insensitive to magnetic field!

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

- Allows unprecedented high granularity

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

- 1 mm²

erika.garutti@desy.de
Prototype has been successfully tested at DESY, CERN and FNAL during last years
Timing resolution with dSiPM

FARICH (Focusing Aerogel RICH) candidate for ALICE, PANDA, Super c-τ, (SuperB):
- another focusing aerogel development
- SiPM photon detector
- first use of digital SiPMs from Philips
- tested at CERN
- excellent timing
SUMMARY

- Other materials beside silicon are not presented here
- Different analog SiPM constructions are not presented here
- Different digital and semidigital approaches are not presented here

- Noise reduction are ongoing and will be improved further
- Crosstalk reduction continues due to improving of trench technology
- Afterpulsing reduction under way by using new materials, technology improvement
- Detection efficiency for UV and IR light are under development
- Timing will be improved both for analog and digital approaches
- Analog SiPM+electronics – with direct connection to computer is a strong desire of SiPM potential users
Voltage stability SiPM 100B for 5V (15%) overvoltage

latest MEPhI/MPI SiPM produced in cooperation with Excelitas

\[ \frac{dG}{GdU} (5V) = \frac{2.0\%}{100mV} \]

\[ \frac{dx}{xdU} (5V) = \frac{5.6\%}{100mV} \]

Relative gain variation, %/100mV
Relative crosstalk variation, %/100mV
Relative PDE(435nm) variation, %/100mV

6th NDIP 2011 E. Popova et al.
"Large area UV SiPMs with extremely low cross-talk"
Temperature stability SiPM 100B

latest MEPhI/MPI SiPM produced in cooperation with Excelitas

ΔV=4V (12%) overvoltage for T=20°C

26.4±0.4mV/°C

var = 0.5 % / °C

Number of pixels fired (595nm)

var = 0.2 % / °C

Cross-talk

var = 2.1 % / °C

6th NDIP 2011 E. Popova et al. "Large area UV SiPMs with extremely low cross-talk"
Schematic structure of the SiPM with bulk integrated resistors ($S=0.5 \times 0.5 \text{ mm}^2$, 10 000 cells/mm$^2$)

- n on p (structure for green light)
- sensitive area - 0.25 mm$^2$
- number of cells - 2 500
- operating voltage - 26.5 V
- quenching resistor value - 200-300 kΩ
Main SiPM’s parameters: Gain vs Voltage for different T

We need to collect SiPM’s spectra for different voltages.

With temperature decreasing $U_{\text{breakdown}}$ decreases too – temperature sensitivity.

$U_{\text{breakdown}}$ and $\Delta U$–are needed for different type SiPM comparison.
Timing resolution study

- tests of the time response of the same type of MPPCs

- NINO chip based readout
- DAQ by oscilloscope
- $\sim 200$ fs laser pulses
- single photon resolution (TTS) $\sigma \sim 80$ ps ($\sim 190$ ps FWHM)

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<table>
<thead>
<tr>
<th>Type: S10931</th>
<th>SPAD size ($\mu m^2$)</th>
<th>Number of cells</th>
<th>Fill factor (%)</th>
<th>Breakdown (V)</th>
<th>Opt. bias for PET [2] (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-100P</td>
<td>100 $\times$ 100</td>
<td>900</td>
<td>78.5</td>
<td>69.3</td>
<td>70.3</td>
</tr>
<tr>
<td>-050P</td>
<td>50 $\times$ 50</td>
<td>3600</td>
<td>61.5</td>
<td>70.5</td>
<td>72.4</td>
</tr>
<tr>
<td>-025P</td>
<td>25 $\times$ 25</td>
<td>14,400</td>
<td>30.8</td>
<td>69.2</td>
<td>73</td>
</tr>
</tbody>
</table>

S. Gundacker et al. NIM A718 (2013) 569
SPTR of a stand alone SiPM cell
min threshold, focused 2 micron spot, <200fs
scope LeCroy WaveRunner 620Zi 2GHz

U=35V
FWHM = 57,7 ps
electronics width = 12 ps
final FWHM = 56,4 ps

U=43V
FWHM = 34,4 ps
electronics width = 12 ps
final FWHM = 32,2 ps