Large area UV SiPMs with very high PDE & extremely low cross-talk

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Homage to Boris Dolgoshein (1930-2010)

- Professor, head of the particle-physics department in MEPHI
- Inventor of streamer chamber (1962)
- Developer and pioneer of Transition Radiation Detector (TRD)
- Since 1993 developing a new photon detector which he gave the name Silicon Photo-Multiplier (SiPM). Collaborating with DESY and then with Max-Planck Institute for Physics in Munich on SiPM
- 1st in the world large-scale SiPM application in Hadron Calorimeter prototype (~10^4 SiPM channels)

Developing UV sensitive SiPM with extremely low X-talk and very high PDE for MAGIC and EUSO experiments, 2002-2010

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A test batch produced in December 2010

- SiPM Sizes
  1x1 and 3x3 mm²
- μ-cell pitch
  50 and 100 µm
  40-80%

18 different modifications
Special features

3+ -fold X-talk suppression

A known way to suppress X-talk:
1. Isolating trenches

New ways:
2. 2nd p-n junction for isolating the bulk from the active region (patented)

3. OC suppression by ion implantation (patent pending)

Very high UV sensitivity

Record high PDE

Geometrical efficiency 80%

Very low temperature dependence

MePhl samples:
Different sizes 1x1mm, 3x3mm, and breakdown voltages 24-34V.

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SiPM vs. MPPC

SiPM: 1x1 mm², 100x100 µm², Geometrical Efficiency ~80%, T=+25°C, λ = 435 nm
Same light impinging on both sensors

SiPM 100B

MPPC
S10362-11-100U No.50

Measurement based on “0” probability

Overvoltage ∆U, V

Number of pixels

SiPM 100B 1x1 (Ubd=33,51)

Hamamatsu S10362-11-100U No.50 (Ubd=68,75)

Overvoltage ∆U, V

Crosstalk

calculated from left amplitude spectra

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X-talk and Excess Noise Factor

Light source variation according Poisson law

\[ N_{\text{fired\_pixels}} = \frac{\langle \text{Mean} \rangle}{A_{1e}} \]

\[ N_{\text{fired\_pixels}} = \frac{N_0}{1 - X_t} - \left( \frac{\sigma}{\langle \text{Mean} \rangle} \right)^2 = \frac{\text{ENF}}{N_0} \]

- \( N_0 \): number of fired pixels calculated from “0” probability
- \( X_t \): crosstalk
- \( A_{1e} \): single cell amplitude

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Timing for 3x3 mm$^2$ SiPM and MPPC

40ps laser, 405nm, single photon mode. T= -20°C

[Graph showing the relationship between FWHM (ps) and SiPM Bias Voltage (V) for different SiPM and MPPC models.]

Preliminary

SiPM Bias Voltage, V

FWHM, ps

- SiPM 50micron 50B
- SiPM 100micron 100B
- MPPC 50micron (S10362-33-050C No254)
- MPPC 100micron (S10362-33-100C No354)

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Timing with 3x3 mm$^2$, type 100B SiPM

40ps laser, 405nm, single photon mode, T= -40°C

Best value measured for 3x3 mm$^2$ 100B SiPM is 205 ps
Record high PDE \(^{(\text{pulsed mode LED, 100B type SiPM, 1x1 mm}^2)}\)

Measurements at MEPHI and at CERN (thanks to Y. Musienko)

- The PDE measured with reference calibrated PIN-diodes is slightly lower than with the reference calibrated PMT
- All results are consistent within experimental errors

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Voltage stability SiPM 100B for 5V (15%) overvoltage

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

\[
\frac{dXt}{XtdU} (5V) = \frac{5.6\%}{100mV}
\]

\[
\frac{d\varepsilon}{\varepsilon dU} (5V) = \frac{0.25\%}{100mV}
\]
Temperature dependence type 100B SiPM

- **U_{breakdown} (V)**

  - Temperature dependence type 100B SiPM
  - $26.4 \pm 0.4 \text{mV/}\degree\text{C}$

- **Pixel gain**

  - $\Delta G/G \sim 0.5 \% /\degree\text{C}$
  - For $U = 37.3$ at $T = +20 \degree\text{C}$ ($\Delta U = 4\text{V}$)

- **Number of pixels fired (595nm)**

  - $\Delta\text{pde/pde} \sim 0.2 \% /\degree\text{C}$

- **Crosstalk**

  - $\Delta\text{Xt/Xt} \sim 2.1 \% /\degree\text{C}$

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PET Spectrometry with LYSO and Na$^{22}$

Self triggering mode
Amplitude spectra Integration time 1$\mu$s
LYSO 3x3x5 mm$^3$
Without collimator

Energy Resolution (FWHM) $\sim$14%

Preliminary. Setup is not yet optimized

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Timing for PET with LYSO and Na$^{22}$

LYSO 3x3x5mm³
Without collimator

Preliminary. Setup is not yet optimized

MPT XP2020

SiPM (MPPC)

CFD (10%)

Energy signal

FWHM (PMT resolution is Not substructed)

SiPM 100B  340ps
SiPM 50B   375ps
MPPC-50   520ps

SiPMs and MPPC are 3x3mm²

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Summary

- MEPHI & MPI, with strong support of Excelitas, have produced SiPMs of 1x1 and 3x3 mm\(^2\) sizes with extremely high PDE (≥ 50\%) in the UV-blue region
- The X-talk is ~ 3-5 \% for saturated PDE (\(\Delta \text{U}/\text{U} \sim 12-15 \%\))
- ENF is ~ 1.02 (due to 4-fold X-talk suppression)
- \(T^\circ\) sensitivity: PDE ~0.2 \%/\(^\circ\)C; Gain ~0.5 \%/\(^\circ\)C
- Time jitter (FWHM) for 3x3 mm\(^2\) SiPM (100 \(\mu\)m pitch) is ~200-300 ps; further improvements are possible
- Dark rate ~ 1MHz/mm\(^2\)
- On the way of becoming commercial product of Excelitas
SiPM Noise

![Graph showing SiPM Noise vs Bias voltage U, V for different temperatures (T) and dark rates.]

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Efficiency measurements

reference: a calibrated PIN diode Hamamatsu S1337-1010BQ

\[ PDE = AR \cdot Internal\text{QE} \cdot A \cdot Geiger(U) \]

Calculated AR transparency

\[ Internal\text{QE} = \frac{QE}{AR} \]

Measured QE for test structure

Measured PDE for 100B SiPM (overvoltage 15%)
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Spectral PDE comparison

Electron-Photomultiplier (PMT) XP2020Q (according to Philips Photonics)

APD EG&G C30626E (NIM A428 (1999) 413-431)

SiPM 1x1mm$^2$ 100B

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