Characterization of a prototype matrix of Silicon PhotoMultipliers (SiPM’s)

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Research activity based on a MoU in between LAL/ FBK-irst/ Pisa University
Outline

◆ Motivation for a SiPM matrix development

◆ Characterization of a prototype matrix of SiPM’s
  • static and dynamic characteristics
  • two read-out systems
    ▪ single-channel amplifier
    ▪ multi-channel read-out electronics

◆ Summary and outlook
Many fields of applications require photon detectors:

- Astroparticle physics (detection of the radiation in space)
- Nuclear medicine (medical imaging)
- High energy physics (calorimetry)
- Many others

Characteristics to be fulfilled by the photon detector candidate:

- Highest possible photon detection efficiency (blue–green sensitive)
- High speed
- High internal gain
- Large detection area
- Single photon counting resolution
- Low power consumption
- Robust, stable, compact
- Insensitive to magnetic fields
- Low cost
From single SiPM to matrix of SiPMs

- **SiPM** – fulfils most of the mentioned characteristics:
  - fast (the rise time of the signal ~ hundreds ps)
  - high internal gain ($\sim 10^5 – 10^6$)
  - low power consumption ($V_{\text{bias}} < 100V$, I ~ tens of $\mu$A)
  - single photon counting resolution
  - insensitive to magnetic fields
  - stable, compact

- **Detection area - a limiting parameter of the SiPM**
  - most devices have 1x1mm$^2$ area
  - devices of 3x3 or 4x4mm$^2$ have been produced
    - dark rate scales with the area of the device (~ 9 or respectively 16 times higher that the dark rate of 1x1mm$^2$ device)

- **Matrixes of SiPM’s are desired**
  - large detection area
  - maintain on each read-out channel a noise level corresponding to a device of 1x1mm$^2$
  - 2D position information
Prototype matrix of SiPM’s

- **Prototype matrix of SiPM’s produced at FBK-irst (Trento, Italy)**
  - 4x4 SiPM’s **on the same substrate**
  - each SiPM
    - element of the matrix – one output channel
    - 1x1 mm²
    - composed of 625 pixels
  - each pixel of the SiPM
    - GM-APD (n+/p) with integrated $R_q$
    - 40x40 µm²
  - total matrix fill factor: 30-35%

- **Characterization performed at LAL (Orsay, France)**
  - for each SiPM of the matrix:
    - breakdown voltage, quenching resistance, post-breakdown dark current
    - dark count rate (estimation of the afterpulses and cross-talk probabilities)
    - gain
    - photon detection efficiency (PDE)
  - two read-out systems:
    - a single-channel voltage amplifier progressively connected to all SiPM’s of the matrix
    - multi-channel read-out electronics developed at LAL
Set-up for tests in dark conditions

**Hardware:**
- voltage amplifier
  - MITEQ – 0.01-500 MHz / 50 Ω/ 45dB gain / 5mV RMS noise
  - Fisher Bioblock climatic chamber -10 to +50°C, PC temperature controlled through RS232
  - Keithley Source Meter 2611 ($V_{\text{max}} = 200$V, $I_{\text{sensitivity}} \sim 2$ pA, connections through triaxial cables)
  - home-made counter with variable threshold on the input signal
  - TDS 5054 oscilloscope (500 MHz, 5 GS/s)
  - Pt100 ohm thermometer read by a Keithley 2700 digital multimeter/ data acquisition system

**Software:**
- dark count rate measurements by C++ program
- IV characteristics, gain, afterpulses & cross-talk analysis, monitoring of the Pt100 thermometer by LabView software

**Diagram:**
- Source-meter
- SiPM1
- SiPM2
- SiPM16
- Dark conditions
- Amplifier
- Counter
- TDS 5054 oscilloscope
- Digital multimeter
- PC running LabView & C++ programs
- GPIB
- Temperature controlled climatic chamber
- dark conditions
- 1
- 2
- 16
- Pt100
**Very good uniformity of the $V_{BD}$ over the 16 SiPM’s of the matrix**

- $V_{BD} \sim 30.5V$; $\sigma_{\text{breakdown voltage}} \sim 0.5\%

**operation voltage:** $V_{bias} \sim V_{BD} + 10\% V_{BD}$

**overvoltage:** $\Delta V = V_{bias} - V_{BD}$

**Relatively high dispersion of the $I_{\text{post-BD}}$**

- $\sigma_{I_{\text{post-BD}}} @ \Delta V=2.5V \sim 12.5\%$

**Very good uniformity of the $R_q$ over the 16 SiPM’s of the matrix**

- $R_q \sim 500 \Omega$; $R_{q \text{ pixel}} \sim 330 \text{k}\Omega$

- $\sigma_{R_{\text{quench}}} \sim 1\%$
Dark count rate (DCR)

- The main source of the SiPM noise - the dark signals
- Mechanisms generating these signals:
  - thermal generation of the carriers – the main source
  - afterpulses – carriers trapped during one avalanche and when they released, they trigger a new avalanche
  - optical cross-talk – “hot carrier luminescence”: ~ 30 photons are emitted during an avalanche of $10^6$ carriers
    (A. Lacaita et al., IEEE TED, Vol. 40, nr.3, 1993)

SiPM dark signals shape

$\sigma_{DCR} @ \Delta V=2.5V \sim 12\%$

$I_{post-BD} = DCR \cdot G \cdot e$

$\sigma_{DCR}$ in agreement with the $\sigma_{I_{post-BD}}$
Afterpulses & cross-talk estimation

- **Afterpulse probability:**
  - parabolic increasing with the bias voltage
  - $P_{\text{afterpulse}} \sim 5\% @ \Delta V=2.5\,\text{V}$
  - $P_{\text{afterpulse}} \sim 10\% @ \Delta V=3.5\,\text{V}$

- **Cross-talk probability:**
  - linear increasing with the bias voltage
  - $P_{\text{cross-talk}} \sim 2\% \Delta V=2.5\,\text{V}$
  - $P_{\text{cross-talk}} \sim 3\% \Delta V=3.5\,\text{V}$

- The afterpulses probability decreases exponentially in time
- About 95% of the afterpulses occur during 30ns after the primary pulse
Gain

- Defined as the charge developed in one pixel by a primary charge carrier:

\[ Gain = \frac{Q_{\text{pixel}}}{e} = \frac{C_{\text{pixel}} \times (V_{\text{BIAS}} - V_{\text{BD}})}{e} \]

- Linear increasing with the overvoltage
  - the triggering probability increases linear with the bias voltage
- Pixel capacitance – the slope of the linear fit gain v.s. bias voltage

SiPM charge distribution

Good uniformity of the gain over 16 SiPM’s

\( \sigma_{\text{gain}} @ \Delta V=2.5V \approx 4\% \)
Set-up for tests in light conditions

**Principle method for the PDE measurement:**
- low incident flux (~ $10^7$ incident photons /s/mm²) – to avoid the SiPM saturation
- the number of the incident photons – evaluated with a calibrated photodiode
- the number of the photons recorded by the SiPM – evaluated by two methods:
  - DC method: $(I_{\text{under illumination}} - I_{\text{dark}})/G_{\text{mean exp}}$
    - $G_{\text{exp mean}}$ – the exp. average value of the gain determined from the charge distribution
  - AC counting method: $N_{\text{signals under illumination}} - N_{\text{signals dark}}$
    - with particular attention on the acquisition parameters to eliminate the afterpulses and the cross-talk
- a good agreement (within 5%) has been found in between the two methods
Photon Detection Efficiency (PDE)

- \( \text{PDE}_{\text{SiPM}} \) @ \( \Delta V = 3.5 \text{V} & \lambda = 420 \text{nm} \approx 8\% 
- \( \text{PDE}_{\text{SiPM}} \approx 8-10\% \) for a very large wavelength range: 420-680 nm

- \( \text{PDE}_{\text{SiPM}} \) is linear with the \( \Delta V \)
- Very good uniformity of the PDE over the 16 SiPM’s of the matrix
- \( \sigma_{\text{PDE}} \approx 5\% \)
MAROC – Multi-Anode Read-Out Chip

- Designed to read-out the 64 channels of MaPMTs for the ATLAS luminometer

- Characteristics
  - technology: AMS SiGe 0.35 µm
  - package: CQFP240
  - area: 16 mm²

- Performances:
  - current preamplifier with variable gain (0-4)
  - 100% trigger efficiency at 1/3 p.e (= 50 fC)
  - $Q_{\text{max}} = 5\text{pC} (=30 \text{ p.e})$
  - noise ~ 2 fC
  - linearity ~ 2%
  - cross talk : ~ 1%

Simplified bloc diagram of the MAROC2

MAROC2 layout
- Mean gain over 16 SiPM’s @ $\Delta V=2.5\,V \sim 1.3 \times 10^6$
- Very good uniformity over all the channels: $\sigma_{\text{SiPM gain}} \sim 5.5\%$
- Good agreement with the measurements performed with the previous set-up (single channel voltage amplifier)
- Talk of G. Llosá on using this system to small animal PET application
Summary and outlook

◆ A prototype matrix of SiPM’s has been fabricated at FBK-irst and characterized at LAL

◆ Geometrical characteristics of the matrix:
  • 4 x 4 SiPM’s
  • each SiPM - 1x1 mm²/ 625 pixels
  • each pixel - GM-APD with integrated quenching resistance/ 40x40 µm²

◆ Functional characteristics of the matrix:
  • $V_{BD} \sim 30.5V$, $\sigma_{Vbd} \sim 0.5\%$
  • $R_q \sim 500 \Omega$, $R_{q\,\text{pixel}} \sim 330 \, k\Omega$, $\sigma \sim 1\%$
  • $DCR \sim 2 \, \text{MHz} \, @ \, \Delta V = 2.5V$, $\sigma \sim 12\%$
    • $P_{\text{afterpulse}} \sim 5\% \, @ \, \Delta V = 2.5V$; $10\% \, @ \, \Delta V = 3.5V$
    • $P_{\text{cross-talk}} \sim 2\% \, @ \, \Delta V = 2.5V$; $3\% \, @ \, \Delta V = 3.5V$
  • Gain $\sim 1.4 \times 10^6 \, @ \, \Delta V = 2.5V$; $\sigma \sim 5\%$
    • two read-out systems: single channel amplifier and multi-channels readout-chip
  • PDE $\sim 8-10\% \, @ \, \Delta V = 3.5V$ for a wide wavelength range (420-680 nm)

◆ For more details on our work you are invited to Poster nr. 172/ PIII