Physics and Experimental Studies of SiPM Nonlinearity and Saturation

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Silicon Photomultiplier – has been developed for single photon applications

Sometimes people use it for very high intensity light registration
Example: Calorimetry

V. Andreev et al. / NIM A 540 (2005) 368–380

For short light pulses due to finite number of cells charge signal (counted in number of fired cells) saturates

Binominal approach:

\[ N_{\text{fired cells}} = N_{\text{total}} \cdot \left[ 1 - e^{\frac{N_{\text{photon}} \cdot PDE}{N_{\text{total}}}} \right] \]
A Monte-Carlo model of a SiPM coupled to a scintillating crystal
2012 JINST 7 P02009
(http://iopscience.iop.org/1748-0221/7/02/P02009)

Figure 10. Dependency of the signal peak position from the deposited energy in the crystal for S10362-11-050C MPPC (400 cells/mm²) coupled with the LYSO crystal at different voltages. Gray lines represent the exponential fit to measured data, while solid-coloured lines represent the Taylor expansion of the exponential model to the first order.

Figure 11. Measured spectra for S10362-11-050C MPPC coupled to the LYSO crystal at 70.1 V at room temperature. Radioactive source was $^{18}F$. Energy resolution without correction for nonlinear effects of 14% becomes in reality 21% after the correction.
Correction for the SiPM non-linearity (new perspective on saturation curve)

for AHCAL SiPM with scintillator tile

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SiPM response curve (ITEP measurement)

- That is real life!
- What we have to do, was not only what you have seen on this plot!
- Some improvement has been done day after day.
Correction for the SiPM non-linearity
(new perspective on saturation curve)

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Natural units

• In physics, natural units are physical units of measurement defined in such a way that certain selected universal physical constants are normalized to unity; that is, their numerical value becomes exactly 1.

-- From wikipedia
If we are studying SiPM properties we have to think in the coordinates of
- fired pixels (together with correlated pixels) – Y
- Number of phe assuming ideal conditions with infinite number of pixels inside SiPM) – x

New way to view SiPM saturation:
Thinking in “fraction”!

\[ y = 1 - \exp(-x) \]
How to normalize the SiPM saturation curve?

Amplifier and SPE spectra (low intensity light)

\[ X_i = < N_{phe} > = -\ln P(0) \]

\[ Y_i = < N_{\text{fired}_\text{pixels}} > = \frac{\text{Mean}}{K_{1e}} \]

Mean = Mean(whole distribution) - Ped_position

\[ Z_i = \text{signal from the reference photodetector, units} \]

We need several Light intensity points provide us enough value of P(0)

Maybe last intensity calibration point (too low \( P(0) \))

\(<N_{\text{phe}}\approx5\)

Calibration of reference photodetector in number of phe’s

5 SiPM samples

SiPM Crosstalk is visible

Extraction number of seeds

Fired pixels > phe
1. Firstly we need to have a **proper** experimental setup

**Example of the setup**

1. Light source, operated in stable mode (no changes in an electrical pulse)
2. Light intensity is changed by filters
3. Uniformly distributed light over the SiPM surface* (over surface with desired number of investigated pixels)
4. Reference stable linear photodetector (the best choice is PIN-diode)
5. Amplifier to obtain SPE spectra for low light intensity (bypassed for high intensity light)
6. Temperature and voltage must be stable and better controlled with needed accuracy
The proper experimental setup

1. Light source, operated in stable mode (no changing of electrical pulse)
2. Light intensity is changed by filters

Due to changing of electrical pulse light pulse shape, wavelength and distribution of correlated photons might be changed too

3. Uniformly distributed light over the SiPM surface* (over surface with desired number of investigated pixels)
   Saturation (nonlinearity) depends on pixel load (number of photons/number pixels (think in fraction)

4. Reference stable linear photodetector - the best choice is PIN-diode (dynamic range of about $10^8$)
   PMT is not the best choice for the reference detector. It has own nonlinearity, especially for pulse signals (parameters of the specific PMT should be checked)...
7. Then we need to understand what we want to study—amplitude (A) or charge (Q)? A and Q are different and have a different behavior.

8. Important – we need to know exactly pulse shape corresponded to our task and the best situation when it can be reproduced exactly in the test setup.

9. We need to know real operation conditions of SiPM (applied voltage, light distribution over the SiPM area, load and serial resistances of a connection scheem)
Amplitude (A) or Charge (Q)?

Before saturation doesn’t matter. But if you have more then one phe/pixel:
Single stand alone cell. Moderate light (several photons/flash) intensities

Focused laser light at the center of the cell, 40ps, 660nm
Scope LeCroy WaveRunner 620Zi 2GHz

Why so significant dispersion of signals amplitudes?
*It is exactly one fired cell (stand alone)*

Suggestion – Geiger discharge starts from several points inside of the cell
Signals from stand alone cell
Fixed overvoltage $\Delta U=1.65V$, different light intensity

Exp signals & SPICE simulations

35V
Experimental waveforms

Simulation 1 photon
Simulation 2 photon
Simulation 3 photon

Amplitude (exp)

U=35V ($U_{bd}=33,35$)
- $N_{pe}=0.069$
- $N_{pe}=1.74$
- $N_{pe}=3.62$

Charge (exp)

Even for very low light intensity we have “2-photons” amplitudes from cell -> it maybe an evidence of photon assisted discharge propagation

28th of October 2013
E.Popova IEEE 2013
Signals from stand alone cell.

Comparison of SPICE simulation and experimental results. Light of different intensity.

But what is about cell charge for high intensity light in reality?
**Pulse shape for different light Intensities. MEPHI data**

Hamamatsu S10362-11-100U No.50, Ubreakdown=68.4V, U=69.5V

- **Fast part**
- **Slow part (recovering)**

Normalized pulse shapes

from 0.4 phe/cell to 30k phe/cell
3. Important – we need to know exactly pulse shape corresponded to our task and the best way – it should be reproduced exactly in the experimental setup.

The same SiPM type

5 SiPM samples

Individual tile energy reconstruction using calibration curve SiPM signal vs energy deposited:

SiPM Crosstalk is visible

1024 pixels in saturation

~2000 pixels in saturation

Pulse shape depended – recovery during pulse duration!!!
- Dynamic range is enhanced with longer light pulse
- Time structure of the light pulse gives large effects in non-linear region.
- No significant influence with changing bias voltage.
- Knowing time structure of scintillator/WLS light signal is crucial.
CALICE MINICAL (preprototype of the tile HCAL)
100 SiPMs individually read out tile+WLS

Energy Reconstruction for SiPM

1024 real pixels inside (agrees with saturation curve for 40ps light)

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

\[ \text{Total number of pixels } m = 1650 \pm 150 \]
SiPM Recovery

**Double light pulses method.** 2 short pulses with high intensity to fire all SiPM cells

*Uniforme illumination over SiPM area*

\[ y(\Delta t) = A_2/A_1 \]

\[ y(\Delta t) = 1 - \exp \left[-(\Delta t - t)/\tau_R \right] \]

But one should be careful – recovery might depend on light intensity (pixel load) - oversaturation
SiPM recovery time. Pulse shape analysis and double light pulses method for charge $Q$.

Light MAX

Smaller light (but still with SiPM saturation)

Both methods give the same results for recovery time vs light intensity

Drawback – no light intensity monitor
We have repeated our measurements with 1x1 mm² MEPHI SiPM (pitch 100µm) under control of light intensity

SiPM pulse for saturation conditions

![Graph showing SiPM pulse for saturation conditions](image)

Amplitude, Charge and \(\tau\) increase with light intensity

Question – what is (are) the reason(s) for this?

Group effect?

SiPM gain \(\sim 10^7\)

June 14 2018
Single cell pulses for high intensities light (fixed voltage $U=35V$). MEPHI cell ($100x100\mu m^2$)

Fast part

$U_{bd} = 33.25\pm 0.05$

\[ Q = (C_{fast} + C_{slow}) \ast (U - U_{br}) \]

Total charge

$C_{fast}$ – readout (parasitic) cell capacitance

$C_{slow}$ – cell p-n junction capacitance

Slow part

$\tau = R_{quench} \ast (C_{fast} + C_{slow})$
**Single cell pulses for high intensities light** (for fixed voltage). MEPHI cell (100x100µm²)

**Charge**

\[ Q = (C_{fast} + C_{slow}) \times (U - U_{br}) \]

**Recovery time**

\[ \tau = R_{quench} \times (C_{fast} + C_{slow}) \]

\[ \frac{Q}{\tau} = \frac{(U - U_{br})}{R_{quench}} = const \]

\[ U - U_{br} = const \]

Q increases due to increasing of \( C_{fast} + C_{slow} \)

Specific technology?
Single cell pulses for high intensities light (for fixed voltage $U=38\text{V}$). FBK UV SPAD. Dia 30 $\mu$m

$\Delta U=12\text{V}$

Very small difference in pulse shapes for different light intensities

Thanks to F.Acerbi
Single cell pulses for high intensity light (for fixed voltage $U=38V$). FBK UV SPAD. Dia 30 $\mu$m

Charge

$Q/\tau = (U - U_{br})/R_{quench} = \text{const}$

Recovery time

$\Delta U = 12V$

$U_{bd} = 26.06 \pm 0.04$

$Q$ increases due to increasing of $C_{fast} + C_{slow}$

$U-U_{\text{breakdown}}$ doesn’t change

June 14 2018

E.Popova SiPM SiPM Nonlinearity...
**Pulse shape for different light Intensities. MEPHI data**

Hamamatsu S10362-11-100U No.50, U_{breakdown}=68.4V, U=69.5V

**Normalized pulse shapes**

- **Fast part**
- **Slow part (recovering)**

from 0.4 phe/cell to 30k phe/cell

\[ Q = (C_{\text{fast}} + C_{\text{slow}})(U - U_{b\gamma}) \] \( Q \) changes with intensity

\[ A = N_{\text{total cell}} \Delta U/R_{\text{quench}} \times 50[\text{Ohm}] \] \( \Delta U \) changes with intensity – potential drops on cell p-n-junction below \( U_{\text{breakdown}} \)

\[ \tau = R_{\text{quench}} \times (C_{\text{fast}} + C_{\text{slow}}) \] \( \tau \) doesn’t change with intensity
Recovery time for high light Intensities (many phe/cell). Double light pulses method

Hamamatsu S10362-11-100U No.50, $U_{\text{breakdown}}=68.4\text{V}$, $U=69.5\text{V}$

Variable intensity

\[ \Delta t \]

Fixed intensity

Voltage on p-n-junction

$U$

Breakdown voltage

As higher intensity of the first pulse as longer time $\Delta t$ before second pulse starts to give Geiger discharge (1); But recovery constant is the same (2)
To analyze SiPM waveform one needs to be sure that there are no external network influence.

Fast component (geiger discharge)

- $I_{\text{AV}}$: SiPM ~ ideal current source
- $I_{\text{AV}}$: current source modeling the total charge delivered by a cell during the avalanche $Q=\Delta V(C_d+C_q)$
- $C_g$: parasitic capacitance due to the routing of $V_{\text{bias}}$ to the cells (metal grid, few tens of pF)

Slow component (pixel recovery)

$C_{\text{eq}} = N\frac{C_q C_d}{C_q + C_d}$

- $R_q$: quenching resistor (hundreds of kΩ)
- $C_d$: junction capacitance (few tens of fF, $C_q < C_d$)
- $I_{\text{AV}}$: SiPM ~ ideal current source
- $I_{\text{AV}}$: current source modeling the total charge delivered by a cell during the avalanche $Q=\Delta V(C_d+C_q)$

Firing microcell
- $R_q\parallel N-1$
- $(N-1)C_q$

Other microcells
- $R_q\parallel N-1$
- $(N-1)C_q$

Parasitic “grid” capacitance
- $C_g$

1) The peak of $V_{IN}$ is independent of $R_q$

A constant fraction $Q_{eq}$ of the charge $Q$ delivered during the avalanche is instantly collected on $C_{eq}=C_q+C_g$.

2) The circuit has two time constants:
- $\tau_{IN} = R_L C_{tot}$ (fast)
- $\tau_r = R_q (C_q+C_g)$ (slow)

Decreasing $R_q$, the time constant $\tau_r$ decreases, the current on $R_q$ increases and the collection of $Q$ is faster.

F. Corsi, C. Mazzocca et al.
Recovery time depends on number of fired pixels and load resistor

\[ \Delta V_{ov}(t, n, N) \approx V_{ov}^0 \left[ \left(1 - \frac{n}{N}\right)e^{-t/\tau_1} + \frac{n}{N}e^{-t/\tau_N} \right], \]

\[ \tau_1 = (R_q + R_s)C_p + R_q C_f, \]
\[ \tau_N = (R_q + R_s + NR_L)C_p + R_q C_f. \]

If \( R_q + R_s \geq (5 - 10)NR_L \)

\[ \tau_r \approx \tau_1 \approx \tau_N \approx (R_q + R_s)C_p + R_q C_f \]
Experimental study of a SiPM recovery time

For 3 x3 mm² SiPM, with 90 000 pixels the recovery time is 31.1 ± 1.8 ns; 2000 pixels 6.5 ± 0.4 ns; one fired pixel 3.1 ± 0.2 ns.

For 1.4 x1.4 mm² device, ~20 000 pixels 15 000 pixels the recovery time is 15.2 ± 0.5 ns.

Recovery Time of Silicon Photomultiplier with Epitaxial Quenching Resistors
Instruments 2017, 1, 5; doi:10.3390/instruments1010005
Summary:

For Geiger discharge in oversaturated conditions (>>1 phe/SiPM cell)

• SiPM charge, recovery time and amplitude depend on light intensity;

• Depending on SiPM cell construction (technology used) high light intensities may affect cell capacitance and/or cause enhanced voltage drop on cell pn-junction (below $U_{\text{breakdown}}$);

Possible reasons for such behavior:

• conventional feedback between ionization rates and instant pn-junction overvoltage becomes too “slow” for extremely fast and strong Geiger discharge development

• very local feedback due to screening effect of free carriers produced during ionization in depletion region starts play a role in this case.

Work has been supported by Megagrant 2013 program of Russia, agreement № 14.A12.31.0006 from 24.06.2013
Spice model of avalanche development in a SiPM cell (transversal propagation)

Transversal avalanche propagation & Avalanche current self-quenching

Dolgoshen-Pleshko model

Corsi model

- Geiger discharge starts in a tiny spot inside a cell (1st disk)
- Current \( J(t) = K_j * V_{ov}(t) \), where \( K_j \) is disk specific conductivity
- Discharge spreads from spot to 1st elementary ring, 2nd, ..., with velocity \( u(t) = u_0 \times V_{ov}(t)/V_{ov0} \)
- The capacitor of the cell discharges through the Geiger-avalanche current, after a while overvoltage drops down to 0

\( C_{fast} \) – important parameter!

\[ I(t) = J(t)S(t) = J(t) \times \pi r^2(t) = \pi k_j V_{ov} (t) \left[ \int_0^t u_0 \frac{V_{ov}(t')}{V_{ov0}} \right]^2 dt' \]

\( V_{ov0} \) – initial overvoltage, \( V_{ov}(t) \) – momentary overvoltage

\( K_j, u_0 \) – are experimental parameters
$U = 35 V, \ T = +23 ^\circ C$

$U_{bd} = 33.25 \pm 0.05 \ (T = +23.5 \pm 1 ^\circ C)$
“One possible explanation could be that a very high number of input photons per pixel may trigger several avalanches simultaneously, giving rise to a slightly higher output signal compared to the single photon signal.” L. Gruber et al. NIM A737 (2014) 11–18
Novel approach for calibration breakdown voltage of large area SiPM

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<table>
<thead>
<tr>
<th>Ne-h/u-cell/pulse</th>
<th>Effective C_{u-cell} (fF)</th>
<th>V_{br(V)}</th>
<th>dV_{peak}/dV_{bias}</th>
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<tr>
<td>800</td>
<td>152 fF</td>
<td>69.76</td>
<td>0.9</td>
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<tr>
<td>12</td>
<td>97 fF</td>
<td>70.05</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Table 1: The results of the measurements for different intensities

\[ Q = (C_{fast} + C_{slow}) \times (U - U_{br}) \]

\[ C_{microcell} = (C_{fast} + C_{slow}) \]

\[ \frac{dI}{dU} = N_{cell} \times C_{microcell} \times F_{rep} \]

Not C but Q

\[ \frac{dI}{dV} = N_{cell} \cdot \frac{d(\Delta Q/ \Delta t)}{dV} \]
Over saturation behavior of SiPMs at high photon
L. Gruber et al./NIM A737 (2014) 11–18

Amplitude analysis of 1x1mm\(^2\) different SiPMs

Advanced Laser Diode Systems
(PIL040) 404 nm, 20kHz,FWHM 32 ps

It has been reported that MPPC pulse shape doesn’t depend on light intensity
Used Amp might be the reason for that