The gain, photon detection efficiency and excess noise factor of multi-pixel Geiger-mode avalanche photodiodes

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Motivation

- Multi-pixel Geiger-mode APDs (MPGM APDs) are very promising candidates for many HEP, astrophysical and medical applications.
- The MPGM APD parameters (gain, QE, excess noise factor, timing response) are reported to be similar or even superior to the parameters of PMTs.
- However, measurements of these parameters (especially QE) is not an easy task taking into account small sensitive area (typically 1 mm$^2$) and rather high dark count rates at room temperature.
- MPGM APDs from different manufactures are studied by many experimental groups. Different technique used by these groups caused some confusion in the parameter’s definitions (especially QE).
- In this work we propose a method to characterize MPGM APDs and present our studies of several devices from three different manufactures.
MPGM APDs studied

<table>
<thead>
<tr>
<th>MPGM name</th>
<th>Area (mm²)</th>
<th>Number of pixels</th>
<th>Geometric factor [%]</th>
<th>Si substrate type</th>
<th>MPGM source</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSPM (or MRS APD)</td>
<td>1</td>
<td>556</td>
<td>70</td>
<td>p</td>
<td>&quot;Photonique SA&quot; and V. Golovin (CPTA, Moscow)</td>
</tr>
<tr>
<td>SiPM</td>
<td>1</td>
<td>576</td>
<td>25</td>
<td>p</td>
<td>B. Dolgoshein and &quot;PULSAR&quot; (Moscow)</td>
</tr>
<tr>
<td>R8-type AMPD</td>
<td>0.5</td>
<td>10 000</td>
<td>?</td>
<td>n</td>
<td>Z. Sadygov (JINR, Dubna)</td>
</tr>
</tbody>
</table>

Pixels are separated electrically and optically. Part of the area is non-sensitive to light.

Geometric factor : \( G_f = \frac{\text{active area}}{\text{total area}} \)
Set-up

- MPGM APD and XP2020 PMT were illuminated with the parallel light from LED through 0.5 mm diameter collimator
- Mechanical system allowed precise positioning (<50 µm) of the APD and PMT in all 3 dimensions
- LEDs with the peak emission of 410 nm, 470 nm and 515 nm were used in this study
- APD was connected to fast linear transimpedance amplifier (gain~40)
- Temperature - monitored using Pt-100 resistor
- Currents were measured using Kethley-487 source-meter
- Amplitude spectra were measured using LeCroy 2249 W CAMAC ADC
- LeCroy 623B discriminator and 250 MHz scaler were used for signal counting
- “Optometrics” spectrophotometer was used for spectral response measurements
- Low temperature measurements were done inside the freezer
Parameter definition: Gain

Each pixel works as a digital device – 1,2,3… photons produce the same signal $Q_1 = C_{\text{pixel}} \cdot (V-V_b)$ (or Single Pixel Charge).

Multi-pixel structure works as a linear device, as soon as

$N_{\text{pe}} = N_{\gamma}^* \cdot \text{QE} \ll N_0 , \quad N_0$ – is a total number of pixels/device

Measured charge:

$$Q_{\text{output}} = N_{\text{pe}} \cdot \text{Gain} ,$$

It was found by many groups that: $\text{Gain} \neq Q_1 ,$

More than 1 pixel is fired by one primary photoelectron!

$$\text{Gain} = Q1^* n_p ,$$

where $n_p$ is average number of pixels fired by one primary photoelectron.
MPGM APDs have very good pixel-to-pixel signal uniformity. Pedestal is separated from the signal produced by single fired pixel $Q_1$.

Photon detection efficiency (PDE) is the probability to detect single photon when threshold is $< Q_1$. It depends on the pixel active area quantum efficiency (QE), geometric factor and probability of primary photoelectron to trigger the pixel breakdown $P_b$ (depends on the $V-V_b$ !!, $V_b$ – is a breakdown voltage):

$$PDE = QE \times G_f \times P_b,$$
Single electron spectrum

When $V-V_b>>1$ V typical single pixel signal resolution is better than 10% (FWHM)). However photons produced during the pixel breakdown can penetrate another pixel and fire it. As a result more than one pixel is fired by single photoelectron.
Gain, single pixel charge, number of fired pixels (I)

**MEPhI/PULSAR APD**

![Graph showing Single Pixel Charge vs. Bias at different temperatures](image1)

![Graph showing Gain vs. Bias at different temperatures](image2)

![Graph showing Number of fired pixels vs. Single Pixel Charge](image3)
Gain, single pixel charge, number of fired pixels (II)

CPTA APD

- Gain*10^6 vs Bias [V]
- Temperature: T=22 C and T=-28 C

Dubna APD (T=2C)

- Single Pixel Charge*10^6 vs Bias [V]
- Number of fired pixels vs Bias [V]
For MPGM APDs with low dark count rate (<2-3 MHz) pedestal events can be easily separated from the event when one or more than one pixel were fired by the incident photons. In this case we can use well known property of the Poisson distribution:

$$<N_{pe}> = -\ln(P(0)) \quad (1)$$

This equation works even in the case of the photodetector with very high multiplication noise!!!

“Peak” counting method overestimates the $<N_{pe}>$. Method which uses the width of the signal distribution underestimates the $<N_{pe}>$. Number of incoming photons ($N_\gamma$) from LED pulse can measured with calibrated PMT (XP2020 PMT, for example). Then:

$$PDE(\lambda) = \frac{N_{pe}}{N_\gamma}$$

LED emission spectra must be measured as well (in pulsed mode !!!)
Photon detection efficiency (II)

CPTA APD

Bias [V]

PDE(515 nm) [%]

T = 22 C

T = -28 C

MEPhI/PULSAR APD

Bias [V]

PDE(515 nm) [%]

T = 22 C

T = -28 C

Dubna APD (T = 2 C)

Bias [V]

PDE(470 nm) [%]

T = 22 C

T = -28 C

MEPhI/PULSAR APD

V-VB [V]

PDE(515 nm) [%]

T = 28 C

T = 22 C
Excess noise factor (1)

Excess noise factor can be measured from the width of single electron spectra and calculated using:

\[ F = 1 + \frac{\text{var}_1}{\langle A_1 \rangle^2} \]  \hspace{1cm} (2),

where \( \langle A_1 \rangle \) is average amplitude produced by single electron and \( \text{var}_1 \) its variance.

Another way (gives the same result) is to compare the \( N_{pe} \) calculated from equation (1) and from \( N_w \) from the width of the measured spectra (number of measured photoelectrons should be small (P(0) should not be very low) ). This method is easier to use:

\[ F = \frac{N_{pe}}{N_w} \]  \hspace{1cm} (3),
Excess noise factor (II)

**MEPhl/PULSAR APD**

- T = 22°C
- T = -28°C

**Dubna APD**

**CPTA APD**

- T = 22°C
- T = -28°C
For the spectral response measurements “Optometrics” SDMC1-03 spectrophotometer (thank you Doug!) was used. We also used a calibrated PIN photodiode as a reference. Spectrophotometer light intensity was significantly reduced using gray filters to the level when the maximum current measured with the APD was only ~30% higher than its dark current. This was done to avoid the non-linearity effects caused by high pixel illumination. Photocurrent measured with the APD was compared with the photocurrent measured with the PIN photodiode. In addition the measurements with the LED pulsed light were used for absolute spectral response calibration (at least 2 different LED measurements were done for each APD).
MPGM APDs spectral response (II)

Dubna APD (U=101.5 V, T=2 C)

CPTA APD, U=40.6 V, T=22 C

MEPhI/PULSAR APD, T=22C, U=59 V

XP2020
Summary

- We developed the method to characterise the basic MPGM APD parameters (gain, photon detection efficiency and excess noise factor).
- Using this method we studied APDs produced by 3 different manufactures.
- The basic properties of these devices such as gain, photon detection efficiency, excess noise factor, as well as their dependence on operating voltage have been measured and compared to those of a PMT XP2020.
- Spectral response was measured in the range of 400-800 nm.
- It was shown that despite very good pixel-to-pixel uniformity, the excess noise factor of these APDs can be significantly greater than one.

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