The influence of Temperature and a Light Guidance on the Crosstalk Probability of a Geiger-mode Photo Avalanche Diode

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Abstract

Geiger-mode photo avalanche diodes (G-APDs) promise to be cost-efficient and robust alternative for classic photomultiplier tubes (PMTs) for many applications. One of the most troubling properties of such G-APDs is their optical crosstalk, where secondary photons originating from charge carrier avalanches might discharge neighbouring cells. Therefore, the investigation of optical crosstalk is of major interest for those who want to use G-APDs for their needs. In this work the dependence of optical crosstalk on temperature and the usage of an acrylic glass light guidance was investigated using dark counts. The results indicate that the optical crosstalk increases with temperature and that the use of a light guidance reduces the crosstalk probability especially at lower temperatures. However, the results also show that the analysis performed in this work is insufficient. More data needs to be taken into account to decrease the uncertainties and the influence of the event selection has to be clarified before any clear statements can be made.

I Introduction

One of the oldest and most popular methods for counting single photons is by the use of photomultiplier tubes (PMTs). Those devices which are typically combined with a scintillator are used in various disciplines where single photon detection is needed, such as elementary particle physics, medical diagnostics or spectroscopy. The combination of high gain and low noise as well as their large quantum efficiency makes PMTs the ideal candidates for those tasks [8]. Unfortunately, PMTs show a so called *aging* effect meaning that their properties such as quantum efficiency and gain change with age [1].

A specific application of PMTs is their use in Imaging Air-Cherenkov telescopes used for the detection of very high energetic gamma ray sources. In such experiments the detectors are often exposed to strong background light such as star or moon light for a long time. Therefore, the PMTs used in the detector suffer from rapid ageing and have to be replaced regularly, resulting in high costs [2].

A more robust alternative of photon detectors suitable for such experiments comes in the form of silicon based photo detectors or more specifically Geiger-mode avalanche photo diodes. Being the first telescope of its kind, the FACT telescope is pioneering this method since its start of operation in 2011 [7].

A Geiger-mode avalanche photo diode (G-APD) consists out of a biased operated p-n junction. The applied bias voltage V_A induces an electric field within the depletion layer of the junction. If the bias voltage is chosen above the breakdown voltage V_B the electric field is large enough such that an electron-hole pair created by a single photon hitting the outer layer of the diode results in a self-sustaining avalanche of charge carriers leading to a macroscopic current at the μA range. The breakdown voltage typically varies between 10 and a few 100 V depending on temperature and type of the G-APD. The performance of the G-APD depends strongly on the over voltage which is given by $V_E = V_A - V_B$. Especially gain and quantum efficiency of the diode strongly depend on it.

An important feature present in PMTs and G-APDs are the dark count events. Thermal excitations can lead to the production of avalanches even in the absence of illumination. The dark count rate increases with temperature and over voltage [5].

A G-APD detector typically consists out of a few thousand single cells. An avalanche triggered by an external photon hitting one of those cells contains many secondary photons which may leak to a neighbouring cell and trigger an avalanche there as well. This effect is regarded as optical crosstalk. Therefore, a single external photon may be counted as one, two or even more photons [2]. Such events counting as one, two or three photons are further referred to as single photon events (SPE), double photon events (DPE) and triple photon events (TPE).

In this work the optical crosstalk properties of a G-APD detector similar to the ones used in the camera of the FACT telescope is studied. More specifically, it is investigated if the crosstalk probability depends on temperature and if it is affected by the use of an acrylic glass light guidance. This is done by investigating SPEs, DPEs and TPEs as measured in dark count events. See section 4 for more details.

II Methods

The G-APDs studied in this work are of the type MPPC S10362-33-100C and produced by Hamamatsu. A single G-APD consists of 900 single cells covering an effective active area of 3x3 mm. The detector is designed to function within a temperature range from -20 to 40 ° C and a bias voltage of 70 ± 10 V [**?**].

Since the performance of the G-APDs depends strongly on their temperature all measurements are performed in a C180 climate chamber by Weiss Technik [9]. The temperature of the G-APDs is monitored by a PT-100 temperature sensor which is glued to the back of the G-APD directly. It was found that the experiment suffered from a lot of electronic noise. To reduce the noise all the hardware parts were connected to a common ground and the diode was placed in a Faraday cage. All the experiments described in this work require the measurement of dark counts only. Therefore, a great effort was made to reduce the flux of external photons. To measure dark counts a continuous trigger was used to randomly record events of a length of approximately 500 ns.

Spare parts of the FACT camera are used as readout electronics in order to simulate the conditions in the real telescope as close as possible. Also, the FACT software is used to readout the signal output of the G-APD. Figure 1 shows a rough schematic of the hardware used in the experiment. Some pictures of the used equipment are attached in the Appendix.

II.1 Breakdown Voltage Measurement

In order to study the crosstalk properties of the G-APDs the breakdown voltage of the used G-APDs has to be known. This is needed since the operation performance of the diode depends on the choice of the over voltage. Since the breakdown voltage depends strongly on temperature one would have to measure it at each temperature separately. Fortunately, for the G-APDs in question a linear behaviour of the breakdown volt-

Figure 1: Schematic of the readout electronics.

age with temperature has been shown. The linear law has a unique slope of 55 mV/K which is the same for every diode of this kind [2]. Therefore, the knowledge of the breakdown voltage at a certain temperature is enough. The absolute values of the breakdown voltage vary from diode to diode depending on fabrication. Since no data sheets of the used G-APDs could have been found the breakdown voltage was determined experimentally at a temperature of 25 °C. The determination of the breakdown voltage can be done by measuring the gain of the diode at different bias voltages. The gain was determined at 8 different voltages in the range of 69.3 to 70.5 V. At each of the different voltages 10'000 randomly triggered events were recorded. See section 4 for further details on how the breakdown voltage was calculated.

II.2 Temperature Dependence Measurement

Two properties of optical crosstalk are investigated in this work: (i) dependence on temperature, (ii) influence of an acrylic glass light guidance. To investigate those properties 30'000 randomly triggered events were recorded each at 5 different temperatures ranging from 5 °C to 25 °C. The temperature range was chosen according to the temperatures measured in the camera of the FACT telescope during its operation [7]. The bias voltage was adjusted with temperature in order to achieve a constant over voltage and therefore a similar performance of the G-APD at each measurement. In addition to changing the temperature each measurement has been performed twice, once without a scintillator and once with an acrylic glass light guidance. The light guidance used in this work are the same which were also used in the design of the original FACT camera. To avoid unwanted effects by unknown optical properties of glue, the scintillators have not been glued onto the diodes but they were fixed onto them using optical fat.

III Results

III.1 Determination of Breakdown Voltage

In order to determine the breakdown voltage of the investigated diode the gain was measured at 6 different bias voltages. The breakdown voltage is defined as the bias voltage where the gain of the diode reaches zero. This point is estimated by fitting a linear function of the form $c + s \cdot V_B$ to the data where c indicates the y-axis intersect and s the slope of the function. The data points are given in Table 1 and Figure 2 shows the resulting graph. The obtained values for the slope, the intersect and the breakdown voltage are given in Table 2.

According to Hamamatsu the breakdown voltage might vary from diode to diode. Unfortunately, the corresponding data sheet of the specific diode investigated here was no longer available. Therefore, it is not possible to say if the value found for the breakdown voltage is correct or not. However, one can state that it is in the voltage range indicated by Hamamatsu.

III.2 Temperature Dependence Measurement

After determination of the breakdown voltage of the diode the over voltage was chosen as 2.4 V. Basically a lower over voltage would have been possible as well but empirically it has been found that a larger over voltage increases the signal to noise ratio in the measurements. Table 3 summarises the results of the measurements. As one can learn from Table 3, the bias voltage has been changed in accordance with the change in temperature in order to keep the over voltage and therefore the performance of the diode at a constant level. Figure 3 displays the change of the crosstalk probability with temperature as well as the influence of a light guidance. The fitting parameters of the two linear fits displayed in Figure 3 are given in Table 4 where c indicates the y-axis intercept and s the slope of the line.

From the inspection of Figure 3 one can learn that the crosstalk increases with temperature. This is also in agreement with the results of A. Biland et al. [2]. Notice that in the work of A. Biland et al. a crosstalk probability of the order of 12% was found whereas a probability around 35% is stated in this work. This is reasonable since A. Biland et al. operated their G-APDs at an over voltage of 1.4 V whereas the an over voltage of 2.4 V is used in this work. One can also learn that the usage of a light guidance seems to decrease the crosstalk probability, where the influence is stronger for lower temperatures.

It was expected that the use of light guidance would not influence the crosstalk probability or if it would it should increase it due to possible reflections of secondary photons from the light guidance surface into neighbouring cells. But the results seem to contradict the expectations. However, one should point out that during the working process it was realised that more data is needed in order to decrease the uncertanities

on the fitting parameters. At the present stage not enough data has been collected and no clear conclusions can be drawn from the results.

In the scope of this work it was also realised that the method by which the events are selected from the timeline strongly influences the results. There is no clear answer to how one should select them.

Table 1: Data used for the determination of the breakdown voltage.

Bias Voltage [V]	Gain [mV 0.5ns]
69.497	169.937 ± 2.816
69.706	187.014 ± 4.440
69.900	209.608 ± 4.271
70.004	225.442 ± 5.120
70.105	232.266 ± 4.476
70.295	246.382 ± 9.210

Table 2: Fitting parameters obtained in the breakdown voltage measurement.

c	s	Breakdown Voltage [V]
-6825.277 ± 391.152	100.647 ± 5.594	67.814 ± 0.117

Table 3: Data points used in the crosstalk probability investigation.

Voltage [V]	Temperature [° C]	Crosstalk [%]
Without light guidance		
69.097	5.09	33.582 ± 3.456
69.382	10.09	34.052 ± 3.149
69.710	15.12	36.777 ± 3.582
69.920	20.12	35.947 ± 3.159
70.202	25.18	37.859 ± 4.377
With light guidance		
69.010	5.12	27.451 ± 2.854
69.383	10.12	32.240 ± 3.312
69.710	15.13	36.137 ± 3.327
69.918	20.15	34.391 ± 2.716
70.199	25.18	36.777 ± 3.924

Table 4: Fitting parameters obtained in the crosstalk measurement.

Without light guidance	
c	s
27.123 ± 2.226	0.415 ± 0.133
With light guidance	
c	s
32.495 ± 0.888	0.208 ± 0.053

Figure 2: Display of the data used to determine the breakdown voltage of the diode. The solid black line indicates the linear fit.

Figure 3: Display of the data showing how the crosstalk probability changes with temperature and by the use of a light guidance.

IV Analysis

The readout software of the FACT camera outputs the recorded signal in the zFits format which is a specific format used by the FACT collaboration. The conversion into normal data arrays can be done using a readout tool which is accessible on github [4]. The software used for the analysis of the data in this work is also publicly available on github [6]. The analysis can be roughly divided into three parts for each measurement point: (i) Search the timelines of the recorded events for multiple photon events (ii) Integrate over those events to differentiate SPE, DPE and so on (iii) Make a histogram and extract gain and crosstalk probability from it.

Step (i): The timeline of a single event can be seen in Figure 4. The data is binned in 1024 bins each having a length of 0.5 ns. In Figure 4 the shape of a typical SPE can be seen. Such events show a very characteristic steep rising edge and a rather flat falling edge. Higher photon events like DPE, TPE and so on posses the same characteristic shape as the SPE but they have a larger amplitude. In addition to the wanted dark count signals one also records multiple signals caused by noise, the most problematic one being ringing events as shown in Figure 5. Generally the amplitude and frequency of the noise increases as the temperature is raised. Due to the presence of the noise a stable algorithm to search for multiple photon events is needed. Following the example of [3] a convolution of the timeline with a kernel of the analytic form $A(1 - \exp -Bt) \exp -Ct$, which resembles the actual signal shape, is performed giving more weight to kernel-shaped events. Such a convolved signal is shown in Figure 6. Subsequently, a numerical derivative of the convolved timeline is taken to search for the characteristic steep rising edges of the dark count events. In order to be considered as a valid multiple photon event the rising edge must also have a minimal amplitude. A complication is added in the form of SPE happening shortly after each other as seen in Figure 7. Such events should not be counted as a DPE since they are not caused by optical crosstalk. In order to avoid counting such events as a DPE an additional condition is implied: For an event to be considered there must not be any other events recorded in a certain period of time before the event in consideration. Also, in order to perform a proper integration there must not be any event shortly after the event in consideration. Therefore, in the end only stand alone events or events sitting on top of other events are considered in the analysis.

Step (ii): The integration over the selected signals is performed numerically using the composite trapezoidal rule. However, the final value of the integral has to be corrected for the variation of the zero line. This is especially important if the considered signal is sitting on top of another event. To do so, the zero line is approximated performing an interpolation between the minimum in front of the signal and the end of the signal as can be seen in Figure 8. The obtained integrals are of the units mV ns and represent the charge released by the charge carrier avalanches in the G-APD. One expects that a DPE triggering two avalanches at once results in approximately double the amount of charge released in a SPE and therefore also in double size of the integral.

Step (iii): The integral values collected within all the events belonging to a certain measurement point are summarised in a histogram. In the best case one can already spot by eye the peaks belonging to the SPE, DPE and even TPE. The gain measuring the charge released by the avalanche triggered by a single photon can be obtained by forming the difference of the positions of the first and second or also between the second and third peak. The crosstalk probability measuring the ratio between multiple photon events (DPE, TPE) and the total number of events can be obtained by estimating the total amount of SPEs, DPEs and

Figure 4: A characteristic signal shape as measured in the experiment before any manipulation is performed.

Figure 5: Problematic ringing noise event. The signal contains many steep raising edges although there is clearly no dark count event present.

Figure 6: In black is the original signal containing a lot of noise. The red line indicates the signal shape after convolution. Notice that the noise is greatly reduced.

Figure 7: Two SPEs happening shortly after each other. Naive integration would lead to a large integration area interpreted as a DPE.

TPEs recorded. This is done by fitting the sum of 3 normal distributions to the histogram and measuring their areas as indicated in Figure 9.

Figure 8: The red line indicates the interpolation of the zero line, whereas the blue area marks the resulting area of the peak.

Figure 9: Visualisation of a histogram. The shown histogram includes all the events recorded at a temperature of 20 ° C. The light red curves indicate the 3 normal distributions describing the individual peaks. The solid red line displays their sum which has been fitted to the histogram.

V Conclusion and Outlook

In the scope of this work the scaling behaviour of the crosstalk probability with temperature found by A. Biland et al. was verified. There are indications that, contrary to the expectations, the usage of a light guidance leads to a reduction of the crosstalk probability which is stronger at lower temperatures. However, it was also found that the amount of data collected is not enough to allow to clearly answer the questions investigated. In following works aiming at answering those questions more data should be analysed. One should also try to reduce the noise in the experiment. Empirically, it was found that the algorithm which selects the events which are taken into account for the analysis greatly influences the outcome and interpretation of the results. It is proposed that one should test the algorithm using known events from a simulation in order to find the most suitable method. At last one should notice that the type of diode investigated here is known to show natural inhomogeneities due to fabrication and multiple diodes should be investigated instead of only one.

VI Appendix

Figure 10: The G-APD of the type MPPC S10362-33-100C which was investigated.

Figure 11: The investigated G-APD with the light guidance fixed to it.

Figure 12: The MSR module used for the read-out of the PT-100 temperature sensors including one of the sensors.

Figure 13: Full setup of the hardware within the climate chamber as used for the measurements.

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