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Measurements of the recovery time of Geiger-mode avalanche photodiodes

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Abstract

A new type of photon detector, the Geiger-mode avalanche photodiode (G-APD) has been developed during recent years. This device has the potential to replace photomultiplier tubes. It has a response to single photons with high detection efficiency. G-APDs are operated in Geiger mode and therefore the recovery time, the time needed until the small photodiodes of this device are fully active again after a breakdown, is a crucial parameter in applications with a high level of ambient light. The recovery time of several types of G-APDs was measured and the results are presented.

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Keywords: Recovery time; Geiger-mode avalanche photodiodes; Air Cherenkov telescope

1. Introduction

Imaging Air Cherenkov Telescopes (IACTs) with a fine pixelized camera made from photomultiplier tubes in the focal plane are currently the most successful instruments for ground-based very high energy gamma-ray astronomy. The 17 m diameter MAGIC telescope [1] is the largest among the new generation IACTs. While starting to exploit the full potential of the instrument, the MAGIC collaboration aims now at an upgrade to improve the sensitivity.

Photosensors with high quantum efficiency and with a red extended sensitivity would allow a major improvement in sensitivity and could lower further the energy threshold. In IACTs one is confronted with an enormous background light from the night sky. This harmful effect can only be minimized by reducing the data recording gate time to the minimally allowed time (in case of the Cherenkov light flash in the order of 1–3 ns) [2]. This requires good single photon response and pulses of 1–2 ns width. Geiger-mode avalanche photodiodes (G-APD) are currently under consideration as a possible photodetector option for an alternative camera design.

In the near future it is planned as first step to replace the central pixel of the existing camera by an array of G-APDs. The purpose is to detect the visible light from pulsars in addition to the Cherenkov light from the high-energy γ-ray induced air shower. This would allow a fast and precise determination of the pulsar period and would ease the analysis of the γ-ray data.

G-APDs are arrays of a large number of very small avalanche photodiodes, called cells, with are connected in parallel via individual resistors to a common bias. They are operated in Geiger-mode several volts over the breakdown voltage and produce for each cell breaking down a standard signal. The single cell amplitude A_i is basically proportional to the capacitance of the cell times the overvoltage:

$$A_i \sim C \bullet (V - V_\mathrm{b}).$$

V is the operating bias voltage and V_b is the breakdown voltage. When many cells fire at the same time the output is the sum of the standard pulses:

$$A = \sum A_i.$$

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After the breakdown of a cell its current is quenched by a voltage drop in the individual resistor. Some time is needed to fully recharge the cell. During this time the signal amplitude is reduced and might be below the threshold of the readout electronic. In addition, the breakdown probability, which depends on the overvoltage, is reduced and the detection efficiency is diminished even more.

Since G-APDs are planned for an operation in an environment with a high level of ambient light, it is very important to know the recovery time. It is an important parameter for the selection of the best structure or for the optimization of the device by the producer.

2. Experimental setup

The recovery time has been measured using two light sources producing short pulses which are delayed relative to each other with a variable delay generator. The intensity of the first pulse was large enough to fire >90% of all G-APD cells. The number of photons was much higher than the number of cells in any of the tested G-APDs. The light of the second LED pulse is attenuated such that not all cells are fired. Fig. 1 shows the display of the pulses seen by an oscilloscope. A block diagram of the measurement system is shown in Fig. 2. A prescaler (PS) was used to divide the pulse generator signal in order to produce three different types of events:

(a) two combined LED light flashes with various delay between them,
(b) only one flash from the delayed LED and
(c) no light pulses at all for the study of pedestals events.

That setup allows to have the LEDs operated at a fixed frequency to provide stable operation of the LEDs and make the measurements relative fast. Gates for the ADC are generated with a frequency f while LED1 is fired only with $f/4$ and LED2 with $f/2$. An ADC spectrum recorded in this way is shown in Fig. 3.

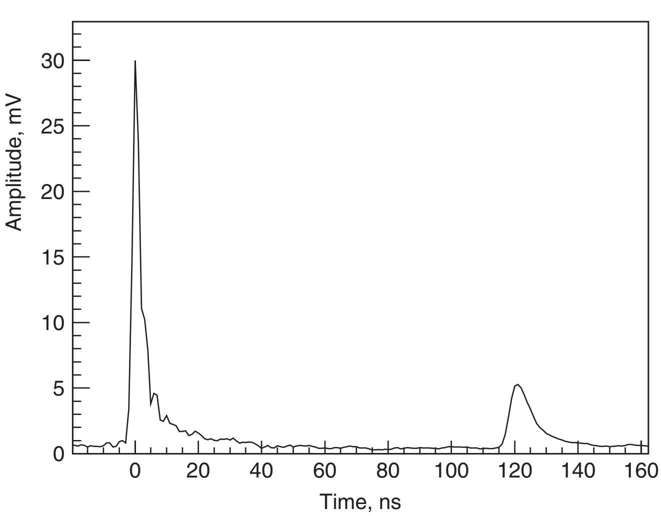

Fig. 1. First and second light flash a G-APD produced by Pulsar seen with an oscilloscope.

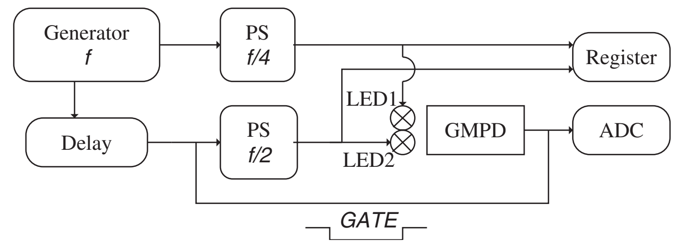

Fig. 2. A block diagram showing the main elements of our detection system.

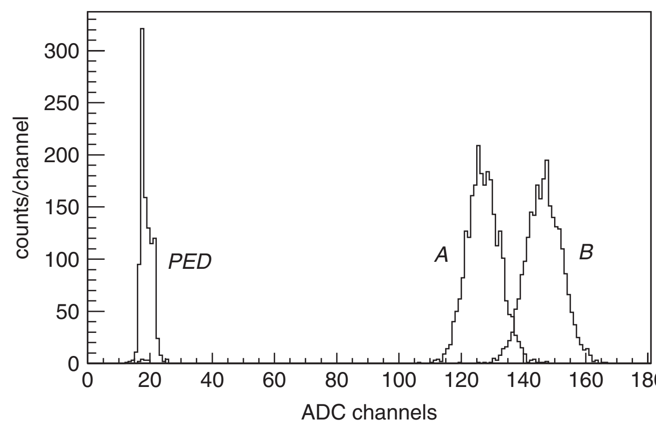

Fig. 3. A typical ADC spectrum of the second light pulse measured with a G-APD: (A)—two LEDs are on and (B)—the first LED switched off; PED—pedestals.

3. Recovery time

We define the recovery time of the G-APD as the time at which the amplitude of a second pulse reaches 95% of the amplitude measured without a preceding pulse.

The time constants are defined from a fit with two exponential functions to the ratio of the amplitudes measured with and without preceding light pulses versus delay between the light pulses. The results of measurements and main G-APDs characteristics are summarized in the Table 1 for a number of different G-APD models.

The recovery time shows a strong dependence on temperature and bias voltage. The recovery time becomes longer with decreasing temperature. Measurements with a G-APD from Hamamatsu (0-100-1.5) show that the recovery time at 0 °C is 190 μs since it is 98 μs at room temperature. The reason is an increase of the resistivity of the polysilicon quenching resistors.

The dependence of the recovery time with the bias voltage can be explained by afterpulses which interrupt the recharging of a cell after a breakdown and starts it anew. Fig. 4 shows the recovery time for the G-APD Hamamatsu 0-50-2 (Fig. 5). A possible explanation is that this device changes abruptly the breakdown mechanism at a bias of

Table 1
Recovery time and time constant for the G-APDs (25 °C)

Producer and name of the G-APD	Cell size (active area) (μm^2)	Number of the cells	Voltage (V)	Recovery time (95%) (μs)	Time constant τ_1 (μs) (%)	Time constant τ_2 (μs) (%)
JINR Dubna R8	7 × 7	10000	99.5	12.1	4.7 (96.8)	153.2 (3.2)
ZS-2mp	28 × 28	800	72.2	578.5	11.2 (96.7)	422.6 (3.3)
Pulsar	20 × 20	576	36.5	2.3	0.42 (80.5)	5.15 (19.5)
CPTA	40 × 40	556	25	2.8	0.92 (98.2)	94.0 (1.8)
Hamamatsu						
0-100-2	70 × 70	100	49.5	110.7	15.6 (89.3)	217.8 (10.7)
0-100-1.5	70 × 70	100	48.9	98.8	15.3 (93.0)	351.2 (7.0)
1-53-1A-1	70 × 70	100	49.4	7.3	5.2 (94.4)	99.8 (5.6)
0–50–2	20 × 25	400	51.0	15.8	0.8 (98.2)	96.9 (1.8)
0-50-1.5	20 × 25	400	50.4	26.5	0.9 (98.0)	75.8 (2.0)
3-22-2A-1	20 × 25	400	52.0	4.9	5.6 (97.0)	250 (3.0)
1-22-2A-1	20 × 25	400	51.6	7.9	6.8 (96.6)	219 (3.4)
1-21A-1	10 × 10	1600	48.3	0.12	0.05 (98.5)	10.6 (1.5)
1-21A-2	10 × 10	1600	48.4	0.11	0.06 (98.4)	8.7 (1.6)

Time constants are presented with relative amplitudes (in percents).

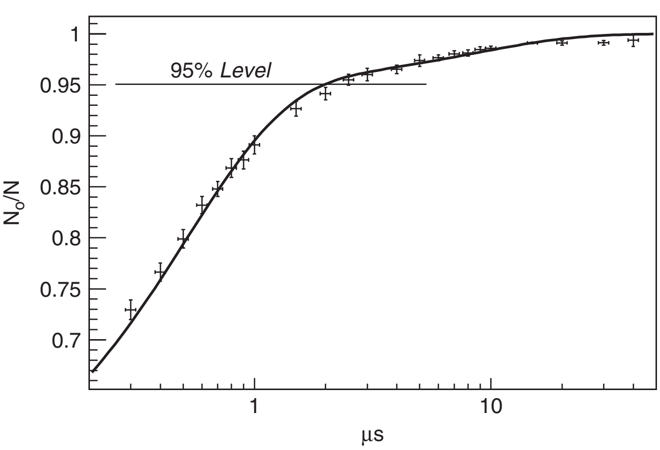

Fig. 4. An example of a test e.g., the amplitude of the measured pulse as a function of the delay.

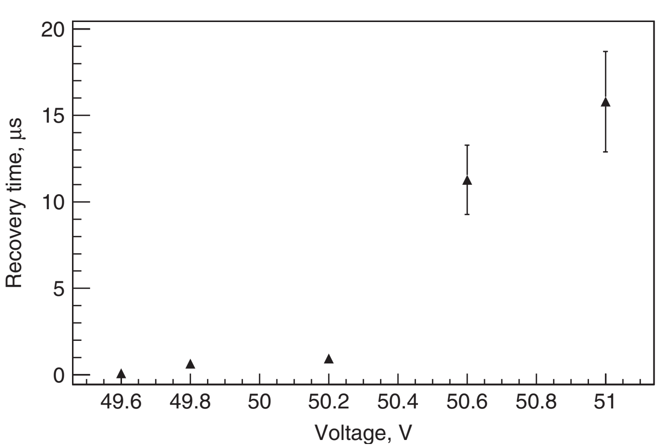

Fig. 5. The recovery time vs. voltage for the G-APD Hamamatsu 0–50–2.

50.4 V. At lower bias the breakdown is laterally limited while at higher bias it spread over the whole area of the cell. The gain changes by a factor of 5 when the bias voltages is increased by 0.4 V. When the breakdown spreads over the whole area many more deep level traps are filled and the delayed release of charge carriers causes more afterpulses.

The recovery time, the recharging of the cells, has two time constants. The dominating one, the fast, can be assigned to the flow of charges from the relative big capacity of the Al-lines that connect all cells in parallel. This capacity can be up to 50% of the capacity of the entire device. The slower time constant probably is defined by the recharging of the whole G-APD from the external bias supply with all the involved resistors and inductances. A similar recovery time with two constants has been reported [3].

4. Conclusion

The recovery of a cell in a G-APD is a relative slow process with time constants of microseconds and the total recovery can take in some cases up to hundred and more microseconds. There is a connection with the cell area and by this with the capacitance of the cells but more and unknown details of the structures contribute. Further studies are needed.

Even in applications with strong background light the probability that one cell is hit by a second photon within its recovery period is small. The background from star light seen by the MAGIC imaging air Cherenkov telescope with its 17 m diameter mirror is some 10^6 photons/(s × mm^2). Assuming a G-APD with 500 cells/mm^2 and a photon detection efficiency of 40% we expect background photons with a rate of 800 Hz per cell. The situation is different in calorimetry. For example in a PET apparatus, where efficient crystals like LSO are used, a big fraction of the cells of a G-APD are fired within few nanoseconds. Several thousand photons with a decay time of 40 ns are produced in LSO by the 511 keV X-rays and can be collected. A long recovery time will limit the count rate and will deteriorate the energy resolution if this limit is exceeded.

The recovery time has been defined as the time needed until the signal reaches 95% of the original amplitude. In an experiment the threshold will be set to 50% of the single photon amplitude and this will be reached with all the devices in less than 100 ns. It will be advantageous to record the history of the signals with a FADC or another sampling device like the Domino Ring Sampling chip [4].

Acknowledgement

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