# Geiger-mode Avalanche Photodiodes as Photodetectors in Cherenkov Astronomy

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***Abstract.*** **Geiger-mode avalanche photodiodes (G-APD) are a new generation of semiconductor photodetectors. Their high photon detection efficiency in combination with mechanical properties (small, lightweight) make them an interesting alternative to photomultiplier tubes (PMT), e.g. for applications in Cherenkov astronomy. In the course of the development of a G-APD based camera for a Cherenkov telescope in the FACT project (First G-APD Camera Test), their properties are analysed and measured in detail. Afterpulses were found to have an exponentially decreasing probability after an initial pulse, which is favourable to the distinct timing regions of afterpulses of PMTs. The angular dependence of the photon detection efficiency was measured and found to be flat.**

***Keywords*: Geiger-mode Avalanche Photodiode, G-APD, Photodetectors**

## I. INTRODUCTION

The invention of the Photomultiplier tube (PMT) about 70 years ago turned out to be one of the major technical contributions to modern physics. They are widely used in applications ranging from medical diagnosis to high-energy physics experiments. In astronomy experiments, such as the IceCube Neutrino Observatory, the Pierre Auger Observatory and Cherenkov telescopes (e.g. MAGIC), PMTs are used to detect Cherenkov light. The recently developed Geiger-mode avalanche photodiodes (G-APDs) have the potential to challenge the usage of PMTs in future experiments by offering similar gain while improving other properties such as the photon detection efficiency. This article describes the basic characteristics of G-APDs and focusses on two properties being of particular interest for the application in Cherenkov telescopes: the angle dependence of the photon detection efficiency and afterpulses.

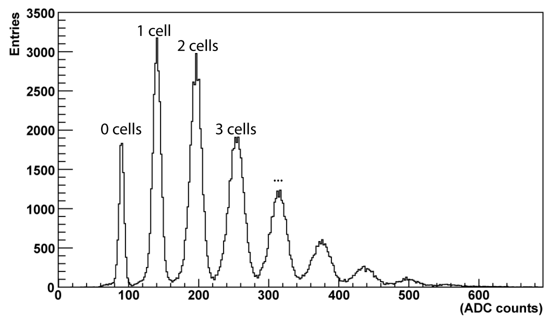


Fig. 1: Pulse spectrum of a weak pulsed LED measured with a G-APD. The peaks correspond to the number of triggered cells $\tilde{N}$ according to equation (3). Taken from [2].

## II. BASIC PROPERTIES

G-APDs are compact, lightweight semiconductor photodetectors. Their operation voltage is below 100 V and thus much lower than for PMTs. While PMTs are damaged by exposure to bright light while in operation, tests exposing G-APDs to bright light inducing a photocurrent of more than a milliampere for several minutes did not affect the performance of the devices.

A G-APD chip is divided into cells connected in parallel via an individual limiting resistor. The design of a single cell is similar to a linear avalanche photodiode (APD). In contrast to the usage of a common APD, the applied bias voltage is above the so-called breakdown voltage where the avalanche process is self-perpetuating (Geiger discharge) [1]. An avalanche can be started by incoming photons generating electron-hole pairs through the photoelectric effect, or by other processes which generate free carriers (thermal generation or field-assisted generation). The probability that a single incoming photon triggers a G-APD cell if no other light is present is called photon detection efficiency (PDE).

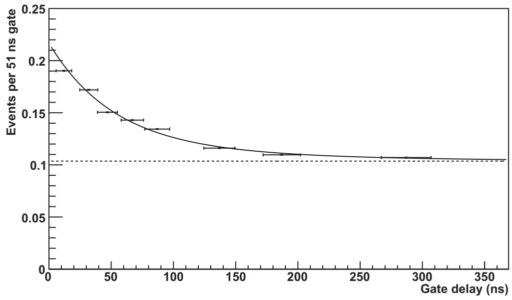


Fig. 2: Number of afterpulses of a G-APD for variable gate delays after an initial breakdown: the afterpulse rate is exponentially decreasing. The dashed line indicates the amount of dark counts. Taken from [2].

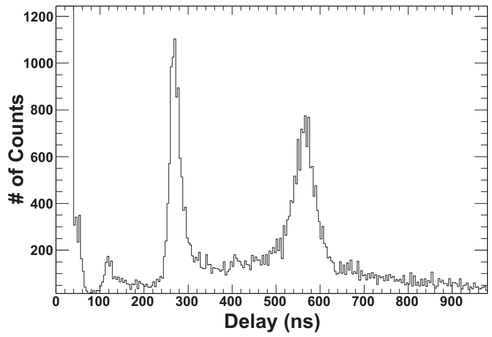


Fig. 3: Delay of afterpulses with respect to the initial pulse for PMTs: the afterpulses occur at distinct times. Taken from [7].

The equivalent parameter of a PMT is the probability that an incoming photon creates an electron-hole pair (quantum efficiency) multiplied by the probability that the resulting electron reaches the first dynode (collection efficiency). The avalanche is stopped by lowering the bias voltage below the breakdown voltage by either a serial quenching resistor or an active quenching circuit. After stopping the avalanche, the cell recovers with a recovery time constant of a few nanoseconds [3]. During the recovery time, a new breakdown in this cell is possible, but has a reduced amplitude.

The charge released per breakdown of a cell divided by the elementary charge (i.e. the gain) is in the order of $10^5 - 10^6$ and is independent of the number of initial electron-hole pairs in this cell. The gain is linear in the overvoltage (bias voltage minus breakdown voltage). Since the breakdown voltage depends on the temperature (52 mV per $^\circ$C)[2], the bias voltage has to be adjusted to temperature changes in order to keep the gain constant. The total signal of a light flash is determined by the sum of the signal of all cells with a breakdown at the same time. For small pulses, the spectrum allows to discern well separated peaks corresponding to the number of cells with a breakdown (see figure 1).

The independence on the number of initial electron-hole pairs per cell introduces a statistical saturation effect. The mean number of cells with a breakdown $N$ for $N_{inc}$ incoming photons which are distributed on $N_c$ cells is given by [4]

$$N = N_c(1 - (1 - \frac{1}{N_c})^{N_{inc} \cdot PDE}). \qquad (1)$$

Usually, an approximative formula is used for calculations:

$$N = N_c(1 - e^{-\frac{N_{inc} \cdot PDE}{N_c}}) \qquad (2)$$

The product $N_{inc} \cdot PDE$ is denoted as $N_{pe}$. The saturation formulae above will be referenced as $N = S(N_{pe}, N_c)$.

A cell in breakdown state can trigger other cells by optical photons emitted in the avalanche process [5]. The crosstalk probability $p_{ct}$ is defined as the probability that a single photon triggers one or more cells through optical crosstalk, whereas $\mu_{ct}$ denotes the mean number of cells triggered through crosstalk. Including crosstalk and its saturation effects, the number of cells $\tilde{N}$ triggered by a light flash is [2]

$$\tilde{N} = N + S\left(\frac{N_c - N}{N_c} \cdot \mu_{ct} \cdot N, N_c - N\right) \qquad (3)$$

with $N$ as defined above.

## III. Afterpulses

A G-APD cell may not only be triggered by an external photon or crosstalk, but also by thermally or field-assisted generation of free carriers. These events are called dark counts and have a rate of 2-3 MHz per device (Hamamatsu S10362-33-100C[1], similar for other Hamamatsu G-APDs) [6]. Additionally, carriers may be trapped during a breakdown. Their delayed release can trigger again the cell where the initial breakdown occurred. The rate of these afterpulses is exponentially decreasing with two components of $50$ ns and $140$ ns [2]. The size of an afterpulse is the sum of the breakdown in the cell (reduced due to the recovery time of the cell) and possibly additional cells due to crosstalk. Except for the cell recovery, the spectrum of afterpulses is identical to dark count events and consequently independent of the size of an initial light flash. A larger light flash will trigger more cells and consequently have a larger number of afterpulses.

Afterpulses in PMTs occur at distinct times after the initial pulse (see figure 3) [7]. The size of an afterpulse is independent of the size of the initial pulse, only the probability for afterpulses correlates with the initial pulse size [8]. This afterpulse behaviour is unwanted in systems where a trigger is generated by the coincident occurrence of signals in several PMTs: the afterpulses of a small signal below the trigger threshold (e.g. a weak Cherenkov flash) can release the trigger and create events difficult to discern from "real" events.

The afterpulse behaviour of G-APDs is favourable due to the absence of a time-correlation. Since the pulse size of

[1] 900 cells, $100 \times 100\,\mu\mathrm{m}^2$, area $3 \times 3\,\mathrm{mm}^2$

a single afterpulse is small (one cell plus its crosstalk), the probability for false triggers is very low and can presumably be neglected.

## IV. Angular acceptance

Photomultiplier tubes suffer from an angle and direction dependent photon detection efficiency due to their asymmetrical internal structure. To investigate the relative photon detection efficiency of G-APDs at various incident angles, a pulsed light source is used. For weak light pulses, the number of breakdowns in the G-APD is Poisson distributed (except for crosstalk effects). The number of events where no photon is detected $N_0$ (which is independent of crosstalk) allows to calculate the Poisson mean value of the number of photons detected by the G-APD:

$$\mu = -\ln\left(\frac{N_0}{N_{tot}}\right) \tag{4}$$

$N_{tot}$ is the total number of events.
The intensity of the light source is adjusted such that the mean number of breakdowns in the G-APD per pulse is around six, the light beam being homogeneous in an area larger than the sensitive area of the G-APD. The G-APD is then tilted by an angle $\alpha$ and the measurement repeated. For geometrical reasons, the number of detected photons decreases with $\cos(\alpha)$ if the detector sensitivity is angle independent.
The G-APD used for the measurement is of the type Hamamatsu S10362-33-050C[2]. This type of G-APD has a protective epoxy layer over the chip surface. This does not influence the measurement above[3], only the incident angle on the chip surface $\alpha_c$ is shifted to a lower value according to Snell's law: $\alpha_c = \arcsin(\frac{\sin(\alpha)}{n})$. Since the maximal measured angle of 85° corresponds only to an angle of approximately 40° at the chip surface, the measurement was repeated with a diode where the epoxy layer was removed. Due to shadowing effects of the package, the measurement is only relevant for angles up to 80°. The measured values are in agreement with the assumption of an angle independent photon detection efficiency (see figure 4). More precise measurements are planned.
This result is an important requirement for the usage of solid light collectors (Winston cones, see [9]) in a G-APD camera. Winston cones allow to increase the effective area, e.g. to eliminate dead space between photodetectors.

## V. Conclusion and Outlook

G-APDs are a promising candidate as light detectors for Cherenkov telescopes. The non-correlation of afterpulses minimizes the probability of afterpulse-induced false triggers. The angle-independent photon detection efficiency enables the use of solid light collectors.
The use of G-APDs as a replacement for PMTs in the camera for a Cherenkov telescope is currently investigated in the First G-APD Camera Test (FACT) project [10]. The camera is planned for the DWARF telescope, an upgrade of an old HEGRA telescope [11]. The DWARF telescope will be part of a worldwide network dedicated to the long-term monitoring of blazars [12].

[2]3600 cells, $50 \times 50\,\mu\mathrm{m}^2$, area $3 \times 3\,\mathrm{mm}^2$
[3]The epoxy surface is approximately flat in the relevant area.

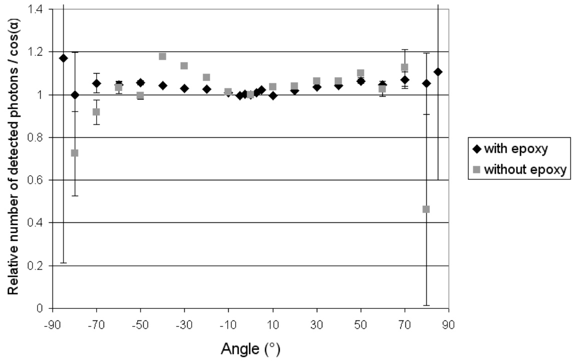


Fig. 4: Relative photon detection efficiency for different incident angles of a pulsed light flash. The G-APD is coated by a protective epoxy layer. Due to refraction, the incident angle at the chip surface is around 40° for an inclination of the light beam of 85°.

## References

[1] D. Renker and E. Lorenz, *Advances in solid state photon detectors*, JINST **4** P04004, (2009).
[2] Th. Krähenbühl, *G-APD arrays and their use in axial PET modules*, Diploma thesis, ETH Zurich, (2008).
[3] H. Oide *et al.*, *Study of afterpulsing of MPPC with waveform analysis*, PoS (PD07) 008, (2007).
[4] A. Stoykov *et al.*, *On the limited amplitude resolution of multi-pixel Geiger-mode APDs*, JINST **2** P06005, (2007).
[5] A.L. Lacaita *et al.*, *On the bremsstrahlung origin of hot-carrier-induced photons in silicon devices*, (1993).
[6] Hamamatsu Photonics K.K., *Multi-Pixel Photon Counter Data Sheet* http://sales.hamamatsu.com/assets/pdf/catsandguides/mppc_kapd0002e03.pdf, (2008).
[7] U. Akgun *et al.*, *Afterpulse timing and rate investigation of three different Hamamatsu Photomultiplier Tubes*, JINST **3** T01001, (2008).
[8] Philips Photonics, *Photomultiplier Tubes. Principles and applications*, (1994).
[9] I. Braun *et al.*, *Solid Light Concentrators for Cherenkov Astronomy*, in these proceedings.
[10] Q. Weitzel *et al.*, *A Novel Camera Type for Very High Energy Gamma-Astronomy*, in these proceedings.
[11] T. Bretz *et al.*, *Long-term VHE gamma-ray monitoring of bright blazars with a dedicated Cherenkov telescope*, in these proceedings.
[12] M. Backes *et al.*, *Long-term monitoring of blazars the DWARF network*, in these proceedings.