



Detection of Cherenkov light from air showers with Geiger-APDs

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Abstract: We have detected Cherenkov light from air showers with Geiger-mode APDs (G-APDs). G-APDs are novel semiconductor photon-detectors, which offer several advantages compared to conventional photomultiplier tubes in the field of ground-based γ -ray detection. Folded with the Cherenkov spectrum the response of G-APDs is up to a factor of three higher when compared with classical photomultipliers. Dark count rates of the tested G-APDs are below that of the night sky light background. According to recent tests G-APDs promise a major progress in ground-based gamma-ray astronomy.

Introduction and Motivation

Ground-based γ -ray astronomy is a rapidly expanding and successful field in astroparticle physics. The Very High Energy (VHE) γ -ray astronomy window was opened by the Whipple collaboration with the detection of the Crab Nebula at energies above 1 TeV using the imaging air Cherenkov telescope (IACT) technique [1]. An IACT records, with a finely segmented PMT camera, the very weak Cherenkov light flashes from VHE γ -ray induced air showers. Since 1989 more than 40 sources of VHE- γ -rays have been detected. Most of them had been discovered in the last four years by the second generation of IACTs that use larger diameter reflectors than the previous generation.

The MAGIC telescope is an IACT with a 17 m diameter reflector. It is currently the largest and technological most advanced IACT. MAGIC is aiming to uncover the so far unexplored VHE γ -ray domain between 30 and 150 GeV, important for the study of several fundamental physics questions, such as the extragalactic background light, gamma ray bursts, pulsars, dark matter and tests of quantum gravity.

Pushing the imaging technique into this interesting energy region requires telescopes with a higher collection efficiency of Cherenkov photons. While it seems difficult to increase the reflector area much beyond the area of existing telescopes, it is more promising to develop photon detectors with higher photon detection efficiencies (PDE).

Since a few years, a new type of semiconductor photon detector is being developed with single photon resolution and a potential for much higher PDEs than that of PMTs. The so-called G-APD is now in the transition from an R&D device to a commercial product. The size of some G-APDs is now sufficiently large to evaluate their possible use in IACTs. We carried out some first tests, which are described in this paper.

After an introduction to the G-APD principle we present two field tests with G-APDs, in which we detected Cherenkov light from air showers. We close with some conclusions and a short outlook.

The G-APD

The G-APD or SiPM, MPPC, MRS-APD, ... was initially developed by several Russian groups [2, 3, 4]. In a G-APD typically 100 to 1000 small avalanche photo diodes (APDs) are integrated per

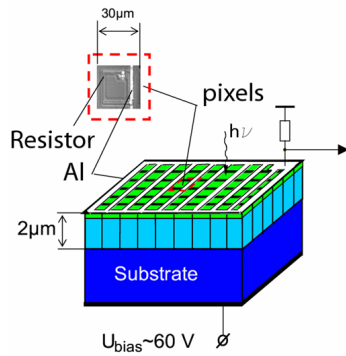


Figure 1: Schematic view of a G-APD; picture from B. Dolgoshein.

mm^2 detector area (cf. Figure 1). Each APD (hereafter cell) is connected via an integrated high ohmic resistor to a common bus. The bus serves two purposes. Firstly, it connects all cells to a common bias, and, secondly, it serves as readout node for all cells. The output signal is therefore the sum of all possible cell signals.

The cells are biased to operate in limited Geiger mode. In this mode an electron or hole (with a somewhat lower efficiency) initiates an avalanche breakdown confined to the cell in which the electron/hole has been generated. Eventually, the breakdown is quenched by the current limiting resistor. The output signal of a single cell has always the same amplitude. In first order the output signal of the G-APD (the sum signal of all cells) is proportional to the number of triggered cells (for small signals the number is proportional to the number of incident photons). The maximum G-APD signal is given by the number of cells of the G-APD.

The biggest advantage of G-APDs is the possible high PDE, which can be up to a factor of three higher than that of classical PMTs. Other advantages are:

- single photon detection capability with standardized output signals
- compactness
- insensitive to magnetic fields
- low operation voltage ($< 100 \text{ V}$) and high gains ($10^5 - 10^6$)

- no damage when exposed to sunlight, even when under bias
- long-term prospects for low fabrication costs

Negative aspects of G-APDs are:

- currently sensors sizes are limited to $< 10 \text{ mm}^2$
- Dark noise rates between 100 kHz and several MHz per mm^2 sensor area at room temperature
- so-called optical crosstalk, i.e. correlated firing of several cells

The aforementioned limitations are introduced by the technologies available to produce these devices. Considerable improvements are expected in the future.

For our tests we used four $3 \times 3 \text{ mm}^2$ prototype G-APDs from Hamamatsu; MPPCs with nearly 60% peak PDE in the blue spectral range, cell sizes of $100 \times 100 \mu\text{m}^2$, $\sim 750 \text{ kHz}$ dark rate at 26° C and signal rise- and fall times of 2 ns and 30 ns respectively.

Detection of Cherenkov light by directly viewing the sky

The effective sensor area was enhanced from $3 \times 3 \text{ mm}^2$ to 30 mm^2 by miniature, hollow light concentrators, which in turn restricted the angular acceptance to $\sim 1 \text{ sterad}$. The collectors were made from aluminized Mylar foil with a mean reflectivity of 85%. The setup was triggered by two 1" PMTs, separated by 25 cm and the G-APDs placed in between them. Light concentrators were put on top of the PMTs, enhancing the effective area to 12 cm^2 and restricting the angular acceptance also to $\sim 1 \text{ sterad}$. The setup resembles the concept of the AIROBICC [5] open PMT array viewing the night sky directly for detecting the Cherenkov light from air showers.

With this setup we viewed the night sky in a rural region close to Villigen, Switzerland. The coincidence signal from the two PMTs triggered a digital oscilloscope from LeCroy, which recorded the signals of the 4 G-APDs.

The trigger threshold for the PMT signals was set to ~ 8 photoelectrons (phe) with a coincidence window of 5 ns. Thus cosmic ray showers with a photon density of > 30 photons/cm² were selected, corresponding to CR energies of > 500 TeV. The trigger rate was about 1 event per 5 min (about 50% accidentals and 50% air shower events), in accordance with measurements of the former AIROBICC experiment.

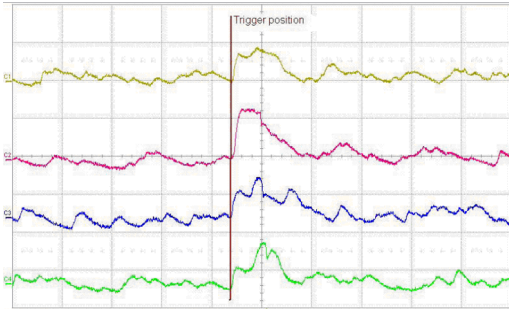


Figure 2: Event trigger when directly viewing the night sky; horizontal scale: 50 nsec per division, vertical: 200 mV per division.

Figure 2 shows the G-APD signals of one recorded event. The baselines fluctuate due to the night sky background light. Because of the proximity to nearby towns the night sky background light was substantially larger than e.g. at the MAGIC site. Note also that a small signal is expected in each G-APD due to the small sensor area. The chance that events so short in time are caused by human generated light flashes are extremely small, as this would require nanosecond light flashes, backscattering from solid objects of small extension and repetition rates following an exponential distribution.

It can also be excluded that the observed events can be explained by charged particles passing both the PMTs and the four G-APDs.

Detection of Cherenkov light using the solar concentrator at PSI

The same setup as before was installed in the focal plane of the solar concentrator at the Paul Scherrer Institute (PSI) [6]. The facility shown in Fig-



Figure 3: Solar Concentrator at the PSI.

ure 3 consists of a planar mirror with an area of 120 m², reflecting the light onto a spherical mirror with 8.5 m in diameter and $f/D=0.5$. The reflectivity of both mirrors is $> 90\%$ down to 380 nm. The test setup was placed in the focal plane of the spherical mirror. The G-APD light collectors restricted the area of acceptance to the inner 15 m² of the spherical mirror but provided efficient shielding against large angle stray light. For the test the planar mirror was pointed to zenith.

The signals of the G-APDs and the PMTs were recorded with a Domino Ring Sampler with 2 GHz sampling frequency [7]. For all events with at least 6 phe recorded in both PMTs within a time window of 5 ns also a coinciding signal was observed in each G-APD. Figure 4 shows the signals of one recorded event.

Discussion and Conclusion

Our tests show that it is possible to detect Cherenkov light from cosmic ray showers by means of G-APDs. The impact of the much higher PDEs of G-APDs on the detection of Cherenkov light is illustrated in Figure 5. In the figure we compare the spectral response of several photon detectors folded with the Cherenkov light spectrum emitted by 50 GeV γ -ray showers. The curves are normalized (normalization between 290 and 700 nm) to the response of a PMT with hemispherical bialkali photocathode, which is coated with a diffusive laquer doped with a wavelength shifter. We define as figure of merit (FM) the normalized

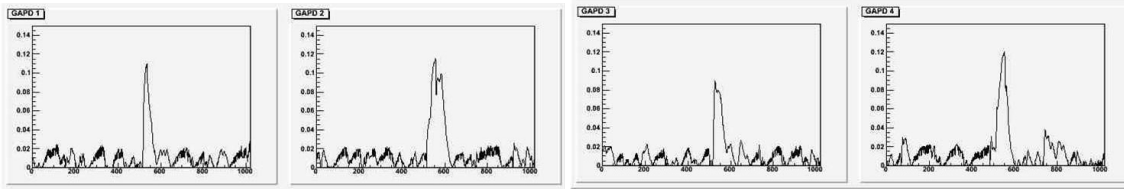


Figure 4: Signals of a triggered event in 4 G-APDs, placed in the focal plane of the solar concentrator.

integral of the folded spectral response in the aforementioned wavelength range. Losses due to imperfect collection efficiencies in the PMTs are also taken into account in the comparison.

- The intrinsic noise rate of the used G-APDs at room temperature was below the level of the night sky background light

As a consequence of the significant increase in PDE we conclude that by means of G-APDs one can either increase the sensitivity of IACTs or one can reduce the reflector area of telescopes while conserving the same performance in case classical PMTs are used.

The tests were carried out in non-ideal conditions, which is the reason why it is difficult to extract precise quantitative results. In a next step we plan to replace one PMT-pixel of the MAGIC telescope with a pixel composed of G-APDs.

Even if available G-APD already show impressive characteristics further improvements are desirable:

- Larger sensor areas of $5 \times 5 \text{ mm}^2$ up to $10 \times 10 \text{ mm}^2$
- A reduction of optical crosstalk to well below 5%
- Further reduction of the intrinsic noise to $< 100 \text{ kHz/mm}^2$

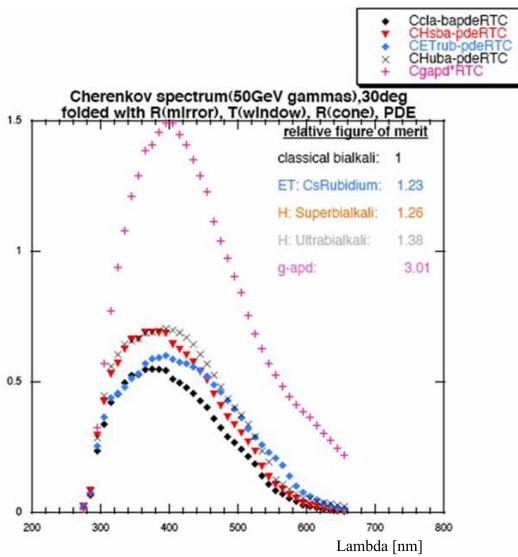


Figure 5: Comparison of the sensitivity of several photon detectors to Cherenkov light from Air showers.

For the used G-APD we calculate a FM of ~ 3 . If we compare the G-APD with a non-coated flat window PMT we calculate an improvement even by about a factor of 4.

In summary we can conclude the following results:

- The two described tests show that it is possible to detect Cherenkov light from air showers with G-APDs
- We estimate a significant increase of photon to pht conversion compared to PMTs

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