First tests and long-term prospects of Geigermode avalanche photodiodes as camera sensors for IACTs

Eckart Lorenz*†, Razmick Mirzoyan*, Hiroko Miyamoto*, Nepomuk Otte‡, and Dieter Renker§

* *Max Planck Institute for Physics, Föhringer Ring 6, 80805 Munich, Germany*
† *ETH Zurich, CH-8093 Zürich, Switzerland*
‡ *Dep. of Physics, UC Santa Cruz, 1156 High St., Santa Cruz, California, CA 95064, USA*
§ *Paul Scherrer Institute, CH-5232 Villigen, Switzerland*

***Abstract*. Geigermode avalanche photodiodes (G-APD) are novel photodetectors, which can detect single photons. This diode might become an alternative to photomultipliers (PMT) in next generation IACTS. Prospects, limitations and development directions will be discussed. Results from first tests will be reported.**

***Keywords*: Solid state photosensors, air Cherenkov telescopes**

I. Introduction

Very high energy (VHE) gamma-ray (γ) astronomy, a section of high energy astroparticle physics, has begun in 1989 and is currently a very successful field of fundamental research. Most discoveries have been achieved by experiments using so-called imaging atmospheric Cherenkov telescopes (IACT). These telescopes detect the very faint but very fast Cherenkov light flashes from air showers initiated by cosmic particles hitting the upper atmosphere. IACTs require high detection efficiency for Cherenkov photon flashes and fast time resolution to filter out the few nsec lasting flashes against the steady night sky light background ($\geq$ 2.10^{12} photons/m^{2}sec sterad, between 300 and 600 nm). Large mirrors project the Cherenkov light onto a fine pixelized matrix of ultra sensitive photosensors in the focal plane. By recording the shower light one obtains a coarse image of the shower. Using a detailed analysis of the shower image one can determine the energy of the primary particle, its origin in the sky map (only for neutral particles) and discriminate γ shower candidates against the many orders more frequent hadronic showers. Further information on the detection methods can be found for example in [Weekes].

In order to make further progress in this research field one has to increase the sensitivity of IACTs and to lower the energy threshold by detecting more Cherenkov photons/shower. This can be accomplished by either increasing the area or/and the photosensor detection efficiency. Beyond 25-30 m mirror diameter optical errors as well as material parameters set practical limits. Another option is to improve the photon detection efficiency (PDE) of the light sensors. Up to now IACTs use photomultipliers (PMT) with a typical peak quantum efficiency (QE) of 25% and a rather narrow sensitivity range. Recently, industry has achieved raising the peak QE to 32 respectively to 42 % for the so-called superbialkali (Sba) and ultrabialkali (Uba) photocathodes. PMTs with Sba cathodes will be used for the first time in the 17 m Ø MAGIC II telescope [2].

Since a few years a new silicon semiconductor photosensor has been under investigation. It has very high gain based on secondary avalanche multiplication and quenching similar to the Geiger counter principle, therefore generically named Geigermode avalanche photodiodes (G-APD). G-APDs (also called SiPM, MPPC, MPGM-APD, SSPM, MRS-APS, MKPD..) have the potential to reach a QE of up to 80% in the spectral range matched to Cherenkov light. The PDE is currently substantially lower but it is expected that rather soon significant improvements will be achieved thus offering a quantum jump in sensitivity for IACTs. In the following we will discuss in chapter II the detection principle and in chapter III some very first Cherenkov light observations carried out in 2007. In chapter IV we comment on some deficiencies and the developments necessary to reach the required performance for IACTs. The paper will conclude in chapter V with a short outlook.

II. The G-APD as a detector for single photons.

When reverse biasing a semiconductor p-n structure, such as for example a high quality silicon diode, the p-n zone is depleted and acts as an isolator with only a small leakage current caused by thermally generated electron-hole (e-h) pairs. When the field strength across the p-n structure is increased to $\approx$ 140 kV/cm the accelerated electrons can produce secondary e-h pairs by impact ionization thus starting avalanche multiplication. As a result an amplification of the current occurs but avalanches develop only from the p towards the n layer, as holes are not accelerated high enough to initiate also avalanches. In this state of biasing also external photons are able to initiate avalanches by e-h generation by absorption. The device acts as a linear mode avalanche photodiode with modest gain. The signal is in first order proportional to the photon flux. If the field strength across the p-n structure is further increased some accelerated holes can also produce e-h pairs by impact ionization. This process will start secondary avalanches on both sides of the pn structure and in turn a sustained current will flow provided the diode is still biased above the so-called breakdown voltage (V_{bd}). This can eventually lead to the destruction of the diode. By adding a series resistor between the bias source and the diode the avalanche current will result in a voltage drop, which eventually will quench the multiplication process once the voltage across the diode drops below V_{bd}- similar to the process in Geiger counters. In such a configuration a single electron can initiate a large signal of standard amplitude given by the diode capacitance and the overvoltage above the breakdown voltage. The gain G is:

$G = (1/q)* C_{diode}*(V-V_{bd})$ (1)

with q being the elementary charge.

The total number of charge carriers in the avalanche process is therefore independent of the number of initial e-h pairs, i.e. such a diode is a digital counter. An important feature for using such diodes as photon counters is the fact that small volumes of appropriately designed diodes can be biased for quite some time well above V_{bd} because the probability of a thermally generated e-h pair in the small volume can be quite low. Such diodes can act as single photon counters with a very high gain up to a few 10^6. It should be noted that after each discharge the diode must be charged up again. During the charge-up time, set by the product of the capacitance and the quenching resistor, the diode is basically insensitive to new photons. Such detectors of very small area were already used in the late sixties for single photon detection. Around 1990 the concept was modified by some Russian physicists by combining many small diodes, each with its own integrated quenching resistor connected to a bus, onto a silicon wafer. The basic element (hereafter called cell) of a so-called G-APD is a miniature photodiode operated slightly above V_{bd}. Fig 1 shows the schematics of such a G-APD. Due to the standardized signal from each cell the G-APD has a very good single electron resolution allowing one to resolve up to a few tens of photoelectrons (PE). Due to the internal photoeffect a high quantum efficiency (QE) can in principle be achieved, i.e. much higher than with PMTs.

On the other hand the small cells must be separated by some inefficient material leading to a lower QE when averaged over the entire area. Cells have typically a sensitive area up to 100x100 microns and a few micron wide dead areas around them. Therefore, at best a QE of 20-70 % can be achieved in standard G-APDs. Such QE can hardly be reached in the high gain counting mode because not all electrons or holes will initiate an avalanche. The probability depends on the diode type and also on the overvoltage above breakdown. A typical photon detection efficiency (PDE) of a blue sensitive p-on-n G-APD set at $\approx$ 1V overvoltage is about 50 % of the QE but can reach $\approx$ 90% at $\geq$ 4 V. Therefore, it is important for performance estimates to replace the QE by the PDE, which is both a function of the QE and the overvoltage ($V-V_{bd}$). Currently, G-APDs are still

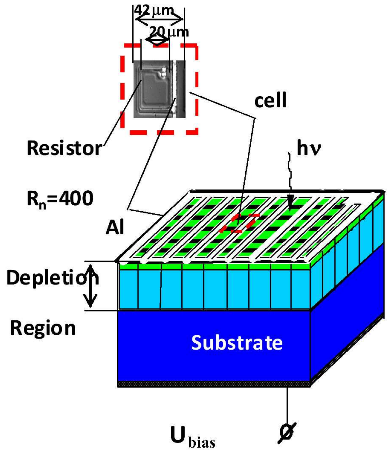

Fig. 1. Basic configuration of a Geigermode apd named SiPm (courtesy B. Dolgoshein).

in an advanced state of development. They have some limitations but quite some potential to replace PMTs in IACTs in a few years. As we simplified the description of the detection process, we refer the interested reader to [6] referring also the relevant references.

Advantages of G-APDs for IACT cameras are:

- A high PDE
- Very compact (< 2 mm thickness)
- High gain
- Insensitive to magnetic fields
- Low bias voltage (< 100 V)
- Very fast time resolution
- Not damaged when exposed biased to day light
- Potential for low cost

Disadvantages are:

- PDE significantly lower than the QE
- PDE depends on overvoltage
- Performance temperature dependent
- PDE sensitive to small voltage variation
- UV sensitivity needs improvement
- Optical cross talk
- Noise rate ($\geq$100 kHz/mm^{2}at room temperature)
- Small size (currently $\leq$ 0.3 cm^2)
- Dynamic range limited
- Currently too expensive

Most of these deficiencies can either be corrected or require a stabilized bias voltage or need constructive changes to make the G-APD a superior lightsensor for IACT cameras, see chapter 4.

In order to highlight the possible improvement we compare in Fig. 2 the QE (λ) of a G-APD (3x3 mm Hamamatsu MPPC) with that of some PMTs of different cathodes: a) a flat window PMT with a standard bialkali (Ba) photocathode, b) the Electron Tube hemispherical PMT 9116 B with a RbCs cathode and a special surface treatment (used in the MAGIC I telescope), c) a hemispherical Hamamatsu PMT with the novel superbialkali (Sba) cathode and d) a flat window PMT with the high QE Ultrabialkali (Uba) cathode.

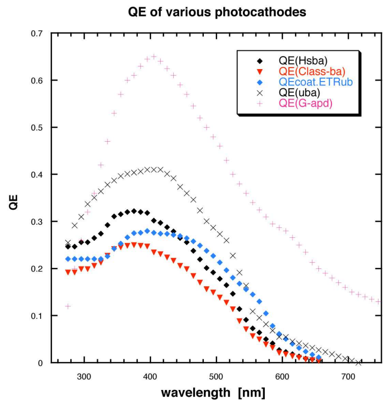

Fig. 2. QE (λ) for different sensors

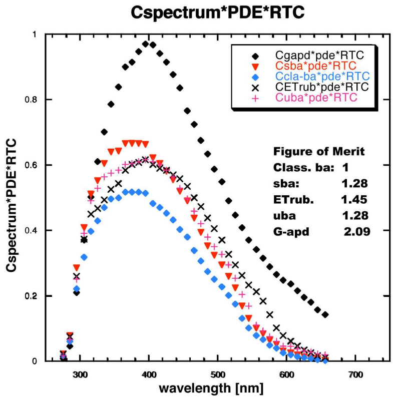

Fig. 3. PDE (λ) folded withthe Cherenkov spectrum and the optical parameters (R,T,C) of the Magic telescope

The G-APD could only be operated at 1.3 V V_{bd} because optical crosstalk becomes excessive at higher V_{bd}. Therefore, the ratio ε = PDE/QE of the G-APD is only 65 %. The flat window standard PMT and the hemispherical Sba PMT have an ε of 0.9, while the RbCs PMT used in Magic has an εg 0.95 (due to a maximized voltage between photocathode and 1^{st} dynode) and the flat window Hamamatsu Uba PMT with mesh dynodes an ε of 0.65 [4].

Fig 3 shows the PDE (λ) folded by the Cherenkov spectrum (50 GeV γ showers at 30° zenith angle at 2200 m altitude) and the reflectivity R of the MAGIC mirror, the camera window transmission W and the reflectivity of the light catcher C. We also calculated the so-called figure of merit (FM) by integrating PDF(λ) between 290 and 650 nm and normalizing the numbers to the value of the standard Ba flat-window PMT (see insert in figure 3). εgs only a guide-number as both the G-APDs and PMTs have fluctuations in design parameters and are often operated at different voltage configurations.

III. Some observations

In order to verify the potential of G-APDs to detect Cherenkov light we have carried out a number of observations, [1]. We used two types of G-APDs, the n-on-p type from Photonique (SSPM_0606BG4MM, area 4.4 mm^2 each, peak QE at 580 nm) and the p-on-n Hamamatsu MPPC with 55-65% peak QE at 450 nm, ≈ 70 V bias, 50x50 or 100x100 μ cell size, ≈ 250 kHz noise/1 mm^2 area at 26°C, τ_{rise} ≈ 2 nsec, τ_{fall} ≈ 30 nsec, see the Hamamatsu data sheet for the MPPCs. In all four tests we could detect Cherenkov light with about the predicted efficiency. In the fourth test, installing 4 MPPCs enlarged by 6x6 mm^2 light catchers in the MAGIC camera and comparing the recorded signal with that of the surrounding PMTs, we could confirm an increase in FM by about 1.8. Fig. 4 shows a recording of a shower both in the different G-APD and PMT pixels. Fig. 5 shows the shower image in the MAGIC camera and the location of the test pixels. Fig. 6 shows a larger statistics correlation between the PMT and G-APD signals when normalizing to the same sensor area. G-APDs detect 1.8 times more PEs/unit area (after optical cross-talk correction). In order to highlight the calibration prospects, we show in Fig. 7 the G-APD spectra with clear peaks for 1 and 2 (3) PEs.

IV. Some comments related to the deficiencies

As noted, current G-APDs have some deficiencies, which need to be corrected to efficiently use G-APDs in IACT cameras. Here we will discuss only the most critical issues. As mentioned, G-APDs have optical crosstalk firing neighboring cells when a cell detects a photon or a noise trigger occurs. For a gain of 10^5 typically 3-4 photons of 1-1.5 eV energy are generated in an avalanche breakdown. Currently, the G-APD gain can easily exceed 10^6 when the cell area is large and V_{bd} is set well above 1 V to reach a high PDE, see eq. (1). A prerequisite for a high PDE is to use G-APDs with large cells and little dead space and to operate them at high overvoltage. This is often impossible because the large photon production at high gain resulting in considerable cross-talk and, in turn, in a large excess noise. One solution is to lower the cell capacitance by constructive means, e.g. by increasing the p-n cell thickness. This allows one to increase the maximally allowed overvoltage, i.e. ε approaches 1 and (the PDE nearly the QE). As caveat the dark counts will increase but also V_{bd} has likely to be increased. Industry is working on such changes. Hopefully, a higher FM, close to 3, will be achieved soon. Alternatively, one can insert grooves between cells but this normally increases the dead area between cells and in turn lowers the average QE. The seemingly high noise of even the best G-APDs is not so critical in the case of use in large IACT. The night sky light background rate will exceed easily 2-4 Mhz/mm^2 G-APD area when observing a dark sky area outside the galactic plane. Very noisy G-APDs can be cooled but water condensation has to be avoided. Another critical issue is the temperature and voltage dependence of the PDE at small overvoltages. The breakdown voltage of the Hamamatsu MPPC rises by 50 mV/degree. At 1-2 V overvoltage an increase of a

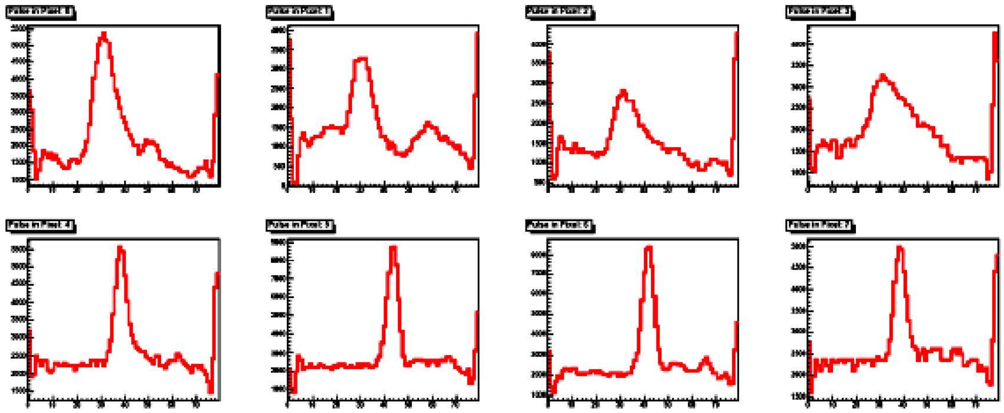

Fig. 4. An event seen by the 4 G-APDs (top) and in the surrounding 4 PMTs (bottom row), digitized by a 2 Ghz F-Adc. The G-APD signals are clipped by 50 Ohm coax cables to ≈ 3 nsec. Pickup peaks at start and end by multiplexer.

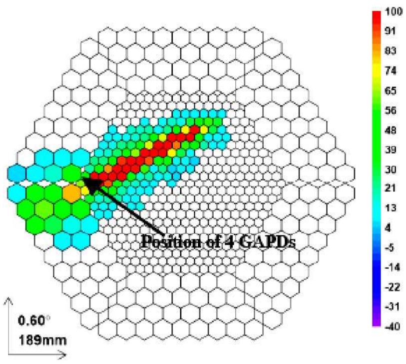

Fig. 5. Event recorded by MAGIC, as shown in Fig. 4

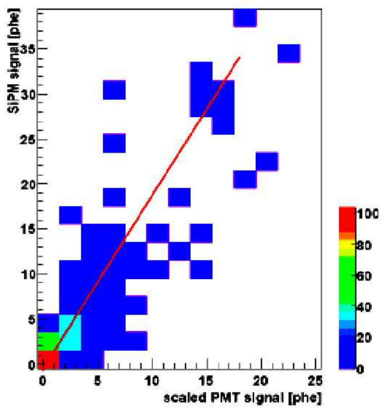

Fig. 6. Amplitude correlations of G-APD and PMT signals (300 events), normalized to same area

few degrees will significantly lower the overvoltage and in turn the PDE. Similar changes occur when the bias voltage is not well stabilized. The solution is to either stabilize the temperature or correct the bias voltage accordingly [5]. In case the G-APD can be operated at high overvoltage the influence of the temperature and voltage drift becomes less critical as the G-APD operates already at nearly a plateau in ε. The generally low UV sensitivity can be increased by a transparent lacquer coating doped with a wavelength shifter. Such improvements have been achieved with PMTs [3] and also with silicon PIN photodiodes.

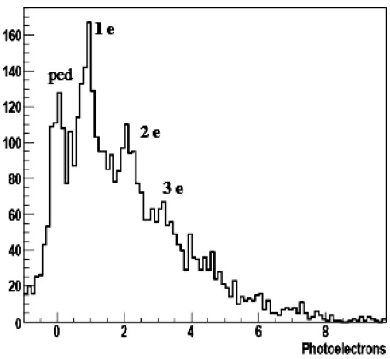

Fig. 7. Pulse height spectra of the G-APDs, recorded by thefull MAGIC readout chain.

V. Conclusions and Outlook

The current studies have shown that G-APDs have the potential to become a superior photodetector for IACT cameras. The gain of the tested G-APDs is too high allowing a large overvoltage to reach a high PDE. The problem is linked to high optical crosstalk. If industry succeeds in to lowering the cell capacitance at the same cell area one should reach a FM of up to 3 compared to PMTs with standard Ba cathodes. Also, a high regulation of the temperature or of the bias voltage is required.

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