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The Potential of SiPM as Photon Detector in Astroparticle Physics Experiments like MAGIC and EUSO

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We discuss the prospects to use a novel photon detector — the so-called SiPM — for the high energy astroparticle physics experiments EUSO and MAGIC. We explain the principle of these photon sensors and present results obtained with some prototypes. Peak photon detection efficiency (PDE) of the devices available is currently about 20%. Already in its existing form Geiger mode APDs offer a very promising replacement candidate for conventional photomultiplier tubes (PMTs) in both experiments, provided some improvements can be achieved.

1. Introduction

The MAGIC air Cherenkov telescope for ground-based γ–astronomy[1] is located on the Canarian island of La Palma. The currently comissioned telescope is designed to detect very high energy gammas (VHE-γ) with energies from a few tens of GeV up to several TeV. When a VHE-γ enters the earth atmosphere it initiates an electromagnetic shower. In the air shower Cherenkov technique a snapshot of the shower is taken by detecting the Cherenkov light emitted by relativistic shower particles. By analyzing these images the energy of the gamma as well as its incoming direction can be reconstructed and correlated with cosmic sources.

The number of Cherenkov photons arriving on ground is typically 100 photons per square meter for a 1 TeV gamma and scales in first order linearly with the γ energy. Experiments with large collection areas as well as highly efficient and fast photon detectors are needed to record these low light fluxes in the presence of a huge light background from the night sky.

The MAGIC collaboration plans to study the physics of some of the most energetic galactic and extragalactic objects known so far. Among these are active galactic nuclei (AGN's), supernova remnants (SNR's) and gamma ray bursts (GRB's). For a detailed description of the physics program we refer, e. g. to the MAGIC design report [2].

EUSO is a proposed spaceborne experiment to detect ultra high energy cosmic rays interacting with the earth atmosphere[3] [4]. It is planned to attach EUSO to the International Space Station in 2012. By looking down on the earth atmosphere EUSO shall be able to detect the fluorescence light emitted by cosmic ray induced extended air showers (EAS).

The detection of fluorescence light from space makes EUSO–like detectors a unique tool to study the nature and origin of cosmic rays at extreme energies ($> 10^{19}$ eV) because of the extremely large collection area.

EUSO will be able to study the GZK-cutoff at around 10^{20} eV with a statistical precision not accessible to ground-based experiments due to the large differences in the observed atmospheric volume. Above energies of 10^{19} eV the deflection of charged particles by the galactic magnetic field

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becomes small. Thus, the direct identification of sources of cosmic rays will be possible.

Theories predict ultra high energy neutrinos [5] [6]. EUSO might open this exciting window of high energy neutrinos in astronomy.

In summary, both experiments will help to reveal fundamental aspects of the so–called ultra relativistic universe.

A key limitation in both experiments is the relatively poor conversion of photons into electrical signals by classical photomultiplier tubes (PMTs).

State of the art PMTs have an efficiency (QE×photoelectron collection efficiency) around 20% between 300 nm and 550 nm. By looking to the signal to noise ratio (SNR)

$$\begin{aligned} \mathrm{SNR} &= \frac{\mathrm{Signal}}{\mathrm{Background}} \\ &= \frac{\mathrm{PDE} \cdot N_{\mathrm{signal}}}{\sqrt{\mathrm{PDE} \cdot N_{\mathrm{background}}}} \\ &= \sqrt{\mathrm{PDE}} \frac{N_{\mathrm{signal}}}{\sqrt{N_{\mathrm{background}}}} \end{aligned}$$

it becomes clear that with an increase in PDE from 20% to 80% the SNR of an event can be improved by a factor two (PDE = photon detection efficiency; N_{signal} = signal photons; $N_{\mathrm{background}}$ = background photons). A higher PDE enhances the energy resolution of both experiments and lowers their accessible energy threshold. Therefore any improvement compared to photomultiplier tubes will convert into better physics. Actually, due to the requirements of the experiment to discriminate γs from hadronic particles in MAGIC, the gain is nearly linear with the improvement of the photon detection efficiency. For efficient γ/hadron separation one needs to record at least 80–100 photoelectrons.

In the following we discuss the constraints on the photon detectors needed for MAGIC and EUSO as well as the principle of a novel photon detector, the silicon photomultiplier (SiPM). We present characteristics of a prototype SiPM produced by MEPhI and Pulsar enterprise [7] and discuss the status of R&D on SiPM for MAGIC and EUSO.

2. Requirements on the photon detector for MAGIC and EUSO

Table 1
Basic requirements for the photon detector for EUSO and MAGIC. For MAGIC the detector requirements are given for a pixel size of (5x5) mm^2.

parameter	**EUSO**	**MAGIC**
required sensitive range [nm]	330...400	300...600
pixel size [mm^2]	4x4	≥5x5
time resolution [ns]	10	1
single photon counting	yes	yes
dynamic range per pixel	100	1000
dark noise per pixel [1/s]	10^5	10^6
rate capability per pixel [1/s]	10^6	10^8
photon detection efficiency	> 50%	> 20%
radiation hardness required	yes	no

Table 1 lists the constraints on the photon detector for each experiment. Some of the requirements are quite different for both experiments. For MAGIC the photon detector has to be sensitive between 300 nm and 600 nm for the detection of the broadband Cherenkov light spectrum. Below 300 nm basically no Cherenkov light will be observed as it is being absorbed by atmospheric ozone. Above 600 nm the Cherenkov light drops while the background light of the night sky is steeply rising.

For the detection of fluorescence light with EUSO the sensitive range can be confined to 330 nm to 400 nm. In this wavelength band the nitrogen emission lines responsible for the fluorescence light are of the highest intensity.

Despite the differences in spectral sensitivity both experiments require a highly efficient UV sensitive photon detector.

For EUSO the maximum allowed pixel size is given by the optical resolution of the lens system which focuses the light onto the focal surface (FS). This resolution is 0.1°, which translates to a point spread function (PSF) of 5 mm diameter on the FS of the current EUSO design.

The angular pixel size of the current MAGIC camera is 0.1°. This translates into a pixel diameter of 30 mm for a 17 m focal length. The PSF of the reflector dish is smaller than the size of a pixel. A pixel consists of a Winston cone attached to a PMT. The Winston cone concentrates the light onto the photo cathode. For a better resolution of the shower one would like to go in future for a better optical resolution and smaller pixel sizes. A practical pixel size would be about $(5 \times 5)\,\mathrm{mm}^2$.

Single photon counting capability and single photon resolution paired with a good photon detection efficiency is of advantage in both experiments, as the light flux per event is very low. A precise knowledge of the number of photoelectrons directly translates into an energy resolution mainly limited by photon statistics.

The acceptable intrinsic dark count rate of the photon detectors is rather high as the light sensors operate in an extreme noisy environment (given by the light of the night sky (LONS)) $\sim 2 \cdot 10^{12}$ photons/m^2 sec sr (300 nm...550 nm) in case of MAGIC and $\sim 10^{11}$ photons/m^2 sec sr (330 nm...400 nm) in case of EUSO. A count rate of 10^5 counts per second per $(4 \times 4)\,\mathrm{mm}^2$ pixel area is tolerable for EUSO and 10^6 counts per seconds per $(5 \times 5)\,\mathrm{mm}^2$ sensor area for the MAGIC camera.

Some other constraints on the photon detector not listed in table 1 are intrinsic gain, low power consumption, low weight and robustness against accidental exposure to light. The latter points are particularly important for the spaceborne EUSO detector.

3. The SiPM working principle

A particularly interesting photon detector candidate for MAGIC and EUSO is the silicon photomultiplier (SiPM). For the last few years mainly Russian groups pursued the development of this type of APD, [7], [8], [9]. In this new approach the single photon counting feature of APDs operating in limited Geiger mode is exploited.

An APD is operating in Geiger mode if it is biased a few Volts above its electrical breakdown voltage. A photoelectron that is then entering the high field region initiates a catastrophic avalanche breakdown and a current will flow through the diode. In the SiPM a resistor quenches the breakdown by limiting the number of charge carriers within the junction.

A Geiger mode APD generates always a standardized output signal independent of the number of primary charge carriers which initiated the Geiger breakdown. The concept of large area sensors with large dynamic range is realized by implementing 500 to a few 1000 small independent APD cells within 1 mm^2 (see fig. 2). The sum signal of all cells is in first order proportional to the number of photons impinging on the sensor surface, provided the number of photons is small compared to the number of pixels.

The main advantage of these novel devices — besides the quasi digitized single pixel signal — compared to proportional APDs is their very high intrinsic gain; therefore expensive low noise preamplifiers are not mandatory. The gain of SiPM is in the order of 10^4 to 10^6 depending on the cell capacity, quenching resistance and bias voltage. The very fast response, low operation voltage and ease of production offer further advantages compared to state of the art APDs. In addition, the detector principle allows to resolve multiple photoelectrons as the signal of a single Geiger mode APD is not subject to multiplication noise as it is the case in a proportional APD. This is shown in figure 1 by the pulse height distribution of light pulses from an LED pulser. The width of the distribution is in perfect agreement with photon statistics, i. e. the full width at half maximum is $2.35 \cdot \sqrt{13.5} = 9$ not showing an excess of $\sqrt{2}$ as in APDs.

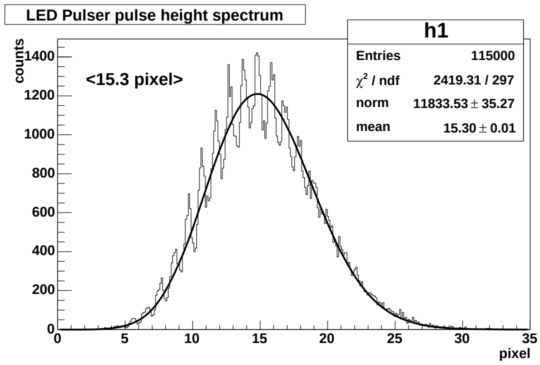

Figure 1. pulse height distribution of light pulses from a LED pulser recorded with a SiPM from MEPhI-Pulsar. The extremly good signal to noise ratio of single pixel signals allows one to count the number of fired pixels. For details on this SiPM see text.

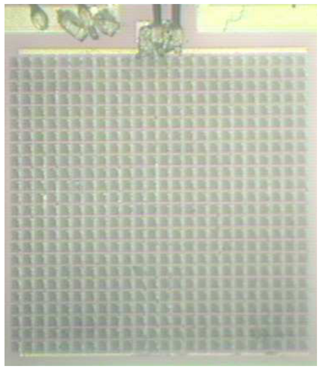

Figure 2. Photograph of the (1×1) mm^2 SiPM provided by MEPhI and PULSAR enterprise. This SiPM consists of 24 x 24 = 576 pixels operating in limited Geiger mode. In the upper part of the picture the bonding wires can be seen which serve both for supplying the bias voltage and as signal readout.

4. Existing Prototypes

Figure 2 shows a (1×1) mm^2 prototype SiPM. This SiPM is produced by MEPhI and PULSAR enterprise [7]. The main characteristics of this device are listed in table 2.

The photon detection efficiency (PDE) is about 20% peak around 540nm. The reasons for the current limitation in PDE are twofold

1. the dead area around each pixel
2. the finite probability for a photoelectron to initiate a Geiger breakdown.

The PDE of this prototype is a factor four lower than the effective QE of a standard APD. Nevertheless, it is comparable to the effective QE of a standard photomultiplier tube.

The current sensor shows low sensitivity in the UV region. The reason is the short absorbtion length for UV photons which is in the range from 10 nm to 100 nm. As the SiPM under investigation has an n-on-p structure, the photoelectrons will not drift into the high field region which is located deeper in the substrate . By inverting the structure to p-on-n the potential distribution within the device will attract the photoelectrons away from the surface into the high field region. This change in the doping is planned for future prototypes.

We are currently working on decreasing the dead area by increasing the single pixel size from currently 20 µm up to 100 µm with a constant inactive space between the pixels. This will boost the active area beyond 70% thus enhancing the PDE. For practical reasons (reduction of thermally generated noise) the sensor will be cooled. We are also investigating the application of light concentrators in order to improve the fill factor. We pursue three different ideas:

- A microlens for each pixel which focuses the light onto the active area.
- A light collector for each pixel which can be solid or hollow.
- The application of a wavelength shifter in combination with a dichroic mirror (light trap).

The last option can only be applied to the EUSO

Table 2
Specifications of the $(1 \times 1)\,\mathrm{mm}^2$ SiPM.

parameter	**value**
Sensor area	$(1 \times 1)\,\mathrm{mm}^2$
Nr. of individual pixels	576
active area	25%
peak PDE (around 540 nm)	20% (s. [7])
bias voltage	50V-60V
gain	$10^5 - 3 \cdot 10^6$
typ. noise rate at room temperature	10^6 counts/mm^2/s

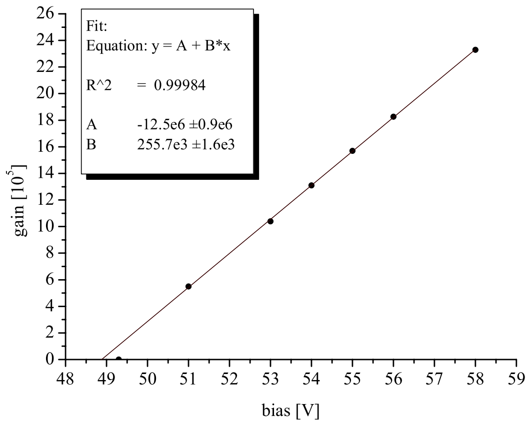

Figure 3. Gain dependence on the bias voltage for the SiPM operating at room temperature

photon detector, as the spectral range of interest is limited to 70 nm. For MAGIC this is not the case and only the first two solutions are feasible. It should be noted that the application of any light concentrator is considered to be a fallback solution if one fails to enhance the intrinsic active area.

The gain of the SiPM can be conveniently set between a few 10^4 and a few 10^6 by changing the bias voltage between 50 V and 60 V. A linear dependence of the gain on the supply voltage can be inferred from figure 3. This bias is very low compared to the ones needed for high gain linear APDs and PMTs where the supply voltage is in the order of 300-1000 V. By a proper design of the avalanche region the gain and breakdown voltage can be tailored to specific needs.

We observe crosstalk, i. e. a correlation between simultaneous firing pixels. The crosstalk depends strongly on the gain of the SiPM. This can be explained by hot carrier induced photon emission [10], i. e. photons emitted in the avalanche that are absorbed in a different pixel and trigger a Geiger avalanche. The SiPM under investigation shows a crosstalk of 40% when operated at a gain $2 \cdot 10^6$; this decreases to 4% at a gain of $5 \cdot 10^5$ which is needed for the MAGIC and EUSO experiments. Work is in progress to reduce this optical crosstalk by introducing trenches in between the pixels which inhibit photons from entering a neighboring pixel.

The intrinsic dark rate of the SiPM depends on the gain as well as on temperature. Typical values for a $(1 \times 1)\,\mathrm{mm}^2$ SiPM are 10^6 counts per second at room temperature when operating at a gain of 10^6. By lowering the temperature of the sensor the dark count rate can be reduced to an acceptable level. We measured a dark rate of 10 kHz at a temperature of -50 °C with a SiPM gain of 10^6.

5. Summary and Conclusion

High energy astroparticle physics detectors like MAGIC and EUSO can largely benefit from new highly efficient, fast and UV sensitive photon detectors. The SiPM has the potential to fulfill all the needs as photon detectors for these experiments. The existing prototypes from MEPhI and Pulsar have shown very similar properties as conventional photomultiplier tubes. With an improvement in UV sensitivity and enlarging the active area, the SiPM will be a replacement candidate for the initial photo sensors of EUSO-like experiments and MAGIC. The advantages of the SiPM principle are:

- single photon response
- large dynamic range
- potential for high photon detection efficiency
- high gain $10^5 - 10^6$, no need for preamplifiers
- ultra compact
- insensitive to magnetic field
- no damage from accidental and prolonged light exposure
- radiation hardness
- low operation voltage
- low intrinsic power consumption (40 µW per mm^2)
- mechanically robustness
- potential for cheap mass production

The disadvantages are:

- The high intrinsic noise which has to be reduced to an acceptable level by active cooling.
- The limitation in photon detection efficiency. We work on enhancing the PDE by increasing the pixel sizes and are looking for ways to enhance the fill factor with microlenses or other means of light concentration.
- The limited spectral sensitive range. We work on enhancing UV sensitivity by changing to a p on n structure.
- The optical crosstalk due to hot carrier induced photo luminescence. This we want to reduce by operating the SiPMs at the lowest possible gain suitable for the experiments as well as by introducing trenches to absorb the photons between different pixels.

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