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Status of Silicon Photomultiplier Developments as optical Sensors for MAGIC/EUSO–like Detectors

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A few years ago a new type of photon detector was introduced; the so-called Silicon photomultiplier (SiPM). In this paper we review the working principle of SiPMs and describe the status of our development. Finally, we sketch the possible application of a $5 \times 5\,\mathrm{mm}^2$ SiPM in Air Cherenkov telescopes.

1. Introduction

The study of the most violent processes in the universe by future experiments requires photon detectors with photon detection efficiencies (PDEs) higher than that of currently available ones. We are involved in photon detector developments for the MAGIC experiment and future EUSO–like space missions.

MAGIC [2] is currently the world largest air Cherenkov telescope. MAGIC has been constructed to study sources of very high energy γ–rays (VHE–γ) in the energy range from a few tens of GeV up to a few tens of TeV. In the experiment, γ–rays are detected indirectly by collecting Cherenkov photons which are emitted in a VHE–γ induced electromagnetic cascade in the atmosphere. For a more comprehensive summary of the physics programm of MAGIC the interested reader is directed to [1].

With an EUSO [4] like experiment, it is planned to study cosmic rays of the highest energies ($\geq 10^{19}$ eV) by detecting from extended air showers fluorescent light with a space born detector, for example as proposed by the EUSO collaboration. The photon yield at the entrance pupil of the detector is in the order of a few hundred to thousand photons distributed over a time window of about $100\,\mu$s.

In both experiments one uses (MAGIC) or plans to use (EUSO) large areas of classical photomultipliers (PMTs) which, beside other disadvantages, exhibit only moderate quantum efficiencies (QE). A light detector with a substantial higher photon detection efficiency ($> 40\%$) would lower the threshold energy of EUSO and MAGIC. This will allow for a considerable overlap with other experiments and thus cross calibration (EUSO/AUGER MAGIC/GLAST) as well as for opening a still unexplored energy region in the electromagnetic spectrum (MAGIC).

We are developing a new type of photon detector — the silicon photomultiplier (SiPM) — which already at the present stage shows a PDE similar to that of PMTs with bialkali photocathodes. In the following sections we will discuss the detector principle and our plans to enhance the photon detection efficiency of these devices.

2. SiPM Principle

A SiPM is an array of microcell avalanche photodiodes (APDs) operating in the limited Geiger mode[1]. A photoelectron generated in the depleted region of a Geiger-APD cell is initiating an electrical breakdown which can be easily detected due to the large current flowing. One possible way to quench the breakdown is to use a resistor which is limiting the current through the junction. This so-called passive quenching is applied in SiPMs.

The main disadvantage of single Geiger-APD cells is the inability to distinguish between one or more photoelectrons, as the output signal is solely determined by the capacitance of the diode. This has been overcome

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[1] We will use the expression Geiger-APD cell for one such APD. In the Geiger mode operation the APDs are reversely biased a few Volts above breakdown.

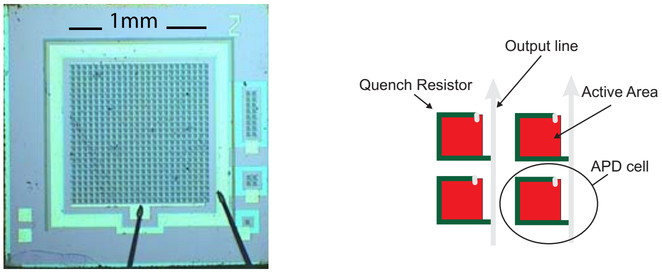

Figure 1. The left picture shows a 576 cell SiPM with a total sensor size of 1×1 mm^2. On the right hand side an exemplary view of four Geiger-APD cells is shown which are part of a SiPM (c. f. text for further explaination).

some years ago by the idea to combine an array of Geiger-APD cells on the same silicon substrate (e.g. [5, 6, 7]) and interconnect all cells in parallel through integrated quenching resistors (s. Fig. 1). The output signal of the SiPM is the analog sum of all individual cell signals. In applications where the number of photons incident on the SiPM per event is much smaller than the number of cells the output signal is proportional to the number of photons.

The SiPM is a noisy detector as it is sensitive to every electron generated in or diffusing into the active region. Typical dark rates at room temperature are $10^5 \ldots 10^6$ counts per second and mm^2 sensor area. In most applications in astrophysics the dark rate can be sufficiently lowered by moderate cooling to about -50 °C. The aim is to reduce the noise to $\leq 10\%$ of the ubiquitous night sky light background.

The photon detection efficiency of SiPMs depends on many parameters. The most limiting one is the dead space between single cells, which can reach 80% in some devices. Nevertheless it has recently been claimed by some groups that some SiPMs now reach PDEs of 20–30% in the blue wavelength region.

Another interesting feature which is intrinsic to SiPMs is the so-called optical crosstalk between individual cells. This is the result of photons which are emitted during a Geiger breakdown[8] and are migrating to neighboring cells initiating additional cells. This leads to output signals that are too large. There are two solutions for keeping optical crosstalk low. Either the SiPM gain is kept as low as possible or one optically decouples cells from each other. The last solution is currently under investigation by several groups.

The main drawback not to use SiPMs at this stage in astrophysics experiments is due to small sensitive areas. In Table 1 we give an overview of parameters of currently available SiPMs.

Table 1. Typical specifications of available SiPM

parameter	**value**
Sensor area	(1×1) mm$^2 \ldots (5 \times 5)$ mm^2
Nr. of Geiger APDs per mm^2	$\sim 100 \ldots \sim 10000$
active area of single SiPM cells[2]	$10\% \ldots 50\%$
peak photon detection efficiencies	$20\% \ldots 30\%$
bias voltage	30V . . . 100V
gain	$10^4 \ldots 10^7$
Geiger APD cell recovery time	~1 µs
typ. noise rate at room temperature	$10^5 \ldots 10^6$ counts/mm^2/s

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[2] This includes the area of Geiger APD as well as the space around it which includes the quenching resistor and space to the next neighboring cell

3. Ongoing Detector Developments

Conventional SiPM Design: In collaboration with MEPhI and Pulsar Enterpise we are developing the above described SiPM concept. Our main efforts are to enhance the PDE in the blue wavelength region beyond 40% and to enlarge the size of SiPMs up to $10 \times 10\,\mathrm{mm}^2$. We try to achieve the first aim by increasing the individual cell size at constant spacing between cells. In this way a geometrical fill factor of 75% seems to be feasible, which might be increased further. An additional increase in light collection can be obtained by using additional light concentrators; this will be explained later in this article.

To reduce optical crosstalk we plan to introduce trenches between cells. First tests have been successfully performed and will now be implemented in the technology of the production of SiPMs [9].

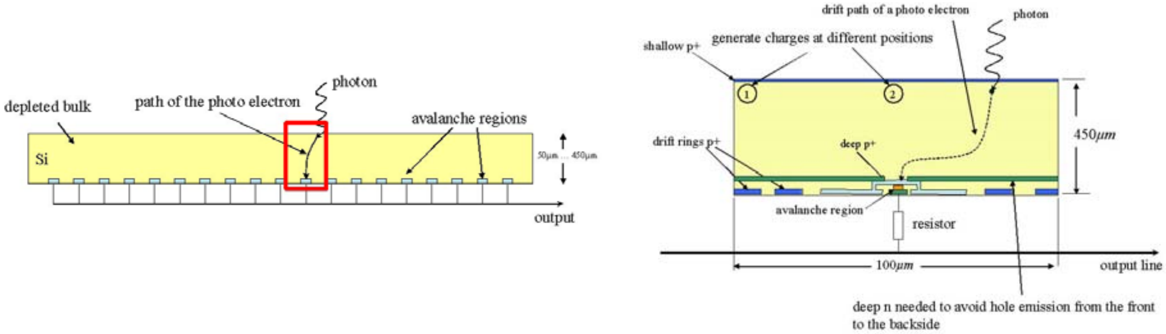

Figure 2. Schematic view of the back illuminated SiPM under investigation by the HLL. On the left side, a cross section through a back illuminated SiPM is sketched. On the right side, a blow–up of a single SiPM cell is shown. The drift path of a virtual photo electron from its point of generation until it reaches the Geiger APD is added.

Backside Illuminated Design In collaboration with the semiconductor laboratory (HLL) of the Max Planck Institutes for Physics and Extraterrestial Physics we develop a different kind of SiPM which promises to be superior to the above discussed SiPM in terms of the geometrical fill factor [10]. In this new concept the readout node of a silicon drift detector (SDD) is replaced by a Geiger APD. Such a Geiger drift cell (diameter $100\,\mu$m) is the basic cell of a novel back illuminated SiPM (s. Fig. 2). The advantages are small cell capacitances and full area efficiency.

The potential distribution in the cell is constructed such that all photoelectrons generated in the sensitive area are focused with high sensitivity into the Geiger–APD structure [10, 11]. The time jitter in the arrival time of photo electrons at the avalanche region due to their generation at different positions in the cell volume was simulated and found to be smaller than 3 nsec. This is mostly dependent on the geometry of the cell and only in some parts on the drift field. The HLL has a long experience in developing semiconductor detectors with low leakage currents; hence dark rates are expected to be tolerable with some additional moderate cooling. Currently we are translating our simulation results into a technology compatible to the one used by the HLL for other silicon photon and X-ray sensors. In order to verify simulations and evaluate the anticipated parameters of the device we aim to produce test structures within this year.

4. Application in Air Cherenkov Telescopes

As SiPM prototypes with sizes of $5 \times 5\,\mathrm{mm}^2$ will be available within the next months, we will discuss shortly a possible application scheme in Air Cherenkov Telescopes, which can also be applied in other experiments which use imaging techniques (e.g. Fluorescence detectors in AUGER).

Practical sizes of picture elements (pixels) in these detectors are typically in the order of a few centimeters. A possible solution to apply $5 \times 5\,\mathrm{mm}^2$ SiPMs will be to compose one pixel out of about 20 SiPMs. The readout scheme of this SiPM matrix pixels is sketched in Figure 3. In this framework, a MMIC is amplifiying each

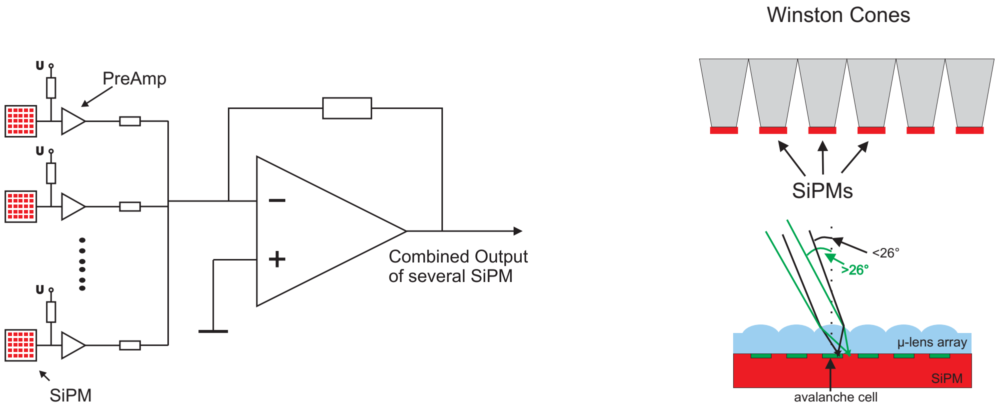

Figure 3. Concept of a possible application of a $5 \times 5\,\mathrm{mm}^2$ SiPM in IACTs. On the left side, a readout is sketched which combines several SiPMs to one output channel. On the right side, two possible methods are sketched by which the effective active area can be increased.

SiPM signal and decoupling the SiPMs. All twenty signals are afterwards combined by an analog adder using a fast current feedback amplifier.

There will be a considerable amount of dead space in between individual SiPMs, which has to be compensated. The distance between active areas of single SiPMs has to be about $4\,\mathrm{mm}$ to allow for sufficient space for bonding. Thus, the effective area per SiPM will be $7 \times 7\,\mathrm{mm}^2$, whereas the active area of each SiPM will be $5 \times 5\,\mathrm{mm}^2$, not taking dead space between Geiger cells into account. This factor of two in effective and active area can be recovered by applying non imaging light concentrators to each SiPM. In addition, one can further improve the photon collection efficiency by applying an additional microlens array to each SiPM to focus the incident light into the active area of each Geiger cell as outlined on the right side of Figure 3. This increase in collection area is constrained by the angular acceptance (Liouville theorem).

5. Conclusions

We are developing SiPMs for future experiments in high energy astrophysics which need photon detectors with much higher efficiencies in the blue wavelength (UV) region than currently available. The SiPM is a promising replacement candidate for conventional PMTs provided some important development goals will be reached. Firstly, SiPM sizes of at least $5 \times 5\,\mathrm{mm}^2$ have to become available, and secondly, the photon detection efficiency has to be raised above 40%. We try to accomplish both requirements by two independent developments, one together with MEPhI and Pulsar Enterprise, and another at the HLL.

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