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High gain hybrid photomultipliers based on solid state p-n junctions in Geiger mode and their use in astroparticle physics.

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Abstract

In astroparticle physics photomultiplier tubes play a crucial role in the detection of fundamental physical processes. After about one century of standard technology (photocathode and dynode electron multiplication chain), the recent strong development of modern silicon devices has brought to maturity a new generation of photodetectors based on an innovative, high-quality, cost effective technology.
In particular the most promising development in this field is represented by the rapidly emerging CMOS p-n Geiger-mode avalanche photodiode technology (G-APD or SiPM), for high-speed single photon detection with high gain and linearity. Most applications will require collection of light from even larger surfaces or volumes, so it is necessary to increase the active surface and the angular acceptance of SiPMs while keeping high sensitivity.
The main purpose of this research is, therefore, to provide an attractive solution to overcome this problem. The idea is to realize a hybrid detector (Vacuum Silicon PhotoMulTiplier,VSiPMT), where the dynodes structure of a classical Vacuum PhotoMultiplier Tube (VPMT) is replaced by an array of G-APDs, which collects the photoelectrons emitted by photocathode and acts as an electron multiplier.

Keywords: SiPM, VSiPMT, Geiger mode APD, Astro-particles, Photon detection, Photomultipliers, Cherenkov effect, MPPC

1. Introduction

In astroparticle physics, photons detectors play a crucial role in the detection of fundamental physical processes. In particular, most of the future experiments which aim at the study of very high-energy astrophysics (GRB, AGN, SNR) are based on photons detection. To date, the photon detection capabilities of the Photomultiplier Tube (PMT) seems to be unrivalled, however they suffer of many drawbacks, such as difficulty in single photon counting, complexity of construction, sensitivity to magnetic fields and faults in cryogenic environments.
To overcome these limitations, alternatives to PMT, mainly concentrated on solid-state detectors, are under

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study. In particular the most promising development in this field is represented by the rapidly emerging CMOS p-n Geiger-mode avalanche photodiode technology (G-APD or SiPM)[3-10], that will allow high-speed single photon detection with high gain and linearity. In order to overcome the limits of its small sensitive surface we propose an innovative design for a modern hybrid, high gain, silicon based Vacuum Silicon Photomultiplier Tube, VSiPMT. This solution is based on the combination of SiPM with vacuum technology: electrons emitted by a photocathode can be collected and focused on an array of G-APDs operating in limited Geiger mode, which acts as an amplifier. The junction works as an electron multiplier with a gain of 10^5 - 10^6, equivalent to the dynode chain of a classical PMT [1].
These developments will provide an attractive solution to the necessity of high detection areas with high sensitivity in several applications, like underwater and under ice neutrino astronomy and Cherenkov telescopes.
Before the realization of a first VSiPMT prototype our group is carrying out a preliminary work divided in three phases:

- characterization of SiPM with a laser source (fully completed)
- simulation of backscattering of electrons over SiPM surface (work in progress)
- characterization of SiPM with an electron source (still to come).

In this work we will describe the most relevant results of the first phase and will present the preliminary results of our simulations.

2. Structure of Vacuum Silicon PhotoMulTiplier (VSiPMT)

SiPMs are based on arrays of diodes operating in a region above the breakdown point (in the so-called Geiger mode). In this bias condition, the electric field is so high that a single carrier injected into the depletion region can trigger a self-sustaining avalanche. The carrier initiating the discharge can be either thermally generated (noise source of the device) or photo-generated (useful signal). The main limitation of a single diode working in Geiger mode is that the output signal is the same regardless of the number of impinging photons. In order to overcome this limitation, the diode can be segmented in tiny micro-cells (each working in Geiger Mode) set on a common anode, with a single output.
The structure of a Silicon Photomultiplier (SiPM) is a combination of a large number of avalanche micro-cells on a single substrate, with individual quenching resistors and common electrodes (Fig. 1).

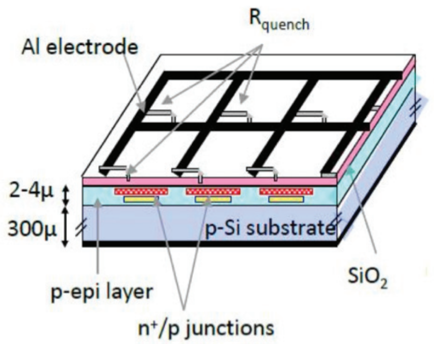

Fig. 1. Structure of the multi cell matrix of a SiPM

Each cell, when activated by a photon, gives the same current response, so that the output signal is proportional to the number of cells hit by a photon and the output signal is the sum of the Geiger mode signals of microcells. The dynamic range is limited by the number of elements composing the device, and the probability that two or more photons hit the same micro-cell depends on the impinging photon flux and on the

size of the micro-cell itself.
The basis of the G-APD micro cell is a reach-through avalanche structure n^+pp^+ where a depletion region thickness of about $1\mu m$ between the thin n^+ layer (thickness = $0.1 - 1.5\mu m$) and p layer is created by a reverse electric field (Fig. 2). On the surface of the avalanche microstructure is placed a thin metal layer ($\approx 0.01\mu m$) with an antireflection coating. Above the n^+ region, a resistive SiO_2 layer (thickness $\approx 0.15\mu m$, $\rho = 30 - 80M\Omega$) limits the Geiger breakdown propagation by a local reduction of the electric field. A quenching mechanism causes the deceleration of the avalanche process and its termination.
At present the silicon wafer cost and the thermal dark current limit the dimensions of the SiPM photo detector at few mm^2. Our purpose for an improvement of its angular acceptance is to combine it with vacuum technology. In particular the idea is to replace the dynodes structure of a photomultiplier with a silicon photodiode (HPD Hybrid Photo Detector) or with an avalanche photodiode (HAPD - Hybrid Avalanche Photo Detector). The design for such a new semiconductor photomultiplier consists of a hemispherical vacuum glass PMT standard envelope composed by a photocathode for photon-electron conversion and an electric field that accelerates and focuses all the photoelectrons to a small focal area covered with the SiPM (Vacuum Silicon PhotoMulTiplier, VSiPMT). Such a device acts both as a non-imaging concentrator and as an electron multiplier with gains of 10^5 - 10^6, similar to the dynode chain of a classical photomultiplier (Fig. 3).

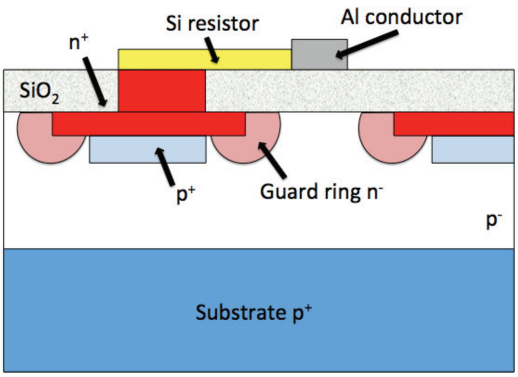

Fig. 2. Schematic structure of a SiPM avalanche microcell.

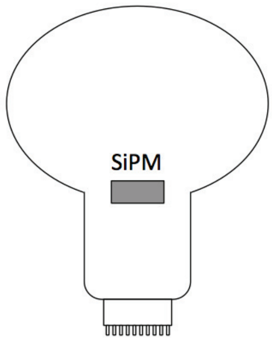

Fig. 3. Basic scheme of a Vacuum Silicon PhotoMulTiplier (VSiPMT)

3. Measurements

3.1. Experimental Setup

The basic performances of the MPPC are measured with light from a pulsed laser. The general scheme of the experimental setup is shown in Fig. 4. The board accommodating the MPPC is placed inside of a dark chamber; the laser, pulsed at a typical frequency of $100kHz$, is connected via optical fiber with a custom connector as coupling device. Two beam splitters are installed along the fiber way in order to reduce the beam intensity and control, for very low intensities, the number of photons: the 1% outputs are used on both splitters, leading to a 10^{-4} reducing factor. The optical power of the installation has been measured using a Newport mod. 815 power meter having a sensitivity of $1nW$ obtaining a response of about 50 to 2350 photons per pulse. The detector's output is connected to the input of a current-to-voltage amplifier, a LMH6624 by National Semiconductor used in inverting configuration and powered at $\pm 5V$. (Fig. 5).

3.2. Characterization with laser source

3.2.1. Gain

Fig. 6 shows the raw signal and the output charge spectrum from a Hamamatsu S10931-025P MPPC taken with an oscilloscope. The MPPC is illuminated by pulsed light from the laser at low intensity and

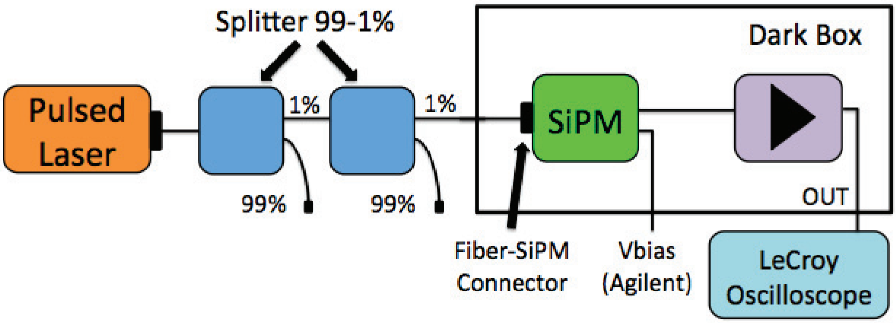

Fig. 4. Scheme of the bench test for the MPPC using laser source and beam splitters.

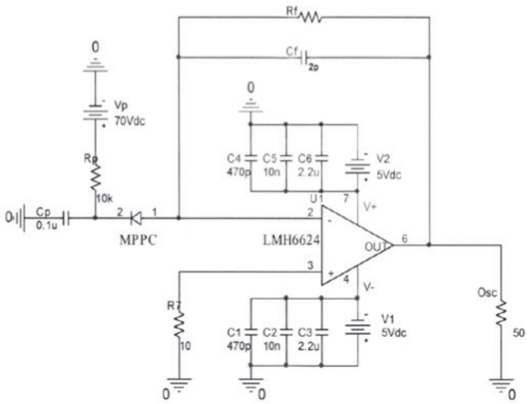

Fig. 5. Schematic diagram of the amplification board

the oscilloscope is triggered externally by the laser. The responses for multiple triggers are overlaid in the figure. The charge corresponding to different numbers of fired cells shows well separated peaks.

We used two independent methods for gain measurement: in the first one the gain is evaluated by measuring the charge of the signal corresponding to the initial number of photoelectrons, while in the second we measured the difference in the amplitudes of signals of 2-1 p.e., 3-2 p.e. and 4-3 p.e.. In both cases the MPPC is put under very low illumination conditions in order to clearly distinguish between peaks of 1, 2, 3 and 4 p.e.. In Fig. 7 the two methods are compared (cyan histogram for first method, yellow histogram for the second), while our results are reported in Fig. 8.

3.2.2. Dynamic Range

SiPMs produce a standard signal when any of the cells is fired. When many cells are fired at the same time, the output is the sum of the standard pulses. Single photons produce a signal of several millivolts on a 50Ω load. For a matrix of $N_{microcells}$ microcells, the dynamic range is limited by the condition that $N_{ph} \times PDE/N_{microcells} < 1$, where N_{ph} is the number of photons, and PDE is the Photon Detection Efficiency of the SiPM. In other words, the average number of photons per cell should be less than 1. If the number of detected photons is much smaller than the number of cells, the signal is fairly linear and saturates when the number of photons is about the number of cells. Saturation is well described by:

$$N_{signal} = N_{microcells} \times \left[1 - exp\left(\frac{-N_{ph} \times PDE}{N_{microcells}}\right)\right] \quad (1)$$

In Fig. 9 it is represented our dynamic range.

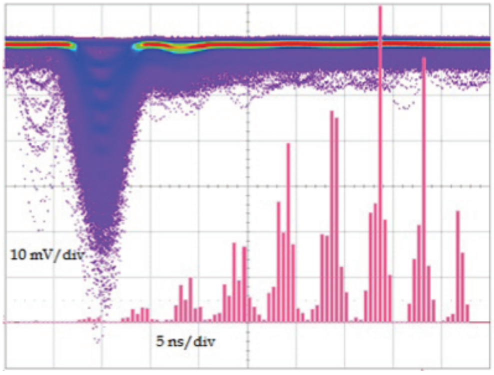

Fig. 6. A collection of pulse signals from MPPC as observed at the oscilloscope.

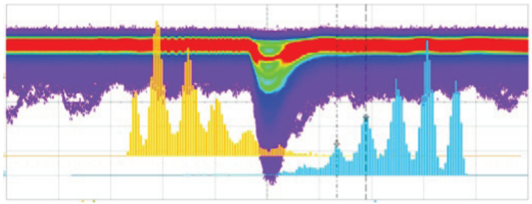

Fig. 7. Pulses from MPPC and gain measurements (binning of left and right histograms are of $5mV$ and $50.0pVs$ respectively).

4. Backscattering simulations: preliminary results

In a VSiPMT photons are converted into photoelectrons by a glass photocathode, while an electric field accelerates and focuses them towards the SiPM. A Geant4-based simulation of our system shows that with a voltage of $10kV$ between photocathode and SiPM the depth of penetration of photoelectrons impinging on the silicon is $1.5\mu m$ [1]. Moreover unlike the case of photons we expect that a part of incident photoelectrons will backscatter over the SiPM surface. For this reason another detailed Geant4-based simulation of our system, including the SiO_2 window, aimed at the evaluation of backscattering probability is in progress. Our preliminary results show that for normally incident electrons with energy of $10keV$ the backscattering probability is $\sim 12\%$.

The next step will consist in the realization of more accurate Geant4-based simulations in order to take into account other fundamental aspects such as the limited geometrical efficiency of SiPMs due to limited fill factor and the light emission in avalanches that causes a cross-talk between neighbour cells [11] and that may hit the photocathode of the VSiPMT and produce electrons.

5. Conclusion and perspectives

In conclusion, in the Vacuum Silicon Photomultiplier (VSiPMT) photoelectrons emitted by the photocathode are accelerated, focused and then amplified by Geiger junctions. Such an amplifier, which would substitute the classical dynode chain, would be free of such intrinsic limitations of classic photomultipliers as poor capability for precise photon counting, complexity of construction, sensitivity to magnetic fields and faults in cryogenic environments, while on the other hand it would present several attractive features such as: small size, low cost, high gain, high efficiency, absence of an external voltage divider, no power consumption, weak dependence on magnetic fields.

These developments will offer an attractive solution to the necessity of increasingly larger active surfaces with high sensitivity in several applications, like underwater and under ice neutrino astronomy, Cherenkov telescopes, liquid Argon detectors, calorimeters and scintillator readout and also for medical applications.

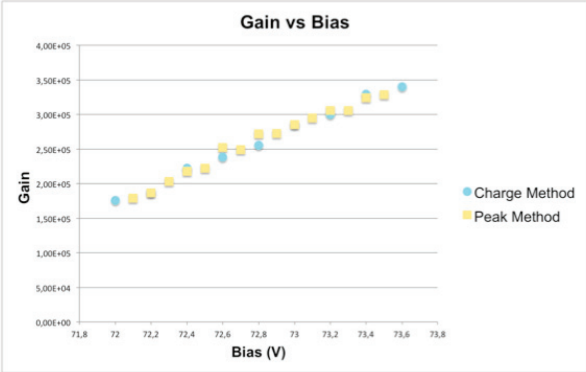

Fig. 8. Comparison between methods for gain evaluation

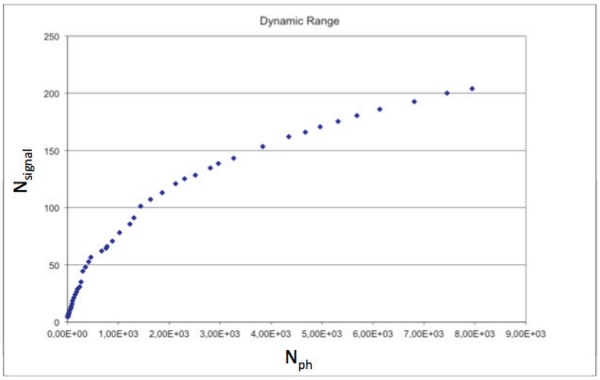

Fig. 9. Dynamic range

As a possible future development, exploiting the improved fill factor of a front illuminated SiPM [2] an ultimate design for a new semiconductor hybrid photomultiplier will be possible. It consists of a hemispherical vacuum tube with a deposited photocathode and a special SiPM in which quenching resistor and electric contacts are integrated in the bulk. The admittance of such a component on the sensitive surface allows an improved geometrical efficiency of a SiPM used as amplifying element. In this way this hybrid PMT results equivalent to those, already existing, manufactured with APD (the gain of an APD is $\sim 10^2$), but with a gain comparable to the standard PMTs (10^6 - 10^7).

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