The Vacuum Silicon Photomultiplier Tube (VSiPMT): A new version of a hybrid photon detector

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A B S T R A C T
The future astroparticle experiment will study both energetic phenomena and extremely rare events from astrophysical sources. Since most of these families of experiments are carried out by using scintillation phenomena, Cherenkov or fluorescence radiation, the development of photosensitive detectors seems to be the right way to increase the experimental sensitivity. Therefore we propose an innovative design for a modern, high gain, silicon-based Vacuum Silicon Photomultiplier Tube (VSiPMT), which combines three fully established and well-understood technologies: the manufacture of hemispherical vacuum tubes with the possibility of very large active areas, the photocathode glass deposition and the novel Geiger-mode avalanche silicon photodiode (G-APD) for which a mass production is today available. This new design, based on G-APD as the electron multiplier, allows overcoming the limits of a classical PMT dynode chain.

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1. Introduction

The future astroparticle experiments will study both energetic phenomena as gamma ray bursts, active galactic nuclei, supernova explosions and extremely rare events as dark matter interactions, proton decays, zero neutrino-double beta decays and low-energy neutrinos from astrophysical sources. The process of increasing the experimental sensitivity below the current limits is steering the development of detectors whose sizes should greatly exceed the dimensions of the largest installations available nowadays. In the construction of such a large-scale detectors, no other option remains than to use natural media as radiators, like the atmosphere, deep packs of ice, water and liquid gas, which are often kept at cryogenic temperatures. In these transparent media, charged particles, originating from the interactions or decays of primary particles, radiate Cherenkov or fluorescence light, which is then detected by photosensitive devices. High Quantum Efficiency (QE), high gain, single photon-counting capability, high linearity, good time resolution, robustness, compactness, no sensitivity to magnetic fields and a low production cost are the required characteristics for a photomultiplier to be used in the next generation of fundamental and applied Physics.

2. A new version for a Vacuum Semiconductor Photomultiplier

To date, the photon detection capabilities of the Vacuum Photomultiplier Tube (VPMT) are unrivalled. Nevertheless standard photomultiplier tubes suffer from some drawbacks such as the fluctuations in the first dynode, the linearity-gain conflict and large fluctuation of transit time spread.

To overcome these limitations, alternatives to VPMT, mainly concentrated on solid-state detectors, are under study. After about one century of standard technology (photocathode and dynode electron multiplication chain), the recent strong developments of modern silicon devices have the potential to boost this technology towards a new generation of photodetectors, based on an innovative and simple inverse p-n junction. Research carried out in Russia [1–4], has shown that these diodes can be operated in limited Geiger mode (G-APD). Presented here is a new design based on the idea of collecting and focusing the photoelectrons emitted by a photocathode on an array of G-APDs, which acts as the amplifier. The junction works as an electron multiplier with a gain of $10^5$, equivalent to the dynode chain of a classical VPMT. Thus the Vacuum Silicon Photomultiplier Tube (VSiPMT) would consist of the following elements:

- a photocathode for photon–electron conversion;
- an electric field to accelerate and focus the photoelectrons on a small area covered by the G-APD array.
3. The Vacuum Silicon Photomultiplier Tube

The present commercial production of avalanche Geiger-mode photodiodes gives the starting point for a new photomultiplier age, based on p-n semiconductors. For instance, in the Hamamatsu production at least three types of n+pp+ Multi-Pixel Photon Counter (MPPC) exist: 1600 (25 μm × 25 μm), 400 (50 μm × 50 μm) and 100 (100 μm × 100 μm) pixels segmented onto a 1 × 1 mm² total area. The achieved gain, 10⁵ at 70 V reverse bias voltage, makes the one photon level detection possible. The question is then how to detect photons from large surfaces and/or volumes, as typically needed in many astroparticle experiments. Nowadays surface and volume reduction can be achieved in three ways:

- by collecting photons and conveying them towards a single SiPM device;
- by enlarging the sensitive detector area by ordering several SiPMs in a pixelated matrix shape;
- by making a photon conversion by a vacuum hemispherical photocathode which focuses photoelectrons on a small low-cost SiPM area (VSiPMT).

In the first case the geometrical area reduction can be obtained by using wavelength shifter fibres embedded in the plastic scintillator body and connected at the other end to the SiPM. In the second case the image compression from large-surface detectors can be realized using matrices of single SiPM pixels. The dead area between sensitive surfaces of the individual detectors may be taken care of by focusing the light to the sensitive area by Winston cones. For what concerns the third case, we propose a new device contained in a vacuum glass PMT standard envelope composed of 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 Geiger SiPM. Unlike SiPM matrices, this device acts both as a non-imaging concentrator and as an electron multiplier with gains of 10⁵ similar to the dynode chain of a classical photomultiplier. In a conventional n+ p p+ structure the n+ layer has to be shallow enough, ≤ 0.5 μm, in order to have an efficient ionization in p region. With standard equipment for detector fabrication, layers with a junction depth of 100 nm can be obtained [5]. In addition the high-field region should be as thin as possible in order to have more ionization beyond it, therefore maximizing the electron trigger probability. Otherwise, at lower voltages, a junction structure p+ n n+ is needed. The ionization should occur in the p+ side, allowing electrons to go through the whole high-field zone with high avalanche efficiency. In both cases photoelectrons spread most of the ionization within the p layer thickness. In contrast with the photon detection, the precise range of the photoelectrons permits the optimization of the thickness of the junction n+ p p+ or p+ n n+ layers, thus minimizing the depletion region. This results in a great advantage for lowering the dark current, and in an increase of the efficiency and the time resolution.

Our design for a novel semiconductor photomultiplier consists of a hemispherical vacuum tube with a deposited photocathode and SiPM. The photoelectrons emitted by the photocathode are accelerated, focused and then amplified by the Geiger junctions (VSiPMT, Fig. 1). Such an amplifier, which would substitute the classical dynode chain, presents several attractive features such as small size, low cost, high gain, absence of an external voltage divider, no passive power consumption, weakened dependence on magnetic fields. Both SiPM matrices and VSiPMTs can be considered as a promising alternatives to classical photomultipliers also for VUV scintillation detection in liquid noble gas experiments that require a high sensitivity to very low energies to detect neutralino dark matter signals (see for instance Refs. [6,7]). The drop of thermal noise at low temperatures, three orders of magnitude at −95 °C for liquid Xenon, enhances the linearity and the single photon detection capability. The above considerations induce to envision a QE of 25% in VUV region [8]. These figures encourage the use of these new devices in cryogenic environment [9].

4. Preliminary results

The selected SiPM to be used in our design is the Hamamatsu MPPC. Preliminary tests were carried out on this device in order to evaluate its light response and to make a complete characterization in terms of gain and photon counting capability. Those figures will be useful as benchmark when the same characterization will be made using the MPPC under electrons. Using a pulsed laser the MPPC was illuminated with a very small number of photons.

Fig. 2 shows a typical SiPM response where different peaks are connected to different fired pixels. On the figure the signals amplitude histogram is superimposed. Peaks are well separated therefore a good photon counting is achievable with this device. The differences between two adjacent peaks was used to estimate the quantity of charge coming from a single pixel and, from that, the gain of the device was calculated. The same measure was performed at different bias voltages and the results are summarized in Fig. 3.

The efficiency of an SiPM to detect electrons is the product of several factors and depends on geometrical efficiency, absorption efficiency and the Geiger-triggering probability which depends on the position where the primary electron-hole pairs are generated. In silicon, electrons have a better chance to trigger a breakdown with respect to holes. If electrons are detected in a n+pp+ junction, the range (i.e. the energy) will determine where the primary electron-hole pairs are generated. If the end of range is in the p region beyond the high-field area, both carriers created along the track will be travelling in the opposite directions, contributing to the avalanche-triggering probability. When a pair is generated before the high field region, the electron is collected at the n+ terminal; thus, it does not contribute to the triggering probability. The hole is forced to pass through the full high-field region and so only holes contribute to the triggering probability. For pairs generated beyond the high field region, the situation is reversed and only electrons contribute to the triggering probability. A lot of simulations were performed to evaluate the range of electron in
silicon and to establish the correct voltage value between photocathode end SiPMT in order to maximize the triggering probability. As shown in Fig. 4 with a voltage of 7 kV the range of photoelectrons impinging on the silicon is 1 μm. This is an encouraging result because such a relatively low voltage allows to realize a VSiPMT with photocathode diameter smaller than 10 in.

5. Conclusions

The proposed Vacuum Silicon Photomultiplier (VSiPMT) utilizes the multi-pixel Geiger-mode junction as photoelectron amplifier. We have estimated the range of electrons in a SiPMT. We suggest that such a device may have an excellent single ionization detection capability overcoming all the limits of a standard dynode photomultiplier. The proposed developments may satisfy the necessity of increasingly larger active surfaces with high sensitivity in several applications such as like gamma air-showers, underwater and under ice neutrino astronomy, Cherenkov telescopes, liquid Argon detectors, calorimeters and scintillator readout, as well as in medical applications.

References