VSiPMT for underwater neutrino telescopes

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Abstract

Underwater neutrino telescopes are nowadays considered as one of the most important aims in the astroparticle physics field. Their structure consists of a cubic-kilometer three dimensional array of photosensitive devices aimed at the detection of the Cherenkov light emitted by charged particles produced by high energy neutrino interactions with Earth.
To date, a crucial role in this kind of experiments has been played by PhotoMultiplier Tubes (PMTs), however they suffer of many drawbacks such as linearity-to-gain relationship and difficulty in single photon counting. The next generation of experiments will require further improvements in photon detectors performances, therefore alternatives to PMTs are under 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), that will allow the detection of high-speed single photons response with high gain and linearity. In order to overcome to 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) based on the combination of a SiPM with a hemispherical vacuum glass PMT standard envelope. In this work we describe the full SiPM characterization realized by our group and present the results of our Geant4-based simulations of backscattering of electrons over SiPM surface.

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

1. Introduction

Photon detectors play a crucial role in many astroparticle physics experiments. In particular underwater (or under-ice) neutrino telescopes are aimed at the detection of the Cherenkov light emitted by charged particles produced by high energy neutrino interactions with Earth. To date, for this kind of experiments, the photon detection capabilities of PhotoMultiplier Tubes (PMTs) seems to be unrivalled. However, the next generation of experiments will require further improvement in linearity, gain, and sensitivity (quantum efficiency and single photon counting capability) of photon detectors, therefore alternatives to PMT, 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, represented by the rapidly emerging CMOS p-n Geiger-mode avalanche photodiode technology (G-APD or SiPM) [18-25]. These solid-state devices present important advantages over the vacuum ones, namely higher quantum efficiency, lower operation voltages, insensitivity to the magnetic fields, robustness and compactness. In order to overcome to 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) based on the combination of a SiPM with a hemispherical vacuum glass PMT standard envelope: 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 [1].
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 (fully completed)
- characterization of SiPM with an electron source (next to come).

The results of the first phase are described in [2], while in this work we will present the preliminary results of our simulations.

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2. SiPM as an electron detector

SiPMs are based on arrays of diodes operating in a region above the breakdown point. 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. Since for a single diode working in Geiger mode the output signal is the same regardless of the number of impinging photons, the surface of a SiPM is segmented in tiny micro-cells (each working in Geiger Mode) set on a common anode with individual quenching resistors (Figure 1).
Each micro-cell, when activated, gives the same current response, and the output signal is the sum of the Geiger mode signals of micro-cells.

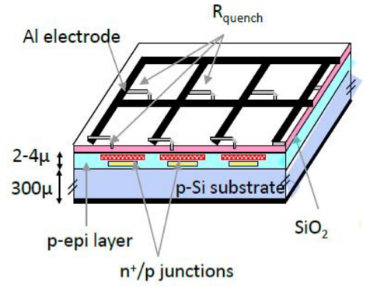


Figure 1: Structure of the multi cell matrix of a SiPM

In a VSiPMT photoelectrons emitted by a photocathode are accelerated and focused by an electric field to a small focal area covered with the SiPM, which therefore works as an electron detector. In this case electron-hole pairs are created by ionization, therefore for this process to happen there is an energy threshold for photoelectrons impinging on the surface of the SiPM, while unlike photons, electrons produce electron-hole pairs along all the ionization track, thus producing a higher signal amplification.
For effect of multiple coulomb scattering the trajectory of electrons in Silicon is continuously deviated from its initial direction, therefore the range of electrons is defined exploiting the so-called Continuous Slowing Down Approximation (CSDA), which assumes that electrons lose their energy gradually and continuously, thus neglecting fluctuations in energy loss. The CDSA range for an electron with initial energy E_0 can be determined integrating the inverse of total energy loss [3]:

$$R_{CDSA} = \int_0^{E_0} \left(\frac{dE}{dx}\right)^{-1} dE \tag{1}$$

The CDSA range is a purely theoretical quantity: it represents the mean path of electrons along their trajectory and it's not equal to the penetration depth along one given direction.
Moreover, when an electron beam impinges on a target a fraction of electrons can be backscattered. Backscattering is mostly due to multiple coulomb scattering, in particular to elastic collisions between beam electrons and atomic nuclei of target (primary electrons) or to anelastic collisions between impinging electrons and atomic electrons of the medium (secondary electrons). In the low-energy range the latter is the most relevant process of energy loss for electrons.
Conventionally the entity of backscattering is quantified by the backscattering coefficient η, that is defined as the ratio between the number of backscattered electrons and the total number of impinging electrons [4]:

$$\eta = \frac{n_{backscattered}}{n_{total}} \tag{2}$$

3. Geant4 simulation: setup

On the basis of a Geant4-based simulation [1] it has been determined that the minimum energy for photoelectrons to penetrate inside the SiPM and to produce electron-hole pairs is 10 keV. However a high fraction of backscattered electrons would imply a significant loss in the output signal, therefore we realized a Geant4 toolkit-based simulation of an electron beam, with given initial energy (in the range from 1 to 20 keV) and direction, impinging on a SiPM, simulating all the typical low-energy electromagnetic processes they could be involved in and focusing our attention on the backscattering process. The SiPM is simulated as a Silicon block with a thin ($\sim 0.15\mu m$) SiO_2 layer (anti-reflecting window).

In Geant4 a detector geometry is made of a number of volumes. Each volume is created by describing its shape and its physical characteristics, and then placing it inside a containing volume. Therefore for the generation of our detector volume we defined a Solid Volume (a geometrical object that has a shape and specific values for each of that shape's dimensions), a Logical Volume, that includes the geometrical properties of the solid, and adds physical characteristics of the volume, and a Physical Volume, that is a placed instance of the Logical Volume [5].
We defined a WorldVolume, simulating a material having approximately the same physical characteristics of vacuum (pressure $= 3 \times 10^{-18}$ Pa, density $= 10^{-25}$ g/cm^3), and inside it we defined a volume (Absorber) containing the Silicon block, inside which we defined the little SiO_2 volume. All volumes have been represented as boxes while all material properties were taken from NIST Standard Reference Database. Both geometry and materials have been defined using standard Geant4 classes (G4Box and G4Element more G4Material respectively).
Interaction processes of $1-20$ keV electrons in Silicon are low-energy electromagnetic processes. In our simulation we used the *G4EmLivermorePhysics* model, obtained by the combination of the model for standard electromagnetic processes with the model for low-energy electromagnetic processes. This model is suitable for the simulation of all low-energy electromagnetic processes in the range from 990 eV to 100 GeV (in particular for multiple coulomb scattering) and for elements with atomic number between 1 and 100 [5].

4. Geant4 simulation: results

First of all we validated our simulation parameters considering a 100 keV electron beam, normally incident over targets with different atomic numbers and comparing the values of backscattering coefficient obtained by our simulation with experimental values and with the values obtained by a validated Geant4 simulation which uses our same PhysicList for low-energy electromagnetic processes [6]. Results are shown in Figure 2.

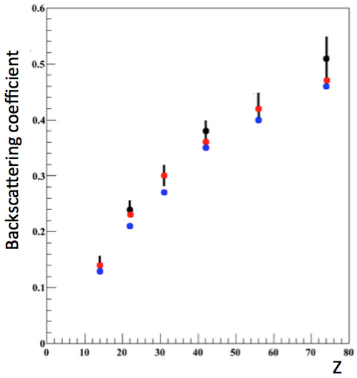


Figure 2: Comparison between experimental values of the backscattering coefficient (black), values obtained by our simulation (blue) and values obtained by the validated Geant4 simulation (red)

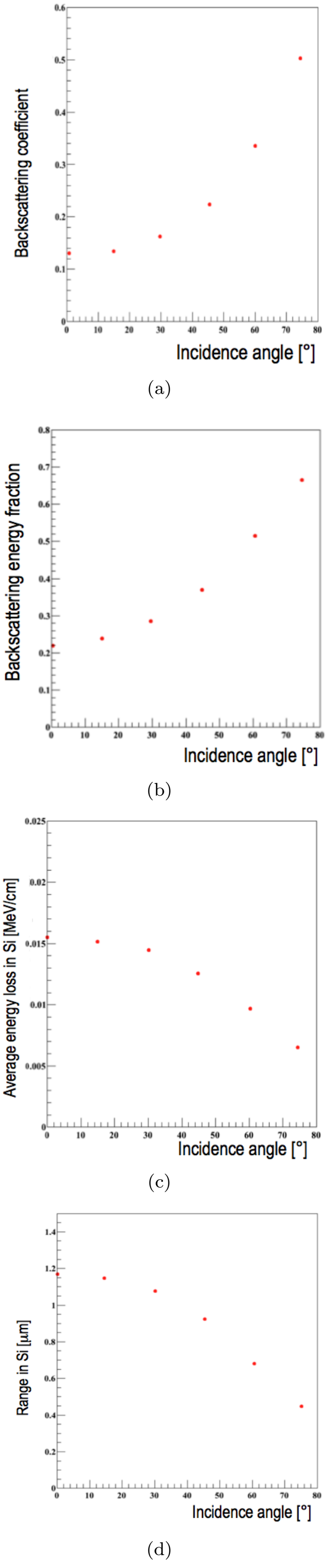
Two sets of simulations have been realized: in the first one we measured backscattering coefficient, range in Silicon, total released energy, backscattering energy fraction and average energy loss in Silicon for a normally incident electron beam, with energy in the range from 1 to 20 keV, while in the second one we measured the same quantities considering an electron beam with given energy (10 keV) and variable angle of incidence θ (from 0 to 75°). The backscattering energy fraction is defined as the ratio between the backscattered energy and the incident energy of the beam:

$$q = \frac{E_{incident} - E_{released}}{E_{incident}} \tag{3}$$

Figure 3 shows that the backscattering coefficient η of a 10 keV electron beam increases with the angle of incidence. In particular $\eta = 12.6\%$ for normal incidence and $\eta \sim 50\%$ for $\theta = 75°$.

Similarly, the fraction of backscattered energy fraction is equal to 0.22 for normal incidence and it increases with angle ($q = 0.68$ for $\theta = 75°$), while, as expected, the average energy loss in Silicon and the range in Silicon of electrons decrease as the angle of incidence increases. This results show that for small angles of incidence we have significantly small values of the fraction of backscattered electrons and of the fraction of backscattered energy.

Figure 4 shows that the fraction of backscattered energy for a normally incident electron beam decreases as the incident beam energy increases, while the backscattering coefficient grows from 0 to 10 keV and then it reaches a plateau region.



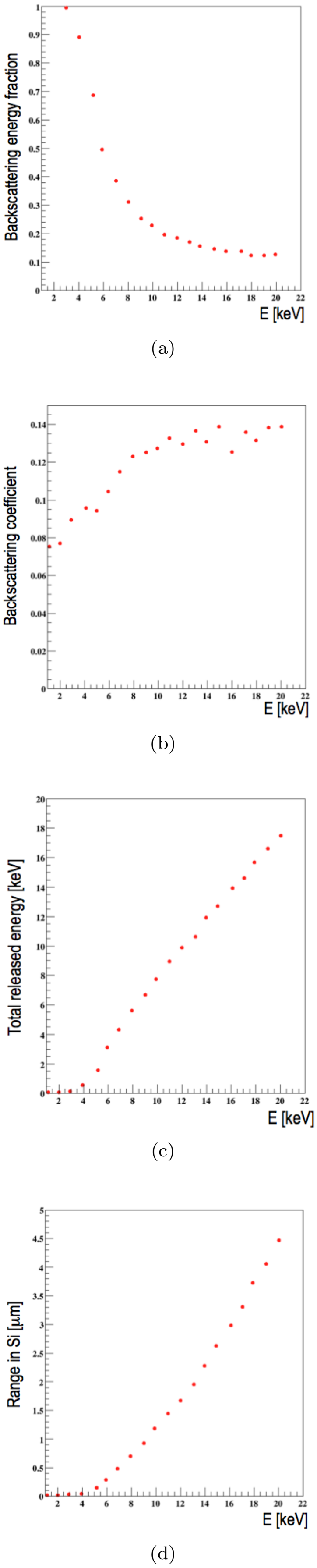
(a)

(b)

(c)

(d)

Figure 3: (a) Backscattering coefficient - (b) Backscattering energy fraction - (c) Average energy loss in Silicon - (d) Range of a 10 keV electron beam as a function of the angle of incidence



(a)

(b)

(c)

(d)

Figure 4: (a) Backscattering energy fraction - (b) Backscattering coefficient - (c) Total released energy - (d) Range of a normally incident electron beam as a function of the incident energy

The total released energy and the range of normally incident electrons on Silicon increase with the incident energy. They both start to be appreciable over 4 keV: in particular at 10 keV the total released energy is $\sim 7.5\ keV$ while the range is $\sim 1.2\mu m$.

Therefore 10 keV electrons are able to pass through the SiO_2 window and to penetrate for $\sim 1.2\mu m$ inside Silicon, with a limited backscattering effect.

5. Conclusions and perspectives

A Geant4-based simulation has been realized to study the backscattering process of electrons over a SiPM surface. In particular, the SiPM has been modeled as a 5mm Silicon box, with a $0.15\mu m$ deep SiO_2 anti-reflective window. We simulated an incident electron beam with energy in the range from 1 to 20 keV, while physical processes we used the *G4EmLivermorePhysics* model, which is suitable for the description of low-energy electromagnetic processes and in particular of multiple coulomb scattering.
The minimum energy for photoelectrons to penetrate inside the SiPM and to produce electron-hole pairs is 10 keV. According to our results, at this energy a normally incident electron beam has a range of $\sim 1.2\mu m$ and a backscattering coefficient of 12.6% while the backscattered energy fraction is only 22%. Therefore for small angles of incidence the SiPM can represent a valid solution to substitute the classical dynode chain of PMTs.
It's important to remark that we're dealing with just preliminary results: Geant4 toolkit is not well validated at low energies and often even experimental values of backscattering show discrepancies. The present work, however, represents the first implementation of an electron backscattering simulation in the range from 1 to 20 keV, so our results are very encouraging.
Our simulation, therefore, is able to provide just a prediction about detector's behavior, while real performances will be evaluated only experimentally, after the realization of a first VSiPMT prototype.

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