A new Design for an High Gain Vacuum Photomultiplier: The Silicon PMT Used as Amplification Stage

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ABSTRACT

Photons detection will continue to be a channel of great interest in the High Energy Physics and Astroparticle Physics fields for medium and big scale experiments in the next future. Thus, new solutions for photon detectors, that overcome the current limits of classical photomultipliers, are welcomed.

We propose an innovative design for a hybrid, modern, high gain Vacuum Silicon Photomultiplier Tube (VSiPMT) which is boosted by the recent Geiger-mode avalanche silicon photodiode (G-APD) for which a massive production is today available.

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 today’s installations. In the construction of such a large scale detectors, no other option remains than using natural media as radiators, like the atmosphere, deep packs of ice, water and liquefied gases, the last often taken at cryogenic temperatures. In these transparent media, charged particles, originating from the interactions or decays of primary particles, radiate into Cherenkov or fluorescence light, which is then detected by photosensitive devices. Hence, the improvement in experimental results relies on the technological development of photo detectors, indispensable devices in industrial monitoring, security control systems and in medical imaging too. High quantum efficiency, 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. CURRENT LIMITS OF THE CLASSICAL PHOTOMULTIPLIERS

To date, the photon detection capabilities of the Vacuum Photomultiplier Tube (VPMT) are unrivaled. Advantages in the utilisation of such a detector go from very high sensitivity to low noise, from a very good achievable Quantum Efficiency to the possibility of building the photo cathode in big windows.

Beside this, what we would like to have from an ideal photon detector would be the single photon counting, an high linearity not related to gain, to be insensitive to magnetic fields, a low jitter in timing and a low power consumption with a simplified supply circuitry. A simpler mechanics and a low costs would be definitely welcomed.

It has to be remarked that a great interest exists in finding new solutions for overcoming these drawbacks.

3. THE CURRENT USAGE OF MIXED SOLUTIONS

A new concept for an innovative photomultiplier, passes, without any doubt, through the use of silicon as the final detection system. Silicon photon detectors exist in a variety of types, and some configurations for hybrid photomultipliers have been already commercially available since several years. What we propose is using a new silicon
photon detector device as a final stage of the PM: the Multi Pixel Photo Counter (PMMC).

Up to now, the applied configurations for the hybrid applications have been based upon p-i-n diodes (p-doped, intrinsic, n-doped silicon wafer) or APD (avalanche photodiode) detectors. In the first case, an intrinsic gain of 1 in the p-i-n diode, makes the total gain of the photo detector due only to the electronic bombardment, in the order of $G=q(V_k-V_p)/3.6\ eV$, where $V_k$ and $V_p$ are the potential on the cathode and diode electrodes respectively. This leads to a typical value of 2000-3500.

A bit better gain can be obtained by the use of APD diodes (Avalanche Photo Diodes) with an intrinsic gain of 50, leading to 50-60 x 10^3. Different models exist made for instance by Hamamatsu (for example R7110U07).

Another interesting solution comes from the development made by D. Ferenc (et al.) [1]. It consists of a sort of “electrons trap” which accelerates primary photo electrons toward an internal target made of a light emitter “phosphorus”, sensitive to electrons ($Y_2SiO_5(Ce)$). Externally to this structure (and so in the air) a Geiger-mode APD array is installed in order to detect the secondary light generated by the flying electrons.

4. THE MPPC COUNTER

MPPC counters (Multi Pixels Photon Counter) represent an innovative, compact, small surface photo detector based upon Geiger mode operation of single pixels arranged in an array, which features:

- Geiger mode cells
- Active area from 1x1 to 3x3 mm² or more
- Number of pixels from 100 to 1600 units
- Low bias (~70 V)
- High gain (~10^5)
- Quantum efficiency can achieve 70%
- Time resolution 250 ps
- Dark counts ~100 kHz @ 25°C for the 10x10 (100) pixel model
- Commercially available - Hamamatsu Multi Pixel Photon Counter

The pixels are completely parallelized and the device is interfaced by just two terminals to the external readout and supply circuitries. A third terminal, which represents the shield, is present in devices with metallic case. The Figure 1 shows the internal structure of the wafer in which the pixels are built up and the equivalent circuit obtained by the parallelization of all pixels. The n⁺ p p⁺ structure is made in such a way that, locally, a very strong electrical field is generated and can reach 10^6 V/cm; moreover an intrinsic resistor, made by silicon oxide, is inserted on top of the sandwich in series with each pixel, providing spontaneous quenching after a discharge has occurred. In the Figure 2 the shape of the electric field inside the structure is represented: note the high field area, of a depth of about 1 micron or less, where the Geiger discharge occurs. A drifting electron or hole can induce a Geiger discharge in that region and, in the case, the quenching resistor reduces the electric field of the discharging pixel causing the process to stop. The induced current is the analogue sum of all occurred discharges that, intrinsically, are of a quantized amount. In such a way the signal has the value:

$$Q = n \cdot C(V_R - V_{BR})$$

Where $n$ is the number of fired cells, $C$ the cell capacitance and $V_R$, $V_{BR}$ the bias voltage and the breakdown voltage respectively [2]. The signal can be simply detected by voltage drop on the shunting resistor provided on the bias voltage supply, as typically done in ionization chambers or any other current-driven detector.

The efficiency of a general silicon photo multiplier is the product of several factors and depends on the geometrical efficiency, the absorption efficiency and the Geiger triggering probability. It can be expressed as:

$$PDE = \varepsilon_{geom} (1 - e^{-\alpha}) \cdot P_{trigger} (1 - R)$$
With \( \alpha = \) absorption coefficient and \( R = \) reflection coefficient.

The quantum efficiency of the sensitive area is defined by the absorption coefficient \( \alpha \) in Si, the thickness of the layers on top of the structure and the thickness of the depletion area (typical QE = 80-90%). The triggering probability \( P_{\text{trigger}} \) depends on the position where the primary electron–hole pairs are generated. Electrons have in silicon a better chance to trigger a breakdown with respect to holes. Thus, to maximize the triggering probability, the photon conversion should happen in the p side of the junction, in order to allow the electrons to cross the high field zone.

5. THE DESIGN FOR THE NEW VACUUM SILICON BASED PHOTO MULTIPLIER (VSiPMT)

The final structure of the proposed Vacuum Silicon based Photo Multiplier (VSiPMT) is a mixing of three, well known technologies:

- the manufacture of hemispherical vacuum tubes with the possibility of very large active areas
- the use of MPPC for which a massive production is today available, as final amplification device for photo electrons.

The aspects which suggested this idea came from the needs indicated in the introduction: large sensitive surfaces are necessary for the photon detection in experiments characterized by a large area and sensitive volume. For this reason the simple MPPC is not suitable as a main photons detector, unless it is not equipped with some sort of “wide angle lenses”.

The previewed layout is in principle quite simple and is illustrated in the Figure 4. An appropriate tube is built with the desired photocathode window, in terms of dimensions, size of the front part, choice of material (quartz, glass) etc., which all depend on the expected application. The same motivations are applied in the choice of the photocathode material. After that a minimum amount of electrostatic arrangement will provide for the photoelectrons to be accelerated and convoyed toward the MPPC situated in a convenient position able to accept them.

The MPPC is normally protected by a thin polymer film on its front window: simple simulations of electrons range in a material like polystyrene indicate that with an energy of 10 keV, electrons penetrate for 10\(^{-3}\) mm only. This condition makes inappropriate the presence of this protective film on the front window, which must be removed. For first prototypes we will take care to remove it by hand under microscopic observation; furthermore we will ask for fabrication without such a protection to the factory.

Studies of electrons range in silicon indicates that an energy of 10 keV should be enough to allow electrons to penetrate for some microns into the silicon crystal. In such a condition a consistent amount of secondary electrons and holes are expected, of the order of 10\(^{3}\) pairs. If not only the hitting photoelectrons coming from the photocathode, but also the path into the silicon of...
secondary electrons is sufficiently spread, the number of pixels which undergo to the Geiger process will be consistent: this is translated into an high output signal, easy to detect and manage (several millivolts). Such a condition can be more easily accomplished by adopting the back-illumination technique.

Definitively, we are planning to start with a prototype which will have a 10 kV overall accelerating voltage and a back-illuminated MPPC. The electrodes design, not yet implemented, will be the object of appropriate studies and simulation of the more convenient electrical field useful to convoy electrons towards the MPPC.

6. EXPERIMENTAL STUDIES AND TESTS

Before coming to a final prototype design, which must be realized in collaboration with industry, preliminary tests are undergoing in Naples’s laboratories. The test we are carrying on are of the following two types:

1. Tests direct to the characterization of the MPPC as a photon detection device.
2. Test for the response of the MPPC to the electrons stimulation.

The first ones are obviously accomplished with photons and are useful to take confidence with the MPPC, to handle all aspects of it and to perfectly know its functioning. These measurements are made by using a picosecond pulsed laser in the blue region (407 nm), used at very low power and pulse rate and attenuated by an optic fiber splitter at 1%.

The devices under test and their characteristics are the following:
- Hamamatsu S10362-11 Series
- Sensitive area 1x1 mm²
- Number of pixels: 1600 (Pixel dimension: 25x25 mm²)
- Fill factor: 30.8
- Spectral response: 270 to 900 nm
- Photon Detection Efficiency: 25 %
- Bias voltage used: 71.3V
- External amplification gain used: 40

The measures are taken into a shielded black chamber.

Very low laser beam power allows to easily reach the limit of detection of one single photon at a time, or detecting a few number of photons. In these conditions, with a threshold level set to 0.5 photons equivalent for the trigger, the single, double, triple photon (and so on) can be distinguished and photon separation resolution can be measured. Typical result is indicated in the Figure 5. Other measurements are currently in progress and will be the objects of future papers.

The second point is provided to study the response of MPPC to the electrons hitting on the sensitive surface. For this measurements a specific electron source has been designed and constructed. The source works under a turbo-molecular vacuum of 10⁻⁸ kPa and can be equipped with both a warm cathode, powered by a 10 W filament (12 V, about 870 mA), or a cold cathode based on a 40 microns diameter spherical pin. The first solution easily produces a large number of electrons (typical current of tens-hundreds µA) at any accelerating voltage (even 100 V), while the second produces low current (tens of nA) but needs a minimum of 4-4.5 kV to start the emission. Characterization of the source is currently undergoing in the lab with the aim of managing the produced electrons on our needs: a good control of the emission and current, of the energy and the possibility of reducing the flux thanks to a deflection or a suppression grid. Once these goals are accomplished we will proceed to the use of the source for studying the relative MPPC response.

7. CONCLUSIONS

We propose an innovative hybrid vacuum photomultiplier based on the use of MPPC as the amplification device (VSiPMT). For these reasons, MPPC are currently undergoing to intense tests in order to characterize them with photons and study their response to electrons. Then a prototype of VSiPMT will be designed and constructed in collaboration with industry.
REFERENCES