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Silicon Photomultipliers and front-end electronics performance for Cherenkov Telescope Array camera development

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ABSTRACT

In the last few years a number of efforts have been undertaken to develop new technology related to Silicon Photomultipliers (SiPMs). These photosensors consist of an array of identical Avalanche Photodiodes operating in Geiger mode and connected in parallel to a single output. The Italian Institute of Nuclear Physics (INFN) is involved in the R&D program Progetto Premiale Telescopi CHErenkov made in Italy (TECHE.it) to develop photosensors for a SiPM based camera that will be part of the Cherenkov Telescope Array (CTA) observatory. In this framework tests are ongoing on innovative devices suitable to detect Cherenkov light in the blue and near-UV wavelength region, the so-called Near Ultra-Violet Silicon Photomultipliers (NUV SiPMs). The tests on photosensors produced by Fondazione Bruno Kessler (FBK) are revealing promising performance: low operating voltage, capability to detect very low intensity light down to a single photon and high Photo Detection Efficiency (PDE) in the range 390–410 nm. In particular the developed device is a High Density NUV-SiPM (NUV-HD SiPM) based on a micro-cell of 30 μm × 30 μm and 6 mm × 6 mm area. Tests on this detector in single-cell configuration and in a matrix arrangement have been done. At the same time front-end electronics based on the waveform sampling technique optimized for the new NUV-HD SIPMs is under study and development.

1. Introduction

Silicon Photomultipliers, also known as SiPMs, are the latest generation of solid state detectors which are recently undergoing a relevant and increasing technological development. The basic structure of a SiPM consists of an array of Avalanche Photodiodes operating in Geiger mode (GM-APDs). Each photodiode contains a pn junction operating above the breakdown voltage (V_{br}) and connected in series to a quenching resistor. All the cells forming the array are connected in parallel to a single output and when activated by a photon (or thermal excitation) can originate a pair of charged carriers electron–hole in the depletion region of the junction triggering a self-sustaining avalanche. Because the current response is the same for each pixel, the output signal of the array is proportional to the number of cells hit by a photon. The role of the quenching resistor is to stop the avalanche and restore the initial condition to detect a new photon incoming.

The growing interest in these devices derives from several advantages with respect to the traditional photomultiplier tubes: insensitivity to the magnetic fields, compactness, ruggedness, low voltage operation and reduced costs. Furthermore SiPMs are showing a potential high PDE which makes them usable in a wide range of application fields where the ability to detect down to the single photon in a light pulse is an essential requirement, such as medical science and high-energy physics. The INFN within the R&D program TECHE.it is contributing to the development of a detector for the camera of the next generation of Imaging Atmospheric Cherenkov Telescope (IACT), the Cherenkov Telescope Array (CTA) [1] with the aim to detect the Cherenkov light emitted in

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the extensive air showers (EAS) that originate when cosmic rays or high-energy gamma rays interact with the atmosphere. In this framework test campaigns on NUV SiPMs [2] produced by FBK [3] have been previously performed showing that these devices are suitable to detect light in the blue–NUV region of the electromagnetic spectrum [4]. The so-called NUV-HD SiPM is a new technology that improves upon NUV SIPMs and is based on a p^+/n junction, cell pitch ranging from 15 μm to 30 μm and a fill factor higher than 50% depending on the cell size. In this paper we show the results of some tests performed on the 6 mm × 6 mm area NUV-HD SiPM and pitch of 30 μm in single channel configuration and in a matrix layout composed of 16 SiPMs.

2. NUV-HD SiPM in single configuration

During the tests we plugged the SiPM in a single channel configuration on a chip package into the evaluation board equipped with an inverting operational amplifier in transimpedence configuration which converts the current of the sensor to a voltage signal ($Z = 1000\ \Omega$). The system composed by the board coupled to the SiPM chip was grounded through a metallic support in order to reduce the electronic noise. The output of the evaluation boards was connected via a LEMO cable to the oscilloscope (LeCroy HDO4104) where signals were collected. The light source chosen is a Picosecond laser emitting at 380 nm, operating in pulse mode and controlled by a single channel driver (PDL 800-B, PicoQuant). Light was propagated through an optical fiber and a lens assured a uniform diffusion of the light incident on the device under test. All measurements have been performed at room temperature, controlled by a system of thermocouples and a Peltier cell and in a dark box in order to assure stable operating conditions during the tests.

Using a sampling of 2.5 GS/s, we acquired 150 ns length waveforms at several V_{bias} corresponding to $4V_{OV}$–$10V_{OV}$, with $V_{OV} = V_{bias} - V_{br}$. The persistence plot from the oscilloscope shows a width of the pulses that is in the order of few nanoseconds and pulses relative to 1 photoelectron up to 6 photoelectrons are clearly observable attesting to the pulse resolution down to the single photons for this kind of detectors. For each set of measurements we acquired 3000 waveforms with the oscilloscope synchronized with the laser, both triggered at 10 kHz.

The charge histogram is obtained by integrating each waveform and confirms a net resolution between the peaks as shown in Fig. 1 which is given as an example for a set of waveforms detected at $36V_{bias}$.

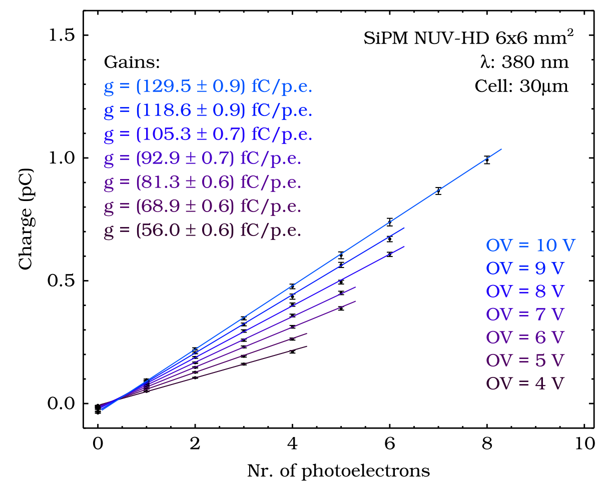

Fig. 2. Charge measurements on the NUV-HD SiPM at different overvoltages.

We fitted the charge pulse histogram with a multi-Gaussian function where each peak can be described by a simple Gaussian function, the mean value obtained for each peak is plotted as a function of the corresponding photoelectron number as shown in Fig. 2. The slope of the curves can be interpreted as the charge Q collected by the SiPM per fired cell and is related to the gain G by $G = Q/e$ where e is the electron charge. Then the average number of charge carriers produced by a photoelectron in the SiPM has a value between 2.95×10^5 ($4V_{OV}$) and 6.82×10^5 ($10V_{OV}$). It is interesting to note that these values are lower than the gain values obtained at same overvoltages for SiPM NUV with pitch sizes of 40 μm and 50 μm [5]. In addition the areas under each peak in the charge distribution histogram were normalized and fitted with a Poissonian distribution (Fig. 3) modified according to Vinogradov's expression [6] which allows us to estimate the mean number of photons detected by the photosensor (mean of the distribution) and introduces a further parameter that takes into account the correlated noise associated to the SiPM, given by the afterpulsing and the optical cross talk. While the photon number is constant with V_{bias}, the correlated noise varies between 11% and 48%.

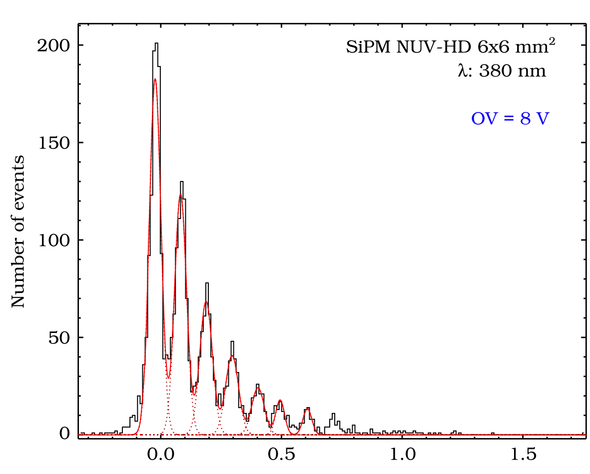

Fig. 1. Spectrum of the signal charge of the NUV-HD SiPM at $8V_{bias}$. The red line is a multi-Gaussian fit. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

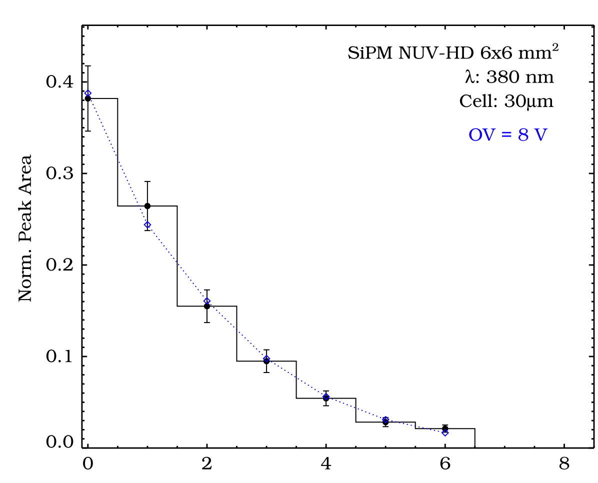

Fig. 3. Poissonian fit according to Vinogradov's correction on the normalized peak areas of the charge distribution.

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3. NUV-HD SiPM in matrix configuration

In preparation for construction of a camera prototype suitable for the Cherenkov Telescope Array, tests on SIPMs arranged in a matrix layout are currently being performed. The setup used for the measurement is similar to the one described in Section 2.

The configuration tested is the array of 16 photosensors shown in Fig. 4 where, in order to reduce the dead area between the SiPMs, V_{bias} is applied to the anode of the device through the bondings on the edge of the matrix. Signals are read from cathode and are consequently positive if compared to those detected from the NUV-HD SiPM in single configuration described in the previous section. First, it has been verified that the breakdown voltage of the 16 channels is uniform as can be noticed in Fig. 5.

In order to optimize the current signal processing, the board has been equipped with 16 preamplifiers based on an AD8000 operational amplifier in transimpedence configuration each coupled to a Pole-Zero network consisting of an RC filter ($R=1000\ \Omega$ and $C=470$ pF). The waveforms detected using this setup and shown in Fig. 6 confirm that the filter attenuates the long signal's tail avoiding the pile up and the consequent loss of information on the waveforms.

Furthermore we acquired signals at three voltages ($6V_{OV}$, $8V_{OV}$ and $10V_{OV}$) and derived a histogram of the maximum amplitude of each waveform. We performed studies on the response uniformity, considering first how the signal amplitude changes with V_{bias} for each channel and then comparing the values obtained for all the SiPMs. By fixing the bias, the amplitude is the same for all the matrix channels and varies between 2.5 mV/PE (at $34V_{bias}$) and 3.6 mV/PE (at $36V_{bias}$). In addition we evaluated the signal-to-noise ratio (SNR) for each SiPM as the ratio between the mean value of the single photoelectron peak in the amplitude histogram to the standard deviation of the pedestral. Fig. 7 shows the SNR as a function of the amplitude reveals a variation of SNR, depending on the channel, between 1.5 and 5.5 whereas the amplitude is characterized by a variation of few percent.

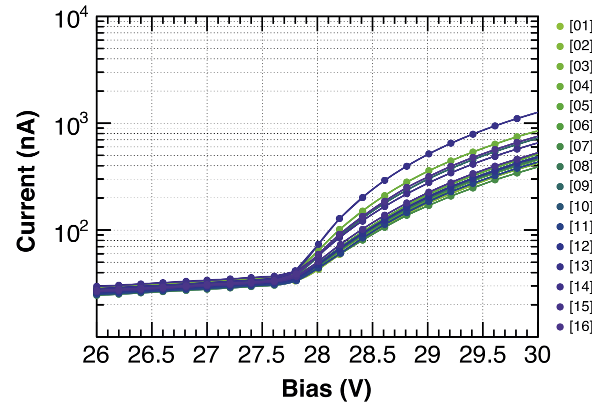

Fig. 5. Reverse IV characteristic of the 16 NUV-HD SiPMs arranged in the matrix layout.

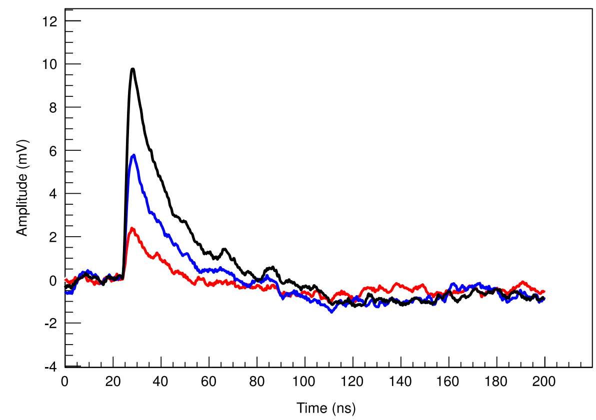

Fig. 6. NUV-HD SiPM output signal detected at $8V_{OV}$ for one channel of the matrix. Red curve refers to single photoelectron, blue and black refer to two and three photoelectrons signals respectively. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

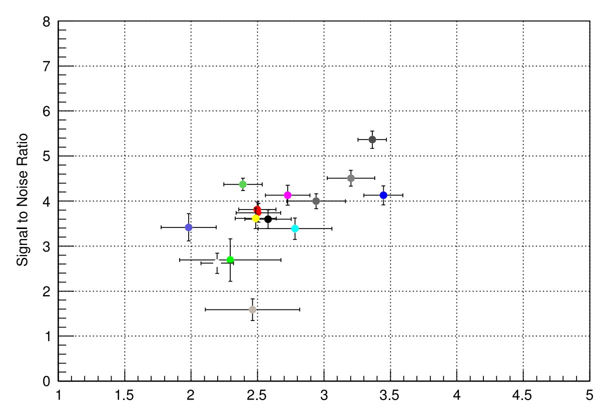

Fig. 7. Signal-to-noise ratio and amplitude of all the NUV-HD SiPMs in the matrix.

4. Conclusions

In this paper the results of tests performed on the NUV-HD Silicon Photomultipliers chosen for one of the camera prototypes of the Cherenkov Telescope Array have been presented. The characterization concerned SiPMs based on a micro-cell of 30 μm × 30 μm and 6 mm × 6 mm area in single configuration and in a matrix layout of 16 photodetectors.

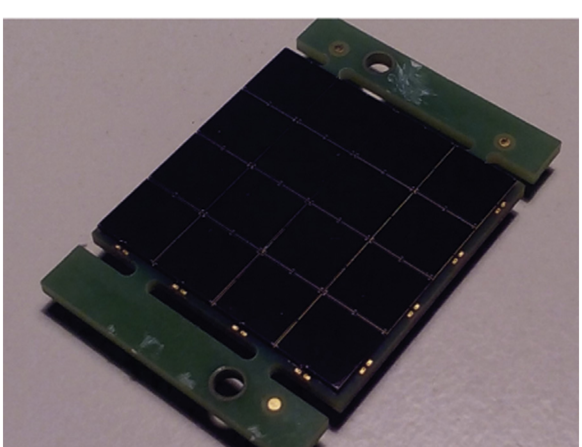

Fig. 4. Picture of the matrix arrangement with 16 NUV-HD SIPMs. Bondings are located on the right edge of the board.

NUV-HD SiPM in single configuration has shown an optimum pulse resolution down to the single photon and gain on the order of 10^5 depending on the bias applied to the device. In addition the contribution given by the correlated noise has been estimated revealing values lower than 0.5.

While studies on the single SiPM concern the understanding of performance of the detector, tests on NUV-HD SiPMs in a matrix arrangement aim to verify the response of the channels in terms of parameters that need to be uniform in all the channels during operation, such as amplitude or SNR.

Further tests to characterize the NUV-HD SiPM are ongoing

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(static characterization, noise, response to light) in order to chose the best operating conditions of this photodetector. In addition studies are in progress to improve the front-end electronics for the signal sampling, optimize the noise and reduce the current signal tail.

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