PROCEEDINGS OF SCIENCE

R&D for a high resolution SiPM camera for the Cherenkov Telescope Array within the CTA+ project

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The CTA+ project foresees the enhancement of the Cherenkov Telescope Array Observatory (CTAO) Southern Site to be constructed at Paranal, Chile. The project aims at increasing the number of telescopes included in the base CTA configuration, called "alpha" configuration. In particular, 2 Large Sized Telescopes (LSTs) and 5 Small Sized Telescopes (SSTs) will be manufactured and tested to be ready for the installation in the CTAO site in order to expand the alpha configuration. In addition, a R&D program is foreseen to improve the technology for a future upgrade of the CTAO southern site. CTA+ aims at developing sensors for a high-resolution Cherenkov camera to upgrade the current camera designs. Silicon Photomultipliers (SiPMs) with a very high sensitivity in the Near Ultraviolet (NUV) wavelength range, compatible with the Cherenkov emission spectrum, and low correlated noise will be employed. In addition, the R&D program includes specific developments of the Through-Silicon-Via technology, which allows for a compact packaging of the sensors and the minimization of dead spaces among pixels. We present here an overview of the CTA+ project, as well as the preliminary characterization of SiPMs recently developed by Fondazione Bruno Kessler (FBK), showing excellent photon detection efficiency in the NUV range and very low correlated noise.

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1. Introduction

Silicon Photomultipliers (SiPMs) are being widely employed in applications in which response to low, faint and brief light signals is required. Thanks to their small pixel size and the relatively low cost per channel, these devices are becoming interesting also for applications in which a deep imaging resolution is necessary, such as cameras employed in Imaging Air Cherenkov Telescopes (IACTs) for very-high energy gamma-ray detection. Indeed, their compactness and low operational voltage (<100 V) allow for a significant simplification of the camera design, while offering a powerful tool for signal calibration thanks to their single-photon-counting capability.

The Cherenkov Telescope Array Observatory (CTAO[1]) project is a huge worldwide project aimed at building a new generation of ground-based gamma-ray instruments. CTAO's goal is to obtain a factor of 5-10 improvement in sensitivity in the 100 GeV to 10 TeV energy range with respect to currently operating facilities, and to extend to energies well below 100 GeV and above 100 TeV by means of tens of IACTs operating simultaneously. In order to provide full-sky coverage, the design of the observatory foresees two arrays of telescopes, one in the Northern hemisphere (CTAO-N), at the Observatorio Roque de Los Muchachos in La Palma on the Canary Islands, and the other one in the Southern Hemisphere (CTAO-S) next to the European Southern Observatory's (ESO's) existing Paranal Observatory in the Atacama Desert, in Chile, with about 100 telescopes in total of different sizes in order to achieve the goals in terms of sensitivity and energy coverage. However, given the high cost of these infrastructure, up to today they have been partially but not completely funded yet. The baseline of the project, known as "alpha" configuration, foresees a reduced number of Small Sized Telescopes (SSTs) with respect to the original design and, in the southern hemisphere, none of the Large Sized Telescopes (LSTs) which were meant to be integrated into the array in the beginning.

2. The CTA+ program

A joint effort of Italian institutions,including the National Institute for Nuclear Physics (INFN) and the National Institute for Astrophysics (INAF), together with many Italian Universities, proposed the CTA+ program within the Italian Resilience and Recovery Plan. The program aims at strengthening the partially funded southern site by increasing the number of telescopes already included in the base CTAO-S configuration by providing 2 LSTs and 5 SSTs. Indeed, the development of these telescopes is currently the main goal of the CTAO, as this would give the opportunity to strengthen the performance of the southern site at the lowest and the highest energies, which are needed for transient physics and extragalactic surveys, as well as in the PeV domain.

In addition to the 2 LSTs and 5 SSTs which will be manufactured and tested to be ready for the installation at the CTAO site, the CTA+ program foresees a R&D activity to develop photo-sensors for a high-resolution Cherenkov camera to upgrade the current camera designs. With the aim of improving the technology, SiPMs with a very high sensitivity in the Near Ultraviolet (NUV) wavelength range, compatible with the Cherenkov emission spectrum, and low correlated noise are being developed. For this scope, the R&D program includes specific developments of the so-called Through-Silicon-Via (TSV) technology, which allows for a compact packaging of the SiPM sensors,

[1] https://www.cta-observatory.org/

minimizing the dead spaces between neighbouring micro-cells and improving the photon detection efficiency (PDE).

3. High-density SiPM evolution

Over the years, the synergy between the SiPMs producer Fondazione Bruno Kessler (FBK[2]) and INFN contributed to the development of an improved versions of NUV SiPMs, with high-density of cells (NUV-HD) and good sensitivity for Cherenkov radiation detection. The optimization process involved simulations, design, fabrication, production, and characterization of the NUV-HD SiPMs with a reduced cross-talk and primary noise, thus leading to the possibility of using larger cell pitch, which have higher fill-factor (FF) and consequently higher PDE. Therefore, the evolution of the technology over the years led to the production of SiPMs with the same area of $6 \times 6\,\mathrm{mm}^2$ and an increased pitch of 40 μm [1, 2].

The NUV-HD SiPMs have deep trenches filled with silicon dioxide between one cell and the neighboring cells to provide electrical and optical isolation, reducing the transmission of secondary photons among micro-cells, as reported in [1]. The possibility to reduce the optical cross-talk, which represents one of the major drawbacks of SiPM, is particularly interesting for SiPM-based cameras such as those developed for CTAO, as it would improve the performances in photon counting and energy resolution without degrading the photon-detection efficiency.

Starting from the NUV-HD technology, the NUV-HD Metal-in-Trench (MT) [3] SiPMs technology was developed introducing metal in trenches, which improves the optical isolation and strongly suppresses optical cross-talk. The MT design allows for a reduction of the internal cross-talk by a factor ~ 10, while also keeping the PDE comparable with the NUV-HD. Studies are currently ongoing in order to develop the TSV technology SiPMs, which would reduce the dead spaces between micro-cells, providing high fill factor and consequently high PDE.

4. NUV-HD Metal-in-Trench SiPM characterization

In this section we will describe the measurements performed on the 1×1 mm^2 and the 6×6 mm^2 NUV-HD-MT SiPMs, specifically developed by FBK for Cherenkov light detection, with different cell pitch ranging from 25 μm to 75 μm.

The rate of random dark pulses, which are thermally generated inside the SiPM structure and are not distinguishable from light-generated signals, was measured in dark conditions and at the ambient temperature. In order to avoid pulse pile-up and to distinguish afterpulsing and delayed cross-talk events from the primary ones, we applied the DLED algorithm [4] to remove the long tail of the signals. Analog signals were acquired with a digital oscilloscope at different bias voltages. A threshold approximately equal to half the amplitude of the single p.e. pulse was used in order to detect peaks corresponding to dark pulses and intrinsic noise of the device. As described in [5], the dark count rate was estimated by analysing the distribution of the time differences between two consecutive pulses, Δt, which is expected to follow an exponential distribution due to Poisson statistics [6],

$$\frac{dN}{dt} \propto e^{-\Delta t \cdot DCR}. \tag{1}$$

[2]https://www.fbk.eu/en/

Results of the DCR as a function of the applied over-voltage are reported in Figure 1.

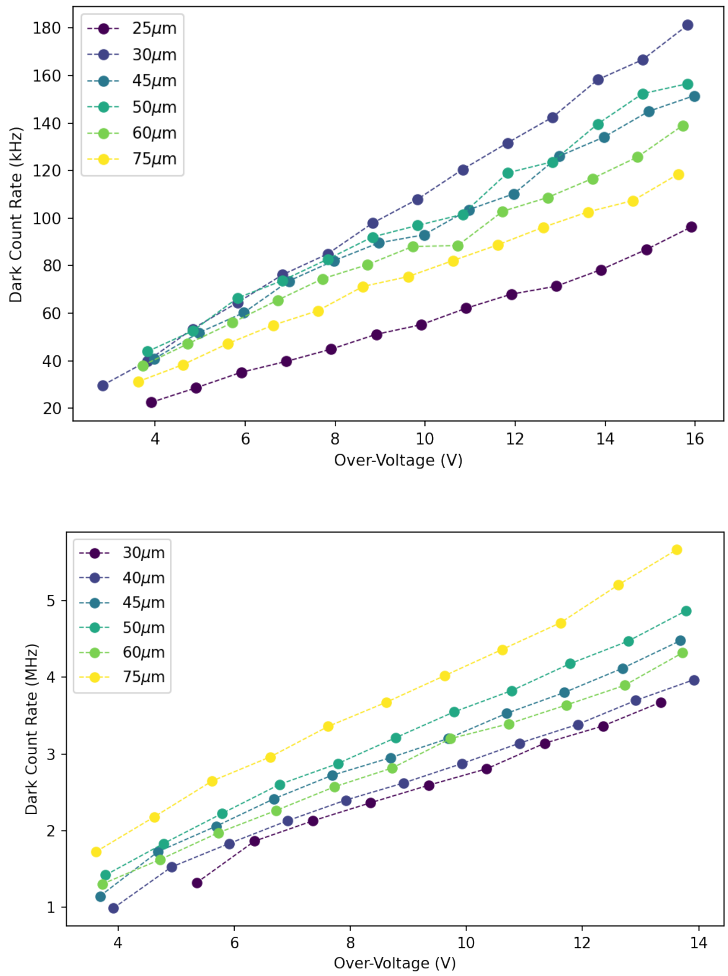

Figure 1: DCR evaluated from exponential fit as a function of the applied over-voltage for the $1 \times 1\,\mathrm{mm}^2$ SiPMs (top) and for the $6 \times 6\,\mathrm{mm}^2$ SiPMs (bottom) for different microcell pitch.

As can be seen from the plots, typical rates for the $1 \times 1\,\mathrm{mm}^2$ SiPMs are tens of kHz, increasing to units of MHz for $6 \times 6\,\mathrm{mm}^2$ SiPMs, as expected given the larger size of the device. However, it is interesting to notice that typical values of the DCR for previous NUV-HD devices, which are already employed in CTAO cameras, are of the order of $\sim$ 3 MHz at over-voltage $\sim$ 6 V, as reported in [2] , while the MT technology with the same cell-size (40μm), at the same over-voltage, exhibits a lower rate of $\sim$ 1.8 MHz.

The distribution of the pulse amplitude as a function of the time difference between pulses can be used to extrapolate information about delayed cross-talk, after-pulses and direct cross-talk probability [5, 7]. The sum of the 3 different correlated noise probabilities for the $1 \times 1\,\mathrm{mm}^2$ SiPMs is reported in Figure 2 as a function of the over-voltage. A major improvement in SiPM performance with respect to NUV-HD SiPMs is indeed found in the correlated noise probability. As reported in [2], the cross-talk probability alone was more than one order of magnitude higher in

NUV-HD devices of the same cell size. This reduction in correlated noise in NUV-HD-MT SiPMs is a confirmation of the better optical insulation obtained.

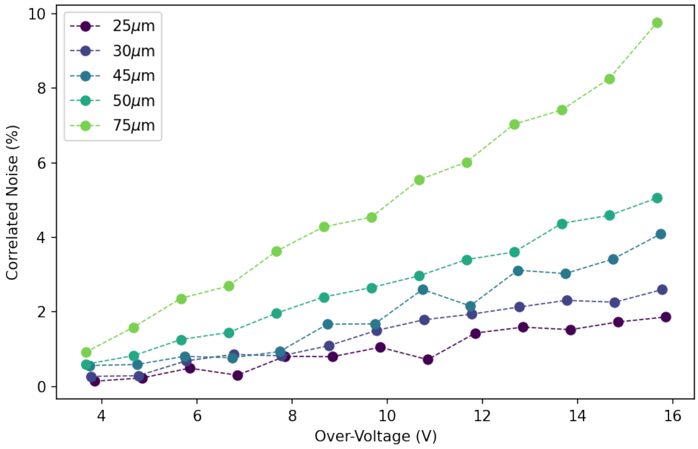

Figure 2: Correlated noise probability as a function of the over-voltage for the $1 \times 1\,\text{mm}^2$ SiPMs of different cell pitch.

Waveforms were then acquired without apppying the DLED algorithm in order to consider the whole tail of the signal. We integrated the waveforms up to 400 ns after the onset of the signal. The gain of the single p.e. as a function of the over-voltage is shown in Figure 3 for different $6 \times 6\,\text{mm}^2$ SiPMs. As expected, the gain increases with the over-voltage and with the cell size, which is related to the diode capacitance. The results obtained are compatible with those obtained for the $1 \times 1\,\text{mm}^2$ SiPMs, and with the gain reported in [2] for 40μm NUV-HD devices, as a confirmation of the fact that the metal-in-trench optical insulation does not affect the gain of the individual micro-cells.

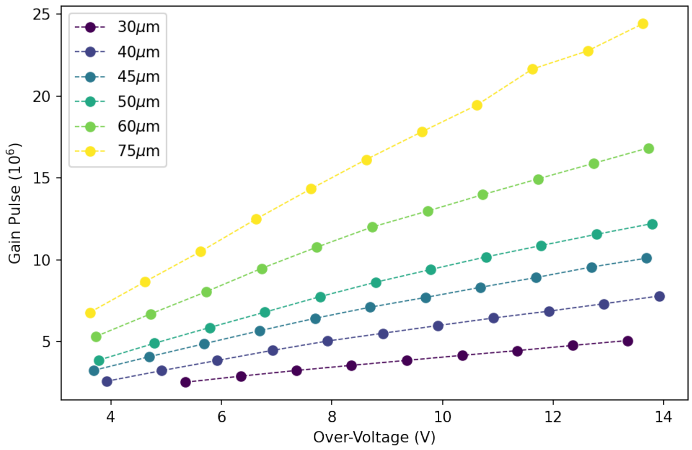

Figure 3: Single p.e. gain as a function of the applied over-voltage for the $6 \times 6\,\text{mm}^2$ HD-MT SiPMs for different microcell pitch.

Finally, we evaluated the PDE by illuminating the devices with a known wavelength peak emission pulsed LED transmitted to an integrating sphere through light fiber. The integrating sphere was used to distribute the incoming beam of light between the port opened toward the SiPM and a reference photodiode [9]. The number of photons impinging on the SiPM was deduced from the reference photodiode current by means of a previous calibration. The number of photons detected by the SiPM was calculated following the procedure reported in [8]. As expected, the PDE increases with the over-voltage up to saturation at about 60%, due to the increasing triggering probability with the higher applied electric field in the sensitive region of the device. This result is in good agreement with the PDE observed in [1, 2].

5. Conclusions

The recent developments in SiPM technology prove they are well suited for astroparticle physics applications, thanks to an improvement of their performances in the NUV domain, making these devices mature and suitable for Cherenkov light detection, as necessary for the CTAO project. The CTA+ program aims at the strengthening the southern site performance by providing 7 telescopes and by including a specific R&D program for the development of improved low cross-talk and compact packaged SiPMs, which will be employed in high-density cameras foreseen for the project.

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