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New developments in the SiPM cryo-electronics for low background dark matter experiments

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Summary. — One of the main issues of the large volume cryogenic detectors searching for dark matter rare events is the radioactive background from the electronic components and cabling that can give a significant contribution. The Silicon Photomultiplier technology in configuration of arrays offers the opportunity to cover wide sensitive surface detector keeping the number of the readout channels at reasonable levels. A low noise cryogenic electronics is needed to equip wide-area assemblies of photosensors to be readout as a single channel with the appropriate timing and single photon resolution. This paper will report the ultimate results of this R&D, achieved by the LNGS working group.

1. – Introduction

The Silicon Photomultiplier (SiPM) technology has become very attractive for light detection, in large scale Time Projection Chambers (TPC) based on noble liquids searching for dark matter signals in extremely low background conditions. The SiPM array configurations individuate a good compromise between a wide sensitive coverage area and a moderate number of readout channels, thus reducing radioactivity amount due to cabling in the detector. Nevertheless, grouping SiPMs into arrays means to face with their large output capacitance increasing with the area of the device that limits the SiPM speed and affects the Signal to Noise Ratio (SNR). To overcome this issue, a dedicated readout cryogenic electronics with specific requirements in terms of low noise and high bandwidth has been developed [1]. The first $5 \times 5\ \text{cm}^2$ tile, with an active area equivalent to a 3 inch photomultiplier tube (PMT) has demonstrated to work successfully in liquid nitrogen with better performance in terms of photon detection efficiency (PDE) and single photon resolution as shown in [2]. Here we present the first prototype of a large area photodetector based on a new tile design, with an overall surface of $100\ \text{cm}^2$ that is readout as a single analog channel.

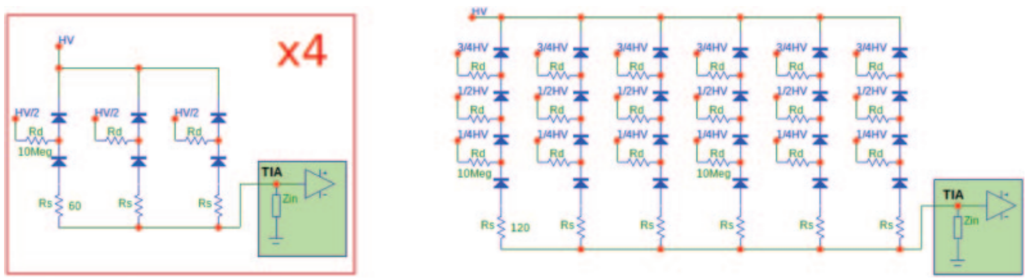


Fig. 1. – SiPM layout configured in $2s3p$ (left) and $4s6p$ (right) ganging. In the first layout 6 SiPMs are connected to an individual TIA. This configuration is replicated 4 times in the way that 4 TIA outputs are connected to an active adder to get a 5×5 cm^2 tile readout. The second layout combines all the 24 SiPMs into a single TIA.

2. – SiPM ganging

In our R&D, we adopted the last generation of photosensors produced by Fondazione Bruno Kessler (FBK): the NUV-HD-LF Cryo. Such devices exhibit better performance in terms of stability at cryogenic temperature with respect to the predecessors NUV-HD-LF adopted in [2]. They benefit from a lower quenching resistor, a reduced dark count rate < 1 mcps/mm^2, a very low afterpulse probability ($< 10\%$), and an internal cross-talk $< 50\%$ at the highest over-voltages. Both technologies are widely described in [3]. The 25 cm^2 tile has been assembled according to a $2s3p$ SiPM configuration taking into account the low SiPM output generated current as a result of the small size and higher quenching resistor. A higher-order ganging, with more devices in series, would have further reduced current. Hence, 6 SiPMs have been connected in three branches, each one with two devices in series. The tile readout has been performed by dividing it into 4 quadrants, each one read out by a single Trans Impedance Amplifier (TIA). Then an active adder performed the sum of the four amplified signals to combine 24 SiPMs into an analog output ($4 \times 2s3p$ configuration). The increased output current of more than a factor three with the same overvoltage in the NUV-HD-Cryo SiPMs with respect to the previous devices (NUV-HD-LF SiPMs) allowed to explore an alternative SiPM ganging: the $4s6p$ configuration. A direct comparison of the electrical parameters between the 2 different SiPM array configurations are detailed in [4]. The $4s6p$ layout is implemented by connecting six branches in parallel, each one with four SiPMs in series, so that 24 SiPMs are readout by an individual TIA. Both SiPM configuration schematics are shown in fig. 1. The $4s6p$ ganging reduces the signal by a factor two with respect to the $2s3p$ due to the series of 4 SiPMs; nevertheless, thanks to the different signal shape of the NUV-HD-Cryo SiPMs, the absolute value of the peak voltage at the output of the amplification chain is higher than the one of the NUV-HD SiPMs configured in $4 \times 2s3p$ ganging. The results have been obtained by operating the SiPMs with the same over-voltage and the same amplifier gain. Furthermore, by choosing appropriate circuit elements it is possible to halve the noise of the tile and maintain the SNR at the level of the $2s3p$ configuration keeping the TIA with the same noise gain and bandwidth as demonstrated in [4].

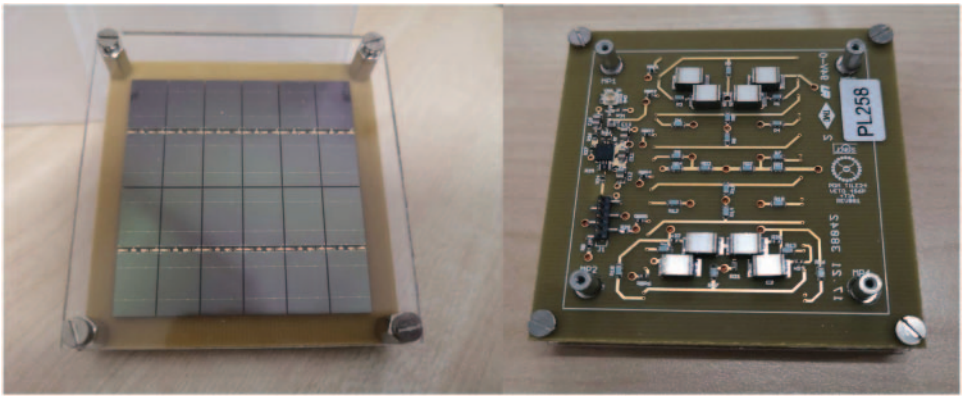


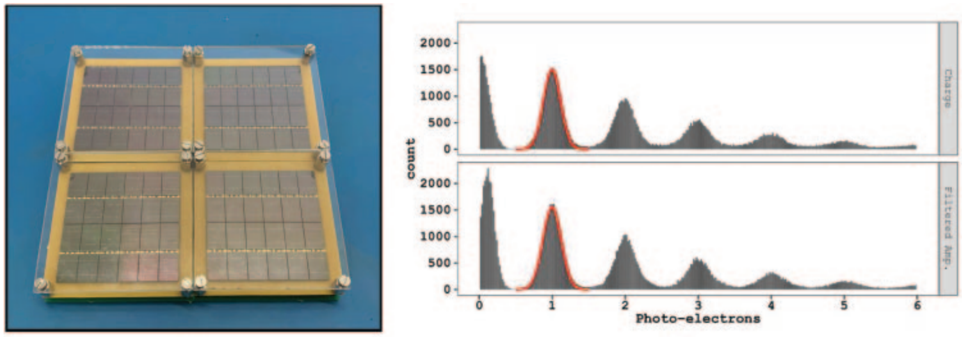
Fig. 2. – Tile+ top (left) and bottom (right) view. The TIA and the rest of the components are integrated into the same PCB.

3. – Tile+

The $4s6p$ configuration brings significant advantages: the single TIA with a $7\times16\,\text{mm}^2$ area, together with the circuit elements can be integrated in the tile printed circuit board (PCB) leading to a new concept of the tile: the tile+. This design removes the necessity to have two distinct boards: one for SiPMs and one for the electronics, thus implementing a self-consistent photodetector module into a compact standalone unit 1 cm high. A reduced number of components mean easier integration in the detector and a lower impact on the radioactivity budget with an appropriate selection of the materials. The current PCB is in Arlon 55NT that is also resistant to thermal stress, while the PCB finish and the SiPM backside are in gold. Finally, the presence of an individual TIA instead of 4 significantly decreases power consumption: in liquid nitrogen the full tile+ dissipates 50 mW. The top and bottom layer of the tile+ are shown in fig. 2: the top layer hosts 24 SiPMs, while the bottom one is made of the PCB hosting all the circuitry. The tile+ dimension is 49.5×49.5 mm^2. This version has been realized with a border of 5 mm with a protective acrylic frame for safe handling during test operations. At the corners of the PCB, four threaded cylindric 5 mm spacers have been soldered during the assembly of the electronic components to provide the capability of integrating several tile+ in wider a PCB. The tile+ has been fully validated in liquid nitrogen showing similar performance to tile $4 \times 2s3p$ in terms of SNR as documented in [4].

4. – A large area SiPM-based photodetector

The signals of four tile+ are summed together before transmission by means of an analog adder with double gain and a bandwidth at 77 K exceeding 80 MHz, that does not affect the pulse shape (the TIA bandwidth is limited to 30 MHz). A high dynamic range differential transmitter working at cryogenic temperatures has been developed to guarantee the signal transmission also in case of scaling up to several photodetectors in a ground isolated environment. The full implemented configuration puts the basis of the first prototype of a large area photo detector with an overall surface of $100\,\text{cm}^2$ readout as a single analog channel (fig. 3). This R&D version has been designed with borders but the final version can be borderless. The device performance has been successfully verified in liquid nitrogen as shown in fig. 3. The peak spectrum for both charge and



(a) (b)

Fig. 3. – (a) Front view of the $100\,\mathrm{cm}^2$ photodetector. (b) Peak distributions in charge and filtered amplitude obtained applying a matched filter algorithm.

filtered amplitude have a similar SNR greater than 13. The SNR is calculated as the ratio between the gain (from a linear regression of the peak position) and the average RMS-AC in the waveform pre-pulse in a time window of $1\,\mu$s.

5. – Conclusions

We have reported the design and the implementation of the very first large area photodetector based on the SiPM array technology operated in cryogenic environments for low background experiments searching for dark matter events. This photodetector is made of $24 \times 4\,\mathrm{cm}^2$ for an overall surface of $100\,\mathrm{cm}^2$ ($96\,\mathrm{cm}^2$ active area) with a low power dissipation of 360 mW including also the adder and the differential transmitter. Thanks to its simple integration, reduced thickness and the selection of radiopure materials, the photodetector can be employed to populate wide areas of light detection planes in low background TPC based experiments.

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