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Development of the first prototypes of Silicon PhotoMultiplier (SiPM) at ITC-irst

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Abstract

In the frame of INFN-ITC-irst collaboration new Silicon PhotoMultiplier (SiPM) prototypes have been produced at ITC-irst (Trento, Italy). Each SiPM covers an area of $1\,mm^2$ and brings together 625 micro-cells of $40 \times 40\,\mu m^2$ size connected in parallel as to form a single read-out element. Each micro-cell consists of a Geiger Mode Avalanche Photodiode (GM-APD) in series with its quenching resistance. This article reports the main characteristics of these prototypes as well as the ongoing activity of our collaboration on the development of SiPM devices for medical and space physics applications.

Keywords: Photodetectors; Internal gain; Silicon PhotoMultiplier

1. Introduction

Detectors efficient for low-light level (LLL) detection and photon counting are today required in a large variety of fields including astroparticle physics, nuclear medicine and high-energy physics. For such measurements, photon detectors typically employed are vacuum photodetectors (photomultiplier tubes—PMT, micro-channel plate photomultiplier tubes—MCP-PMT or hybrid photodetectors—HPD) [1,2]. The main advantages of such devices are high internal gain (10^6–10^7), very good timing resolution (hundreds of ps) and good single photoelectron resolution. However, these devices have low quantum efficiency limited by the photocathode materials, high operation voltages, they are sensitive to magnetic fields and the vacuum technology used for their fabrication confers them a bulky shape and sensitivity to handling.

The search for new photon detectors which can overcome the drawbacks of vacuum photodetectors has lead to the development of solid state photon detectors (PN or PIN photodiodes, avalanche photodiodes—APD and avalanche photodiodes in linear Geiger-mode—GM-APD) [3,4]. These solid-state devices have important advantages over the vacuum ones, namely higher quantum efficiency, lower operation voltages, insensitivity to the magnetic fields and robustness and compactness. The step-by-step evolution of solid-state photon detectors was mainly determined by their internal gain: a PIN has no gain, an APD has a gain of few hundreds and the GM-APD gain is 10^5–10^6. A gain comparable with that

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of the vacuum photodetectors allowed the GM-APD to achieve single-photon sensitivity and to be used in LLL applications.

Essentially, a GM-APD is a p–n junction that operates above the breakdown voltage. At this bias, the electric field is so high that a single charge carrier injected into the depletion layer can trigger a self-sustaining avalanche (so-called Geiger discharge). The Geiger discharge mechanisms in avalanche diodes were studied 40 years ago by Haitz and McIntyre [5,6] and important progresses on suitable quenching circuits controlling these mechanisms were given by Zappa et al. [7]. However, a GM-APD has the disadvantage that it acts as a binary device, having a standardized output signal independent of the number of incident photons. A new structure called Silicon Photo-Multiplier (SiPM) proposed by Golovin and Sadygov [8–10] overcome this inherent limitation bringing together on the same substrate many micro-cells connected in parallel, in which each micro-cell is a GM-APD in series with its integrated quenching resistance. Therefore, the SiPM acts as an analog device with an output signal representing the sum of the signals from all fired micro-cells and it becomes a suitable solid-state device for LLL detection and photon counting applications, including the detection of the space radiation in astroparticle physics, medical imaging in nuclear medicine, and calorimetry in high-energy physics [11].

In this article we present the characteristics of the first SiPM prototypes developed and produced at ITC-irst in the framework of the INFN–ITC-PAT collaboration (MEMS Project) as well as the ongoing activity of the same collaboration on the development of these devices for medical and space physics applications.

2. Detector description

Fig. 1 shows a photograph of the SiPM prototype from ITC-irst. The device, fabricated on a p-type epitaxial layer, consists of a matrix of 625 micro-cells covering an area of 1 mm^2. Each micro-cell ($40 \times 40\,\mu m^2$) is composed by a shallow n$^+$–p junction (GM-APD) in series with a poly-silicon quenching resistance (R_{quench}) [12]. All micro-cells are connected in parallel through the aluminum layer on the photo-sensitive side and the substrate on the other side. The active area of junctions is covered by an anti-reflective coating optimized for short-wavelength light.

3. Detector characteristics

A simple equivalent circuit of the SiPM is shown in Fig. 2. A reverse bias voltage (V_{bias}) is applied to each junction through the common substrate electrode to deplete the n$^+$–p junctions and the induced current is read on the resistor side electrode.

The breakdown voltage (V_{break}) and the R_{quench} values have been determined from the reverse and forward current–voltage (I–V) characteristics, respectively, using a

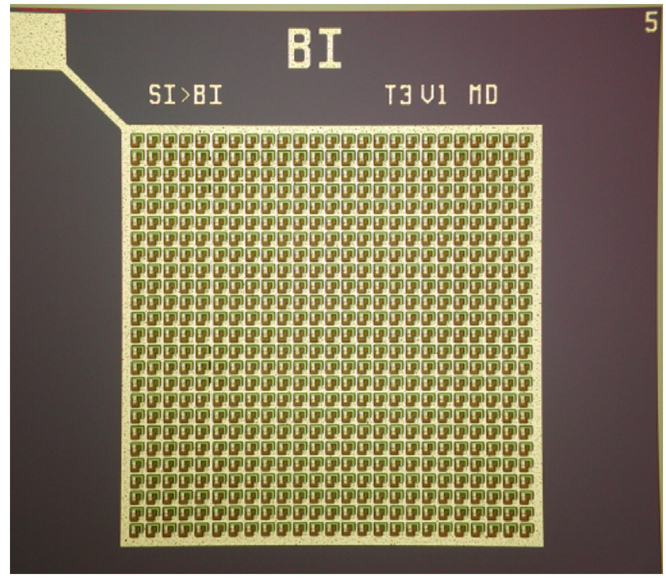

Fig. 1. Photograph of a SiPM prototype from ITC-irst.

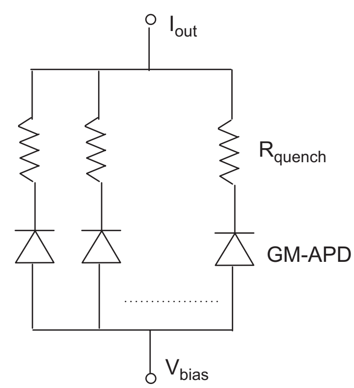

Fig. 2. The equivalent circuit of the SiPM.

HP 4156C Semiconductor Parameter Analyzer. A V_{break} of ~31 V has been obtained for both single micro-cell test structures and SiPM devices (see Fig. 3a and b), thus demonstrating a good uniformity of the V_{break} over single micro-cells and different SiPM's distributed on the wafer.

The value of the quenching resistor extracted from the forward characteristics of the micro-cell test structure is of ~300 kΩ, whereas for the SiPM a value of ~500 Ω has been determined (see Figs. 4a and b), in good agreement with the expected value ($R_{SiPM} = R_{micro-cell}/N_{micro-cell}$, where $N_{micro-cell} = 625$). Measurements have been repeated on a statistically meaningful number of devices on each wafer, showing a very good uniformity of the resistance values and confirming the reliability of the poly-silicon technology used for the R_{quench} fabrication.

The primary electron/hole pair initiating the avalanche process in a SiPM micro-cell can be generated either by an incident photon or internally, i.e., by thermal generation effects, after-pulses or optical cross-talk, all of which are responsible for dark counts. A dark pulse from a SiPM

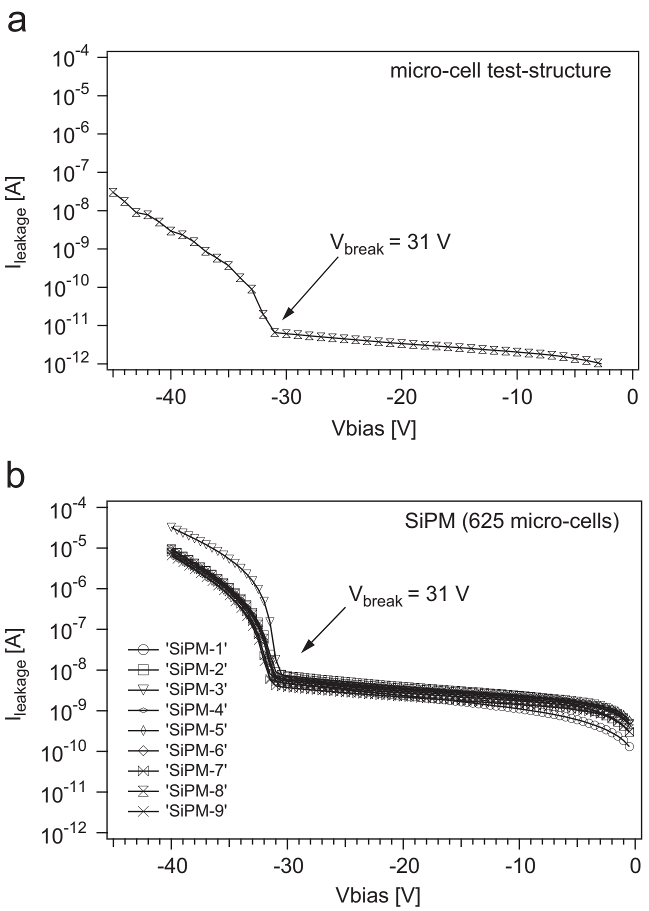

Fig. 3. *I–V* reverse characteristics of (a) single micro-cell test structure and (b) nine SiPM devices each with 625 micro-cells.

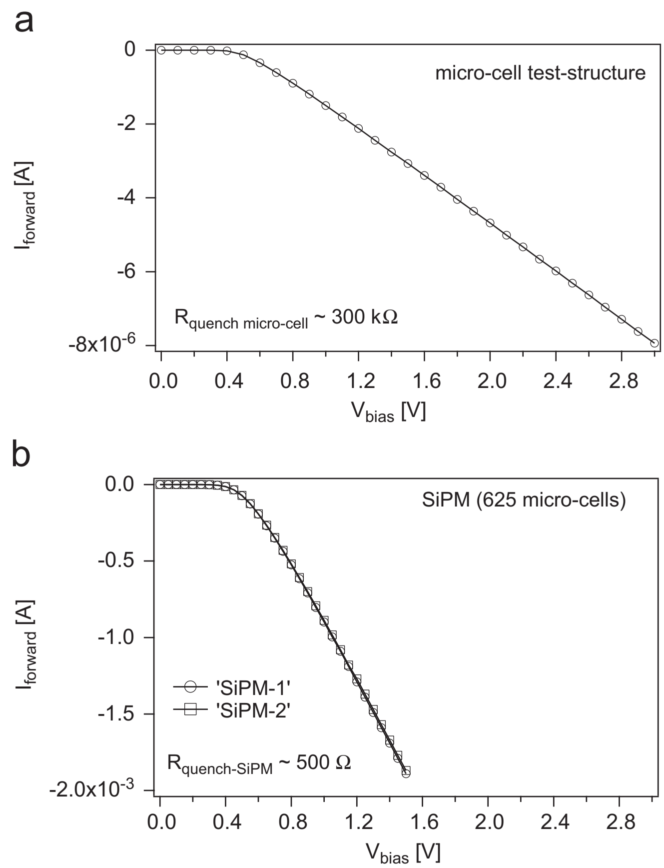

Fig. 4. *I–V* forward characteristics of (a) a single micro-cell test structure and (b) two SiPM devices.

micro-cell is identical to a photon pulse and its analysis allows important information on the device characteristics to be achieved, including the rise time, the recovery time and the internal gain of the micro-cell.

Fig. 5 shows the dark pulse from a SiPM micro-cell measured at 4 V above breakdown with a 2 GHz LeCroy digital oscilloscope. To amplify the signals with minimum distortion of their original shape a two-stage preamplifier based on a fixed gain (10 V/V), wide band (1.8 GHz) commercial amplifier (THRS4303) has been used. A rise time of ~1 ns (limited by the used read-out system) and a recovery time constant of ~20 ns demonstrate the fast timing characteristics of the SiPM signals.

The SiPM gain (G) is determined by the charge (Q) that can be released from a micro-cell after the breakdown: $G = Q/\mathrm{e} = \Delta V\, C_{\text{micro-cell}}/\mathrm{e}$, where $\Delta V = V_{\text{bias}} - V_{\text{break}}$ is the overvoltage, $C_{\text{micro-cell}}$ is the micro-cell capacitance and e is the electron charge. The time integration of the micro-cell dark pulse allowed the measurement of the gain, which was found to increase linearly with the overvoltage. In particular, gain values in the range 5×10^5–2×10^6 were measured for overvoltages ranging from 1.5 to 5 V, as shown in Fig. 6. From the slope of the linear fit presented in Fig. 6 a $C_{\text{micro-cell}}$~50 fF is obtained, that is very close to

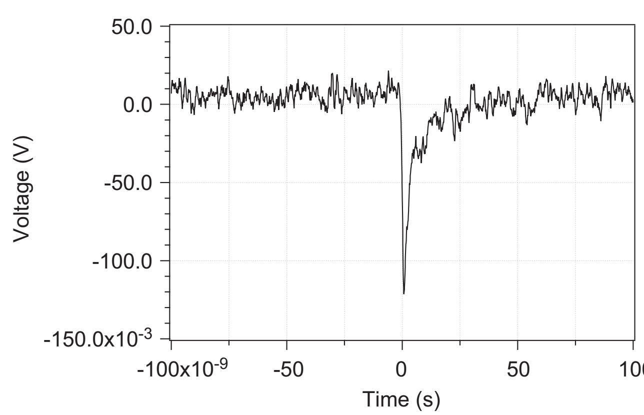

Fig. 5. Dark pulse from a SiPM micro-cell at 4 V over V_{break}.

the theoretical (design) value. Moreover, using the values of $R_{\text{micro-cell}}$ and of $C_{\text{micro-cell}}$, a time constant $\tau = R_{\text{micro-cell}} \cdot C_{\text{micro-cell}}$~20 ns can be calculated, in good agreement with the recovery time constant of the micro-cell dark pulses (see Fig. 5).

The SiPM dark count rates as a function of the pulse amplitude (thresholds) for different overvoltages are shown in Fig. 7. Note that these measurements have been

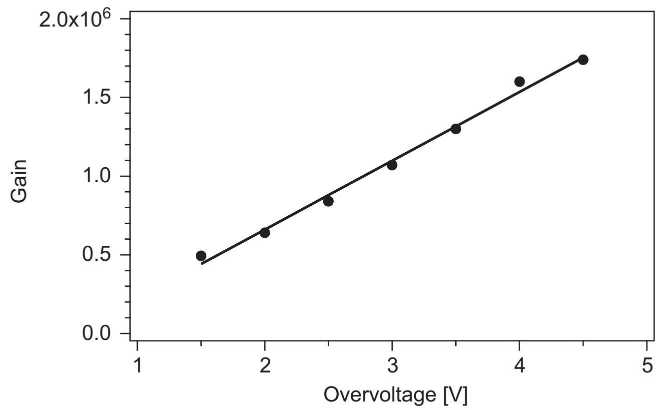

Fig. 6. SiPM gain as a function of the overvoltage.

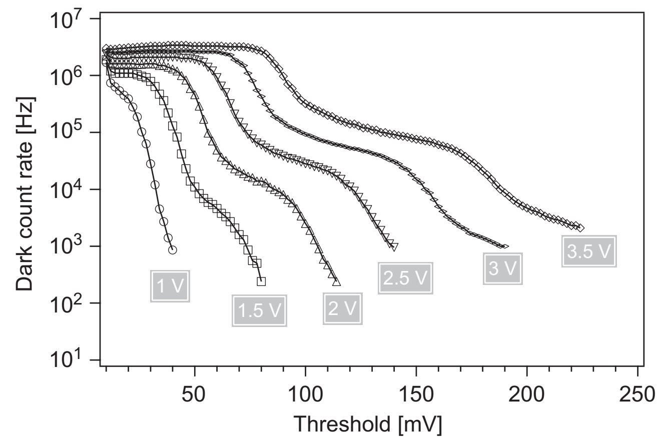

Fig. 7. SiPM dark count rate as a function of pulse amplitude (threshold) for different overvoltages.

performed at room temperature (~23 °C). The dark count rate for a threshold at 1 photoelectron (ph.e.) level varies between 1 and 3 MHz for ΔV values from 1.5 to 3.5 V. At 3 ph.e. level the dark count is just few Hz at $\Delta V = 1.5$ V and ~1 kHz at 3.5 V. Keeping in mind that these are the very first SiPM prototypes produced at ITC-irst, these values of the dark count rate are acceptable. Nevertheless, significant improvements are expected from the following fabrication runs for which an optimized technology is being developed.

A red light-emission-diode (LED) source having a low intensity was pulsed for short time duration (~8 ns) to record the single photoelectron spectrum presented in Fig. 8. The single (double, triple, etc.) photoelectron peak(s) are clearly visible, demonstrating an identical performance of all the micro-cells and an excellent single photoelectron resolution of the device.

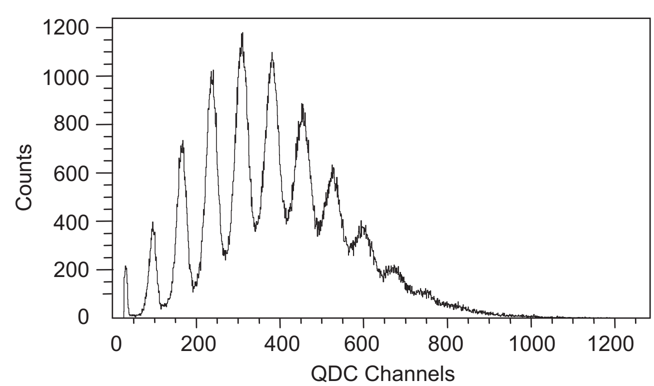

Fig. 8. SiPM single photoelectron spectrum measured with a pulsed low-light-level LED at 33.5 V.

4. Conclusions

In the framework of the INFN–ITC–PAT MEMS Project, a research project aimed at the development of SiPM for medical and space physics applications started around 1.5 years ago. Considerable effort has been devoted to the development of the fabrication technology at ITC-irst, enabling the first prototypes of these devices to be fully functional with good electrical characteristics and excellent single photoelectron resolution. In particular, well-controlled and spatially uniform values of the breakdown voltage (~31 V) and of the micro-cell quenching resistance (~300 kΩ) have been obtained. Moreover, quite a large gain ($\sim 2 \times 10^6$) at 5 V over the breakdown voltage has been measured, whereas the maximum dark count rate at room temperature, measured at 3.5 V over the breakdown voltage and at 1 ph.e threshold level is 3 MHz, which is acceptable considering that these first prototypes were not optimized from this point of view. In this respect, dedicated process steps are being developed, which are expected to yield a significant reduction of the dark count. In summary, results reported in this paper demonstrate that ITC-irst technology meets the requirements for the fabrication of good quality SiPM.

Quantum efficiency measurements are under way, with emphasis on the low-wavelength range (350–500 nm). Results will be reported in a forthcoming paper.

Acknowledgments

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