A Novel shallow-junction high photon detection efficiency Silicon Photomultiplier obtained with a 0.35 μm CMOS process

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The Silicon photomultiplier (SiPM) is a modern photodetector composed of an array of p/n-junctions (microcells) operated in Geiger mode, with individual passive quenching resistor, currently commercially available in custom-optimized technologies.

Modern trends in the design of SiPM consist of a full implementation of the photo-detector within standard CMOS, which enables the monolithic integration of read-out electronics and photo-detector on the same chip, with a significant reduction of power consumption and simplification of the operational conditions. Several tests of SiPM and SiPM-like detection structures were reported in the literature at CMOS scale ranging between 0.8 and 0.09 nm. A first problem encountered in such devices is a large dark noise rate up to 3106 kHz/mm^2 , due to either shallow trench isolation or higher doping concentration of the standard CMOS wells. A second problem to be addressed is the lower photon detection efficiency, down to 2-3% at 420 nm, due to additional isolation layers covering the sensitive window of the detection structures in standard CMOS technology.

Here we show that, introducing into a 0.35 µm CMOS process a novel dedicated shallow implantation, with optimized optical window and anti-reflective coating, it is possible to obtain a 1 mm² SiPM with a PDE of 43% at 420 nm, thus 1.5x higher than in previously obtained structures in CMOS technology and compatible with the performances of commercial custom-technology.

As the used process is compatible with standard CMOS electronics, the SiPM opens the possibility of an integrated development of SiPM and electronics on the same chip within this production line.

Materials and Method

For the design of the SiPM we used an advanced mixed-signals CMOS process providing 4 metal layers, two polysilicon layers, high resistance polysilicon and two types of transistor gates (3.3 V and 5.0 V). With respect to previous published results, we introduced here a novel shallow p+/n well junction, obtained with a novel type of enrichment implantation in the standard CMOS n-well. Moreover, an optical window was open above the sensitive area and anti reflection coating (ARC) layers were formed above it with thickness and composition optimized for a wavelength of 420 nm. Lightly-doped p-type guard rings were used to prevent localized breakdown at the edges of the diode.

The key result presented in this poster is the high photon detection efficiency (PDE) of the device. We measured the PDE in response to a set of light emitting diodes (LEDs) with central wavelength ranging between 370 nm and 630 nm (THORLABS L-SERIES) operated in pulsed mode with a period T = 20 ns. We mounted the LEDs on an integrating sphere (THORLABS IS200). We mounted a photodiode with known responsivity $R(\lambda)$ (THORLABS FDS10X10) at one output of the sphere and we measured its photocurrent I_{phot} and its dark current I_{dark} using an electrometers for ultra-low current measurements (KEITHLEY 6517B). We mounted the shallow junction SiPM on the other output of the sphere. We biased it with a negative voltage applied to the anode and we connected the cathode to ground.

We performed the experiment at room temperature and at a bias voltage of 24.4 V, 25.4 V, 26.4 V, corresponding to a range between 2 V and 4 V above the breakdown voltage. We collected the signal from the cathode on a 50 Ω load resistor and we amplified it of a factor 20 with a voltage wide-band amplifier. We read out the amplified signal with the digital oscilloscope (TEKTRONIX DPO71604B) at a sampling frequency of 50 GS/s and with a bandwidth of 16 GHz. The synchronization output of the LED driver was used as trigger signal. The waveforms were stored in a computer and analyzed with digital signal processing methods.

The integral of the waveform was calculated summing the measured voltage amplitudes in the time window Δt of 80 ns. The arbitrary units of the calculated integral were calibrated in pC using an independent measurement with a charge to digital converter (CAEN V792N). For each wavelength, the average number of detected photons n_{det} at the SiPM was estimated from the number of events without detected photons n_0 after collecting a total number of events N, by supposing a Poisson statistics: $n_{det} = -\log n_0/N$. The average dark count rate (DR) was measured for each point. The number of expected dark pulses during the acquisition time t was estimated as $n_{dark} = DR \, x \, \Delta t$. The photon detection efficiency was calculated as:

$$PDE = [(n_{det} - n_{dark}) \text{ x } \frac{A_{pd}}{A_{sipm}}] \,/\, [\frac{I_{phot} - I_{dark}}{R(\lambda)} \; x \; T],$$

where A_{pd} and A_{sipm} are the active areas of the photodiode and SiPM respectively. The measured PDE is shown in figure 1. The peak PDE is approximately 43% at a wavelength of 420 nm and bias voltage of 26.4 V.

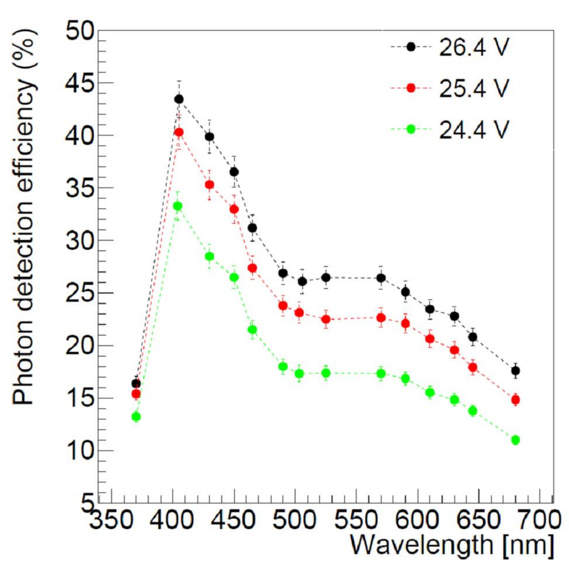

Fig. 1 Measured PDE of the newly proposed shallow junction SiPM

Tab. 1 Measured parameters of the novel high PDE SiPM

Parameters	SiPM
Breakdown Voltage	22.4 V
Gain (25.4 V)	4x10^6
Cross talk (25.4 V)	8.8%
Dark rate (25.4 V)	480 kHz/mm²
Single photon time resolution	(78 ± 2) ps (FWHM)
Temperature dependence	(27.9 ± 0.9) mV/K
Photon detection efficiency (420 nm, 26.4 V)	43%

In order to complete the overview of the features of the novel shallow-junction with improved PDE obtained in this poster, we propose here the measurement of other key parameters of the device. We evaluated the current-voltage characteristics of the SiPM in dark condition using a Keithley 2636A source meter that obtains measurements of the current of the device in reverse bias mode. The breakdown voltage is approximately 22.4 V. Due to the different profile implantation it is 3 V lower than in the previous developed standard 0.35 µm device. The variation of the breakdown voltage with temperature is a critical parameter when evaluating the stability of the operation of the SiPM. We measured it, by placing the SiPM in a optically and thermally isolated container, whose temperature was set by a temperature controller (LAKESHORE 325). A vacuum electromagnetic valve (GDC-J25) controlled the flow of nitrogen used to cool the system and connected the two terminals of the SiPM to the semiconductor analyzer (AGILENT B1500A). The linear temperature coefficient is measured as (27.9±0.9) mV/K.

The dynamic characterization of the SiPM in dark condition consists of the measurement of dark count rate and cross talk. All measurements are performed at a room temperature of 25 C. The voltage amplitude of the signal of the SiPM is measured on a 50 Ω load resistor and amplified of a factor 20 with a voltage amplifier. The signal is sent to a threshold discriminator (CAEN N844). The number of pulses above threshold are registered within a 1 s observation time window. The results of the measurement at 24.4 V, 25.4 V, 26.4 V, corresponding to a range between 2 V and 4 V above the breakdown voltage are shown in figure 2.

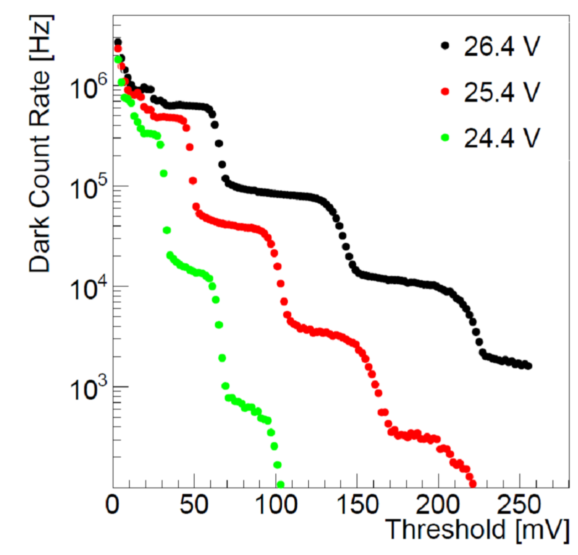

Fig. 2 Dark count rate of the novel high PDE SiPM

Finally we show in Fig. 3 the response of the SiPM to a multi-photon state obtained with a picosecond fast pulsed diode laser emitting light at a wavelength of 440 nm (PICOQUANT LDH-P-C-440) and driven by the pulsed diode laser driver (PICOQUANT PDL 800-B) at a frequency of 2.5 MHz.

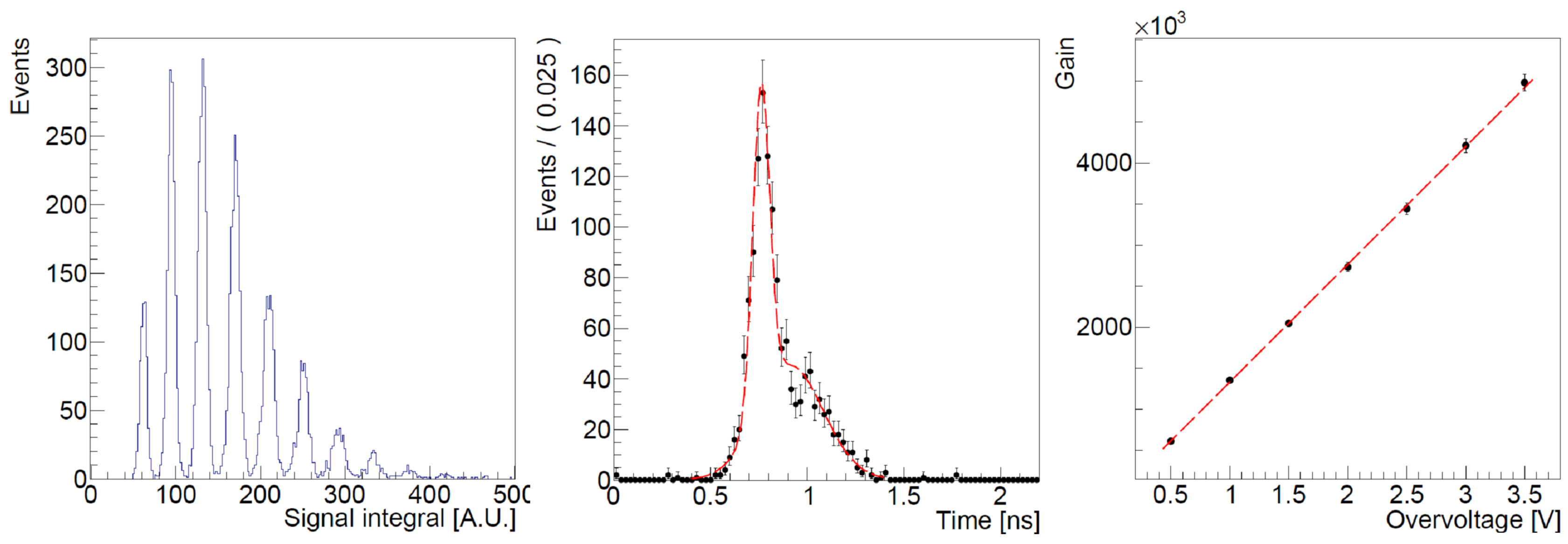

Fig. 3: Integral (a) and time (b) response of the novel high PDE SiPM to a fast pulsed diode laser and (c) dependence of the gain on the bias voltage

Results and Conclusions

The results of the characterization of the SiPM are summarized in table I.

A unprecedented high 43% maximal PDE at 420 nm can be produced using a 0.35 µm CMOS process. The average performances like the multi-photon state resolution, the gain and the SPTR are competitive with the custom-technology SiPMs on the market.

The dark count rate of 480 kHz/mm² at 3 V excess voltage is higher than in the best custom technologies, but still in the acceptable range for the application of the device to radiation detectors. The shallow-junction high PDE SiPM in 0.35 µm CMOS technology proposed in this poster will be used for the development of intelligent single photon sensors with integrated digital electronics, with expected application to automotive, medical and high energy physics devices.

Acknowledgement

I thank I.R.C.C.S Neuromed, RheinMain University and the PET-Lab for the support to my research and the 5th INFIERI Summer School. I thank the people listed above for their good cooperation in the research. Especially I want to express my thanks to my supervisors Nicola D'Ascenzo and Andreas Brensing.

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