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Studies of SiPMs for the CMS HCAL Upgrade

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After 5 years of R&D with multiple companies we developed custom large dynamic range SiPMs with large PDE and fast recovery time. Here we report on the final SiPM parameters of the 2014 preproduction run from Hamamatsu (HPK) who has produced a series of 175 arrays with a total of 1400 SiPMs. An overview of all results of our measurements of photon detection efficiency, spectral response, cell recovery are reported in this paper. Results from a study on the radiation hardness of silicon photomultipliers (SiPMs) are also presented. The SiPMs were exposed to 62 MeV protons at fluences up to 1x10^{12} protons/cm^2. The SiPM's main parameters were measured before and after irradiation. The effects of the proton radiation on breakdown voltage, gain, photon detection efficiency, dark current and noise for these devices are shown and discussed.

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1. Introduction

The CMS Barrel (HB) and Endcap (HE) Hadron Calorimeters are scintillator sampling calorimeters with embedded wavelength shifting fibres (WLS) in scintillator tiles. The fibres from the sampling layers are ganged together to form towers which light is detected by photosensors. The photosensors that are currently used are hybrid photodiodes (HPDs). The HCAL upgrade is required for the increased luminosity (3×10^{34} cm^{-2} s^{-1}) of SLHC Phase I. A key aspect of the HCAL upgrade is to add longitudinal segmentation to improve background rejection, energy resolution, and electron isolation at L1 trigger. It will also allow better management of the radiation damage which will occur in the high-η region of the calorimeter, reducing the response of the individual tiles. The increased segmentation can be achieved by replacing the HPDs with silicon photomultipliers (SiPMs). The SiPMs for the CMS HCAL upgrade have to operate in a very hostile SLHC radiation environment. The integrated dose of neutrons with E>100 keV during the lifetime of the SLHC is expected to be in the range $1\div2\times10^{12}$ cm^{-2} 1 MeV equivalent neutrons for the HCAL readout box regions. The SiPMs should have good linearity for a wide range of scintillating signals and excellent reliability. The CMS R&D program has invested significant effort into the development of SiPMs which can replace the HPDs, bringing better and more stable performance to the HCAL [1]. After 5 years of R&D with multiple companies we developed custom large dynamic range SiPMs with large PDE and fast cell recovery time. We have also developed a custom ceramic package with a very thin 0.3 mm quartz window with Kyocera. Each package holds 8 channels of SiPMs.

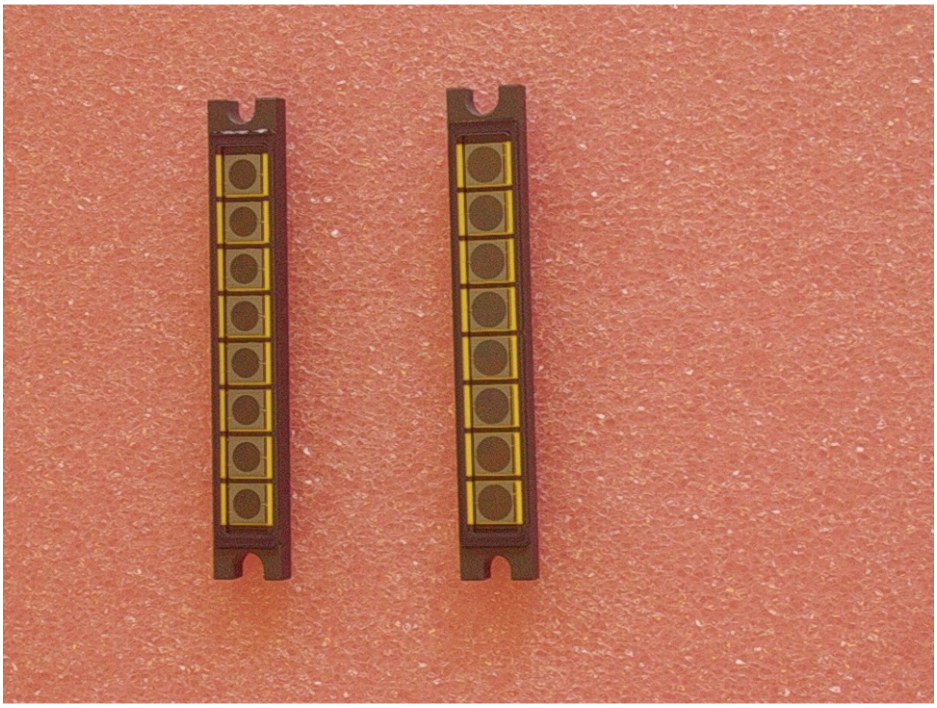

Figure 1: *Custom CMS HCAL 8 channel array with 2.8mm and 3.3 mm diameter SiPMs.*

Here we report on the final SiPM parameters of the 2014 preproduction run from Hamamatsu (HPK). An overview of all results of our measurements of photon detection efficiency, spectral response, cell recovery are reported in this paper. Results from a study on the radiation hardness of silicon photomultipliers (SiPMs) are also presented.

2. Preproduction Hamamatsu SiPM arrays for the CMS HCAL Phase I Upgrade

At the end of 2014 Hamamatsu (Japan) has produced a series of 175 arrays with a total of 1400 SiPMs. To simplify the construction of the HCAL readout modules and to protect the SiPMs, the individual devices are packaged in eight-SiPM arrays in a ceramic carrier. The carrier provides separate bias voltage and signal pins for each SiPM in the array. It has two alignment pin holes to align the fiber bundles from the detector to the SiPMs. The entire ceramic package is covered by a thin 0.3 mm quartz window with antireflective coating with cut off at 420 nm to suppress any residual Cherenkov light produced in the incoming fibers. Fig. 1 shows the arrays of 15 micron cell devices in 2 sizes; 2.8 mm and 3.3 mm diameter with respectively 27500 and 38500 cells. The 2.8 mm will read out a sum of 4 fibers and the 3.3 mm will read out a sum of 7 fibers coming from the HCAL scintillators.

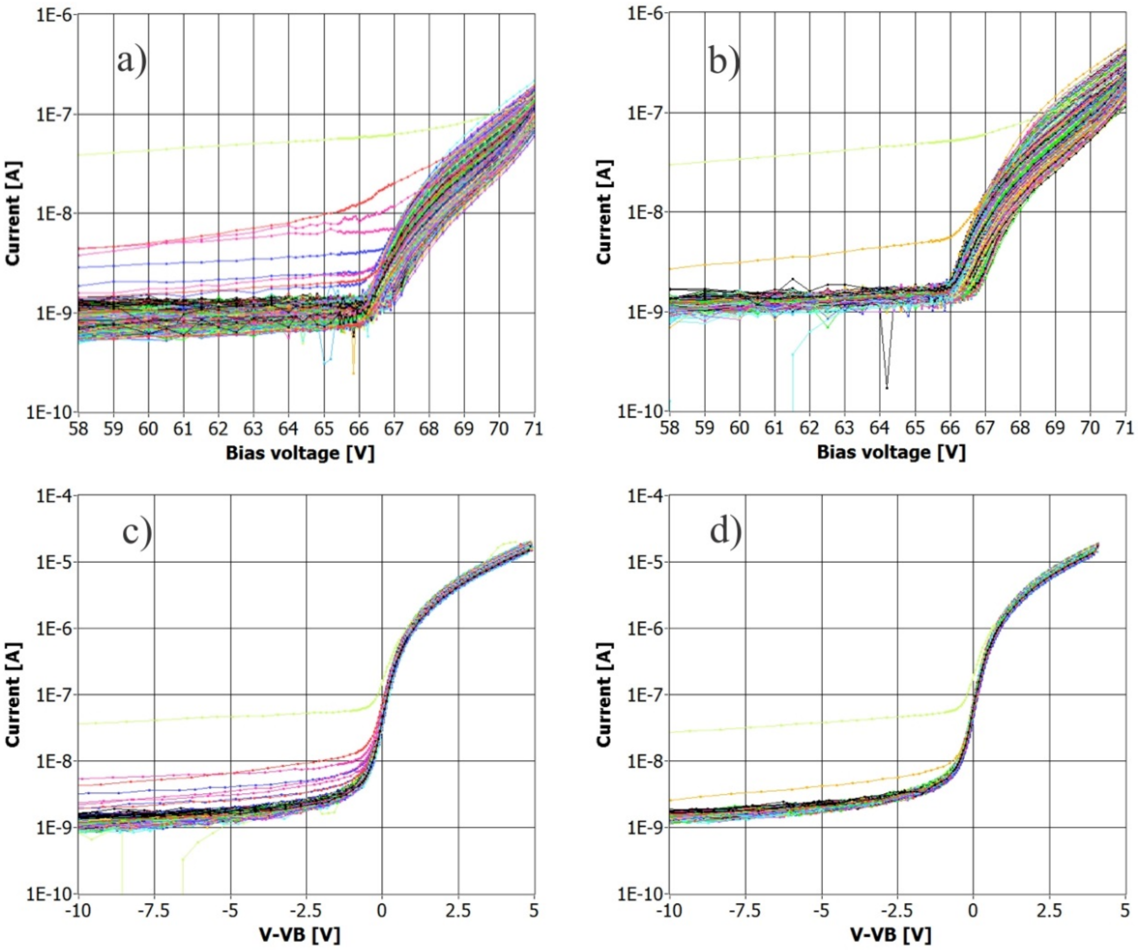

Figure 2: *Dark current and LED response vs bias voltage at T= 23°C. a) Dark current of all 123 2.8 mm arrays. b) Dark current of all 52 3.3 mm arrays. c) LED response of all 2.8 mm arrays vs. overvoltage d) LED response of 3.3 mm all arrays vs. overvoltage.*

3. Quality Assurance measurements.

3.1 Dark current and response to LED vs. bias voltage

For the quality assurance of many arrays, an 80-channel test setup was created allowing the measurement of I-V characteristics of 10 arrays at a time. The setup uses an 80 channel Keithley 7001 switch box in combination with a Keithley 6487 pico ammeter. A 520 nm LED was placed in the dark box to uniformly illuminate all 80 channels to measure the SiPMs breakdown voltages and their relative responses to the green light. Fig. 2a and 2b show the dark current vs bias voltage of all 984 channels of the 2.8 mm arrays and 416 channels of the 3.3mm arrays respectively at 23°C. Fig. 2c and 2d show the current of the same arrays under uniform LED illumination plotted vs the overvoltage. One can see that some channels in Fig 2a and 2b show a higher surface current (current below breakdown > 10 nA. We verified that the currents are stable after 2 weeks of operation at 60°C and temperature cycling between -10°C and 50°C for up to one week. Dark current distributions (measured at 3 V overvoltage) for all 2.8 mm and 3.3 mm SiPMs are shown in Fig. 3.

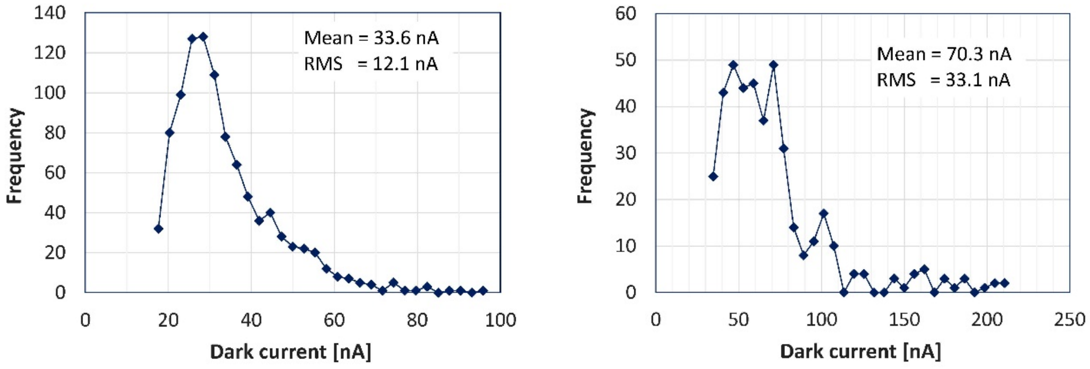

Figure 3: *Dark current distributions of all 984 channels of the 2.8 mm arrays (left) and 416 channels of the 3.3mm arrays (right) at 3 V overvoltage.*

Relative responses of all 984 channels of the 2.8 mm arrays (left) and 416 channels of the 3.3mm arrays (right) to a green LED light were measured at 3 V overvoltage. Light illuminating all 80 SiPM positions of the set-up was measured with a precision <0.5% using specially calibrated 2.8 mm and 3 mm arrays. From Fig.4 we can conclude very uniform gain x PDE product for all 1400 channels.

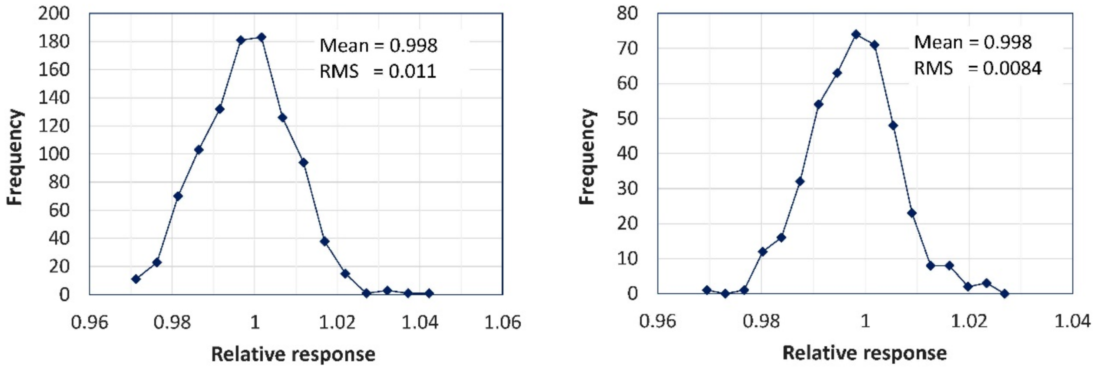

Figure 4: : *Relative response distributions of all 984 channels of the 2.8 mm arrays (left) and 416 channels of the 3.3mm arrays(right) at 3 V overvoltage.*

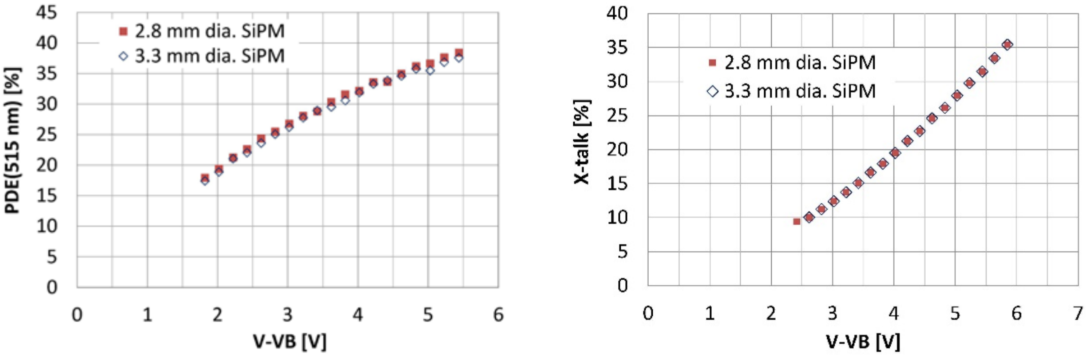

Figure 5: *PDE (left) and crosstalk (right) vs. overvoltage.*

3.2 Photo-detection efficiency and crosstalk vs. over-voltage

The Y11 WLS fibers in the CMS HCAL have an emission peak of 515 nm. Fig. 5 shows the HPK SiPM PDE at 515 nm and the crosstalk vs. overvoltage. HPK uses a transparent MFQR (Metal Film Quenching Resistor) to deliver high PDE for the small cell pitch devices of 15 x15 µm. Because the HCAL has a limited internal sampling resolution 100%/√E and a very low light yield per MIP, a trade of between PDE and crosstalk is made by not using trench technology.

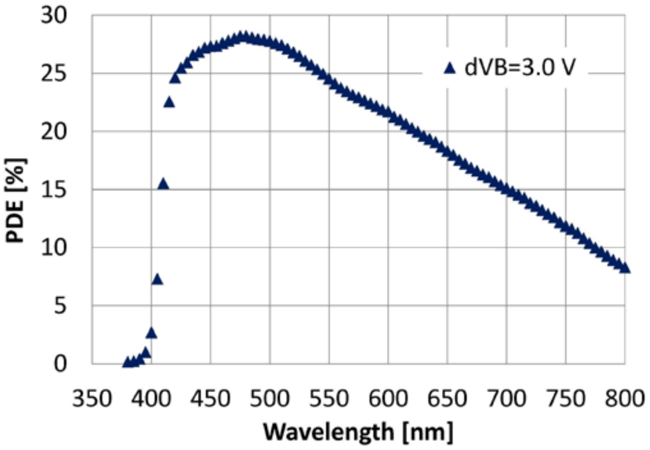

Figure 6: *PDE vs. wavelength at 3 V overvoltage.*

Fig.6 shows the spectral response vs. wavelength. The setup and the experimental techniques used in these measurements are described in detail in [5]. The cut off at 420 nm due to the window coating is clearly visible.

3.3 Response to fast laser and recovery time

The Y11 WLS fibers have a decay time of 11 ns. To reduce the influence of the SiPMs on the total time response to a minimum, a specification of recovery time was set to 10 ns. In order to accomplish this we specified a maximum value of 1.2 MΩ quenching resistor (Rq) for the preproduction series. In addition, HPK reduced the series resistance (Rs) present in larger area devices using segmentation. Fig.7 shows the response of the 2.8 mm and 3.3 mm arrays to a 30 ps (FWHM) 405 nm laser diode pulse into 15 Ω input resistance. From the pulse shape, we found the recovery time of 7 and 8 ns respectively.

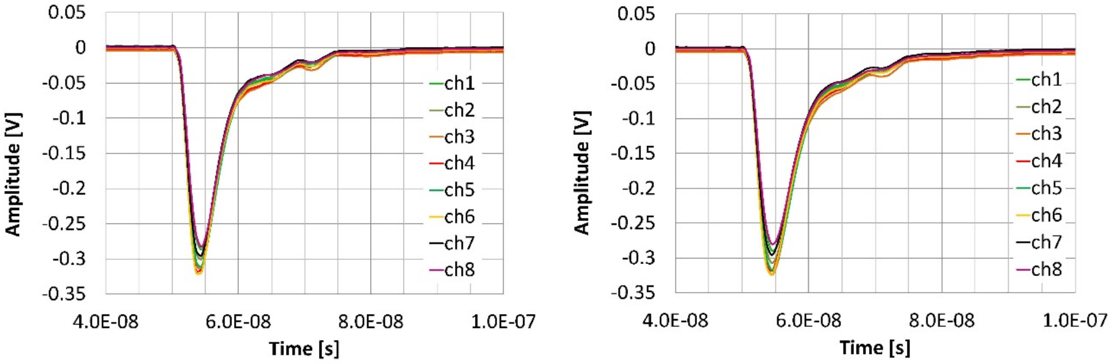

Figure 7: *Pulse shape of 2.8 mm array into 15 Ohms (left) and pulse shape of 3.3 mm array into 15 ohms (right).*

3.4 Radiation test to 2 *10^{12} 1 MeV equivalent n/cm^2

The 2.8 mm SiPMs were exposed to 62 MeV protons with fluences up to 10^{12} protons/cm^2 (~2×10^{12} cm^{-2} 1 MeV equivalent neutrons) at the Université Catholique de Louvain (Belgium). “Clones” of the SiPMs were selected and kept non-irradiated for comparative measurements. The SiPMs were irradiated under bias (at 3.0 V overvoltage), their dark currents were monitored during irradiation. The “clones” were SiPMs produced from the same wafers. Their parameters (breakdown voltage, Gain, PDE etc.) were identical to the parameters of the SiPMs, which were used for irradiation. After irradiation, the diodes were annealed 1000 min at 60 °C to stabilize their currents [6]. The SiPM parameters were measured at the CERN APD Lab. All the measurements were performed at T=23 °C inside a temperature stabilized box.

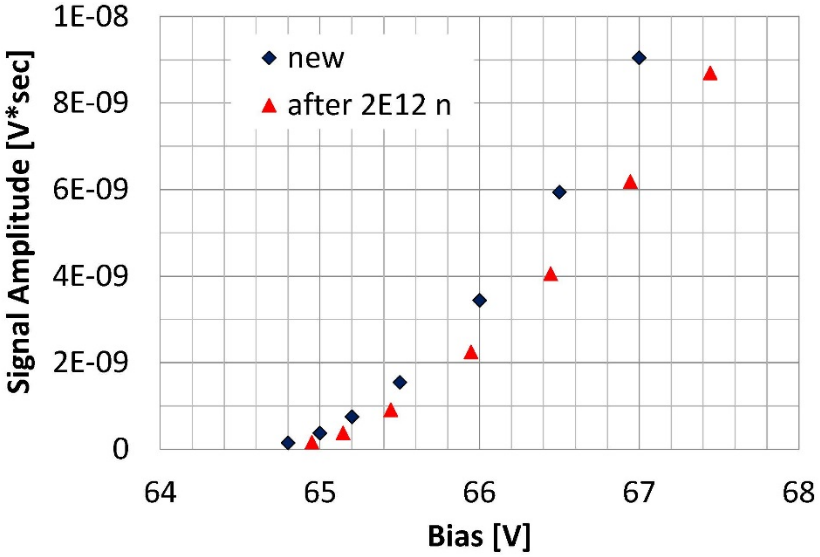

Figure 8: *Dependence of the signal amplitude on the bias voltage measured for new and irradiated Hamamatsu SiPMs.*

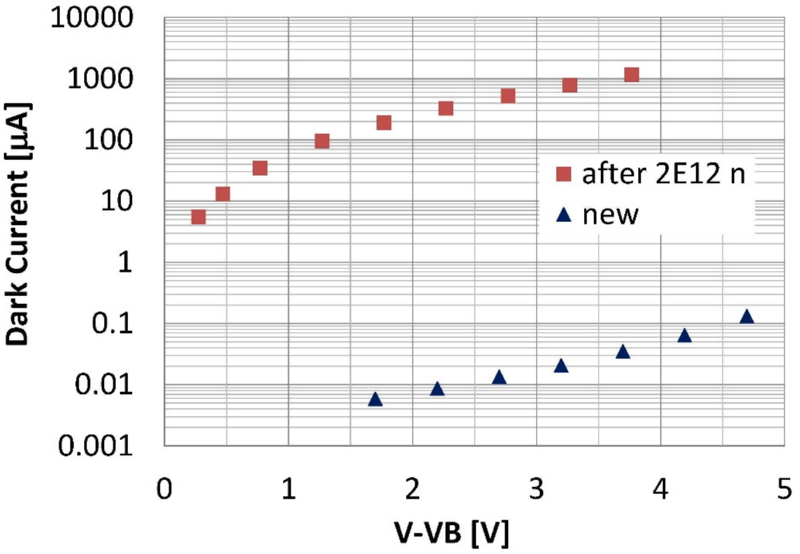

Figure 9: *Dark current vs. overvoltage measured for the Hamamatsu SiPM before and after irradiation.*

Responses of the SiPMs to calibrated LED pulses as functions of bias voltage were measured for irradiated and non-irradiated SiPMs. The green (515 nm) LED was fired by a PM 5786 pulse generator. The amplitude of the LED (λ=515 nm) pulse was the same for all of the SiPMs (irradiated and non-irradiated): N_{γ}~4200 photons/pulse. The SiPMs were illuminated via a collimator of 2 mm in diameter. The duration of the LED pulse was measured to be 20 ns FWHM.

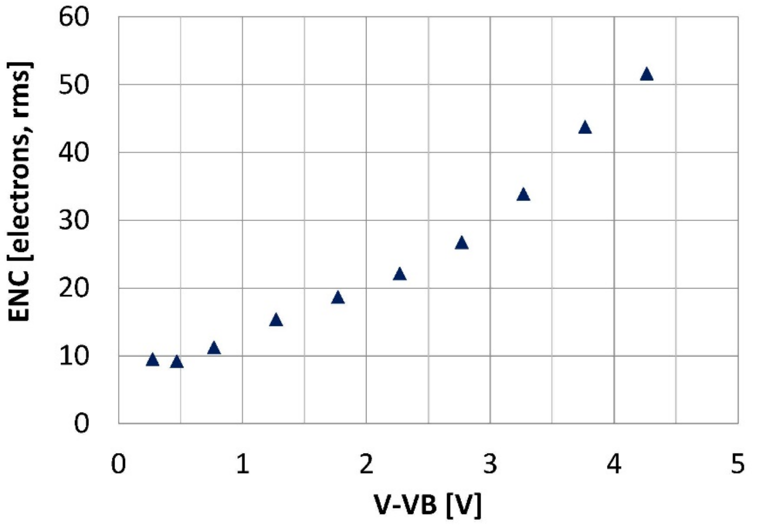

Figure 10: *Noise vs. overvoltage measured for the Hamamatsu SiPM after irradiation.*

The calibration of the LED pulses was done with the reference XP2020 PMT. The bias voltage to the SiPMs was applied with the Keithley 6487 picoammeter/voltage source. The signals from the

SiPMs were amplified with a fast transimpedance amplifier (gain=20) and digitized with a Picoscope 6404 digital oscilloscope. The recorded waveforms were integrated during a 50 ns gate. The results for the Hamamatsu 2.8 mm SiPMs are shown in Fig. 8. One can see that the LED signal amplitude measured by the irradiated Hamamatsu SiPM was reduced by 38% at 67 V. Most of this reduction is due to the 175 mV breakdown voltage shift measured for this SiPM after irradiation (for more details see [7]).

A significant increase of the dark current and noise (equivalent noise charge) was measured for the irradiated SiPM. Figure 9 shows the dependence of the dark current vs. overvoltage measured before and after irradiation. Dark currents as high as 500 or 600 μA were measured at 3 V overvoltage at room temperature after annealing (they were a factor of 2 higher before annealing). Such high currents can cause local increase of the SiPM temperature and can be one of the reasons for the measured gain reduction after irradiation.

Figure 10 shows the dependence of noise vs. overvoltage measured for the irradiated SiPM. The signal integration time was 50 ns during this measurement. The noise scale was calibrated using measurements of the signal amplitude width [2]. One can notice the noise increase with overvoltage. There are two major reasons for this increase. One of them is the increase of the Geiger discharge probability as the voltage increases. Another reason is an increase of the optical crosstalk between the SiPM cells.

4. Conclusion

Recent developments of small cell SiPMs make it possible to use them in large dynamic range detectors like the CMS HCAL. Enormous progress has been made in the PDE with these smaller cell devices. Other benefits of the small cell devices are lower gain, faster recovery time, radiation hardness and lower noise. After evaluation of many manufactures we did a preproduction run of 1400 SiPMs with HPK. The most important results from an evaluation of this preproduction run were presented. We found good uniformity of gain, PDE and pulse shape. This uniform behavior could be especially valuable in the final calibration of the CMS.

Results from a study of the radiation hardness of silicon photomultipliers (SiPMs) are presented. Recently developed high density (>4500 cells/mm^2) SiPMs were exposed to 62 MeV protons at fluences up to 1×10^{12} protons/cm^2 (~2×10^{12} cm^{-2} 1 MeV equivalent neutrons) at the UCL (Belgium) proton cyclotron (LIF irradiation facility). After irradiation the diodes were annealed (1000 min at 60 °C) to stabilize their currents. Responses of the SiPMs to calibrated LED pulses as functions of bias voltage were measured for irradiated and non-irradiated SiPMs. The LED signal reduction of ~38 % was measured with the irradiated Hamamatsu SiPM at 67 V. Most of this reduction is due to the 175 mV breakdown voltage shift measured for this SiPM after irradiation.

A significant increase of the dark current and noise was observed after irradiation. Dark currents as high as 500 or 600 μA were measured at 3 V overvoltage at room temperature. 20-30 electrons (RMS) noise was measured for the irradiated SiPMs at 3 V overvoltage and 50 ns integration gate.

The results obtained by this study provided important information for the implementation of SiPMs in the readout of the CMS HCAL at the LHC.

Acknowledgments

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