COMPARATIVE STUDY OF PERFORMANCE OF SILICON PHOTOMULTIPLIERS FOR USE IN CHERENKOV FIBRE OPTIC BEAM LOSS MONITORS

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Abstract

Silicon Photomultipliers (SiPMs) are semiconductor photo-sensitive devices built from a matrix of Single Photon Avalanche Diodes (SPADs) on a common silicon substrate, working in the limited Geiger mode and with a common readout. The fast counting ability, high timing resolution, immunity to magnetic field up to 15 T, low power consumption and relative small temperature dependence together with the small dimensions make SiPMs excellent candidates as commercially available solid state detectors, and a promising alternative to traditional photomultiplier tubes for single photon detection. Nevertheless, SiPMs do suffer from erroneous counting due to noise effects that can deteriorate their performance. These effects are, in general, heavily dependent on manufacturing quality. In this contribution, results are reported from the characterization of different models of SiPMs in terms of noise spectra and response to light, and a procedure for determining the quality of manufacturing is described.

INTRODUCTION

SiPMs suffer from erroneous counting due to dark noise effects, mainly caused by three phenomena:

1. electron-hole pairs created in the depletion layer by random thermal ionization (dark count);
2. parasitic avalanche triggering by photons created during a primary avalanche migrating to a neighbouring cell (optical cross-talk);
3. time-delayed release of a "hot" carrier by a trap level due to imperfections in the lattice, leading to a time-delayed second avalanche phenomenon (after-pulsing).

Optical cross-talk has been reported to be sensibly reduced for SiPMs featuring optical trenches (strips of material with different refraction index placed between neighboring cells, which deflect photons away from the active area [1]).

Dark noise levels and SiPM performance in general are heavily dependent on manufacturing quality and techniques, and on features such as the number of SPADs in the array; nevertheless, the user can tailor a given device to a particular end by modifying either or both the operating temperature and the bias voltage. In general, though, SiPMs are operated at room temperature for simplicity and because the lower dark count obtained by cooling the device comes at a price of highly increased after-pulsing, due to the longer trapping time at lower temperatures [2].

Bias voltage, on the other hand, is a more useful parameter to vary, as quantum detection efficiency, detector response and dark count rate sensibly increase for increasing bias. Increasing the bias voltage increases the electric field across the depletion layer, hence the carriers acquire the energy needed for impact ionization in a shorter path, leading to more secondary carriers being liberated; it is therefore more likely that a free carrier (created by an impinging photon, or by thermal ionization) will result in an avalanche event. From a user's perspective, it is important to be able to assess the manufacturing quality of available SiPMs and exploit the properties of varying the bias voltage.

SiPMs feature characteristics peculiar to the collective behaviour of the array, such as multiplication of the dynamic range and cross-talk noise. While increasing the number of SPADs in the array linearly increases the dynamic range, as more photons can be detected (provided the photon beam is large enough to cover the whole active area, which is usually not a problem), it also equally increases the rate of dark count events: high dynamic range comes at the price of sacrificing single photon detection.

In this work, a novel procedure to characterize SiPMs in terms of their manufacturing quality is described by monitoring dark count signal and device response for varying bias voltage. A comparative measurement of optical cross-talk is also included.

EXPERIMENTAL RESULTS

Data analysis algorithm

All the data shown here have been taken on four recent state-of-the art models of SiPM, issued in 2009, from ST Microelectronics (SiPM model H and model F, package TO-39) and Photonique (SSPM_0611B1MM and SSPM_0701BG for ultraviolet and visible light respectively, in package TO-18). All these models have about 400 SPAD cells in a 20×20 array of 1 mm^2 active surface area.

Data acquisition is carried out using a custom-written code to post-process direct current readings from an oscilloscope, rather than using a charge-to-digital converter. This allows probing accurately the high overvoltage region, in which dark noise peaks are more closely packed and superimpose severely.

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The code makes use of efficiency optimized, existing time-domain filtering algorithms to obtain a first estimate of the peak characteristics. The algorithm is based on the idea of approximating the curve with straight lines of different lengths and gradients and optimized endpoint locations, depending on the features of the analyzed signal.

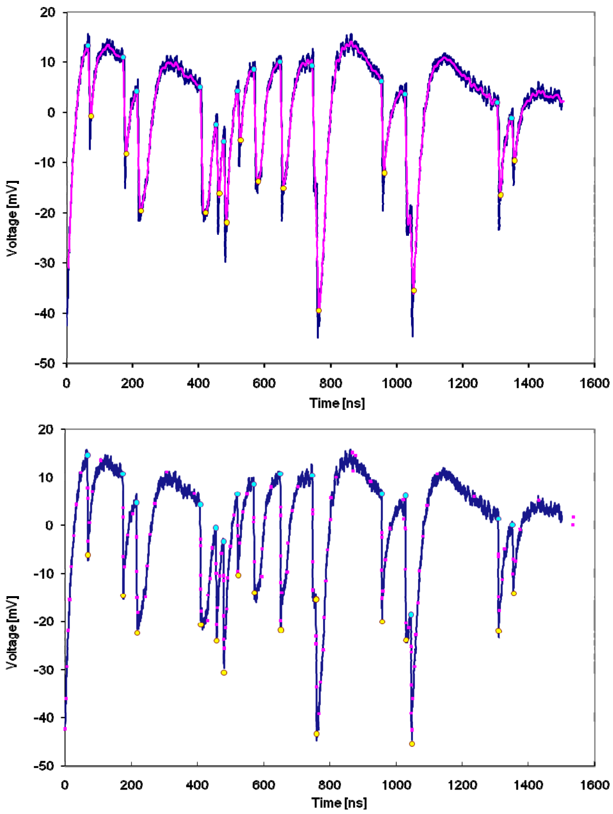

Figure 1. Comparison between the performance of a linear filter and a non-linear algorithm for identifying peaks in a signal. The original oscilloscope trace is shown in dark blue in each plot; the filtered trace obtained with the conventional linear filtering is shown in pink in the top plot; in the bottom plot the points indentifying the segments found by the non-linear algorithm are pink.

The code analyses the signal from the oscilloscope and draws a best fit line through the first two points. It then includes the following point in the fit, and accordingly updates the two parameters of the best fit line together with the deviation ε of the new point from the best fit and the overall goodness of fit σ (measured as the standard deviation of the data distribution around the best fit). If ε exceeds the corresponding preliminary parameter which measures the average noise amplitude the new point is not included in the fit and a breakpoint is inserted, where two different best fit lines merge: i.e. the starting point of a new best fit line. At the same time, the line just ended is traced back again with the same procedure: usually this process results in a starting point different from the one which was assigned in the beginning. The best fit error σ calculated for this back-traced line is then compared with the best fit error σ of the previous line and the configuration which optimizes the error is chosen. The program then moves on to the next line. This backward tracing process produces results comparable with the longer procedure of finding an optimum breakpoint position by making a piecewise linear fitting.

Fig. 1 shows a comparison between the performance of a linear filter and our non-linear algorithm. The traces in this figure were produced in the high overvoltage regime, which is the most challenging from the point of view of the signal analysis, and whose features vary significantly from the low overvoltage regime, in which the peaks are wider and neatly separated. In particular, a high overvoltage produces faster, higher peaks which are often superimposed on each other: i.e. peaks often start before the signal has been able to recover from the preceding peak and the voltage has dropped back to zero.

Analysis of heights of signal peaks

The analysis of the average peak height in the dark noise signal from the SiPM, as a function of the bias voltage, provides a measure of the response of the system. In Fig. 2 the peak average height is plotted against bias voltage for all SiPM samples.

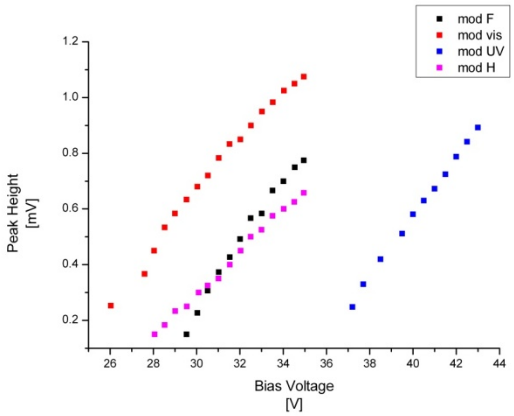

Figure 2. Peak height in SiPM signal against bias voltage for all SiPM samples.

In all cases the variation of average peak height with bias voltage can be well approximated by a straight line, indicating linear detector response. From the intercept of the best fit line with the horizontal axis one can find the effective breakdown voltage, reported in Table 1. The slope of the best fit line gives the reciprocal of the diode resistance R_d, also listed in Table 1. It can be noticed how the two SiPMs coming from the same company (Photonique) present very similar values of R_d. The relatively large values of R_d are the effect of the design of the SPAD cells, in particular the small area needed to pack them in a compact array and thus enhance the dynamic range of the device, and the thin depletion layer.

From the table it can be noted that in all cases the breakdown voltage extrapolated from the data is lower than the value quoted by the manufacturer. This is due to the fact that the manufacturer uses the inverse current-

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voltage characteristic to estimate the breakdown voltage, which does not take into account the statistical nature of the avalanche triggering mechanism. Indeed, we observed avalanche events even at voltages sensibly smaller than the breakdown voltage quoted by the manufacturer, some of which (the ones with better signal to noise ratio) are also included in Fig. 2.

Table 1. Measured breakdown voltage V_b and diode resistance R_d for four SiPM samples. The nominal breakdown voltage provided by the manufacturer is also shown.

SiPM Model	Nominal V_b (manufacturer) (V)	Measured V_b (peak height) (V)	Measured R_d (kΩ)
F	29.2	27.9	8.68
Vis	29.2	23.1	10.6
H	29.2	26.1	13.3
UV	37.2	34.7	9.24

Cross-talk noise

Cell-to-cell variation of the cross-talk probability, *p*, could result from local manufacturing inhomogeneity or from the different geometrical location of individual cells. For example, cells situated at the border of the device would have less probability of causing a secondary avalanche, as photons escaping beyond the border of the active area border would be lost for this purpose.

A measurement of the noise resulting from cross-talk is possible through analysis of the dark noise spectrum. Indeed, the current (or charge) signal read on a SiPM is the superposition of all the individual cells firing together. Since the rise time Δt of the avalanche is of the order of a few nanoseconds, whilst the time constant for subsequent exponential decrease of the peak current is almost two orders of magnitude longer, any event (such as cross-talk) which happens on a few ns timescale or shorter and causes N cells to fire will appear as a peak N times as high as the one due to an individual cell firing. Since the pure dark noise signal is expected to have a Poisson distribution, analysis of the measured distribution can provide an indication of cross-talk characteristics.

An analytical expression for the SiPM signal, which describes the actual probability distribution including cross-talk noise, was derived. By fitting this distribution to the experimental data, it is then possible to infer the cross-talk noise probability, and to correct for it.

Fig. 3 shows the value of p for all SiPM models at different values of bias voltage. As one would expect, the cross talk probability increases linearly with bias voltage [3], due to the increasing detection efficiency of the SPAD cells: the same variation in detection efficiency affects also the overall dark count rate.

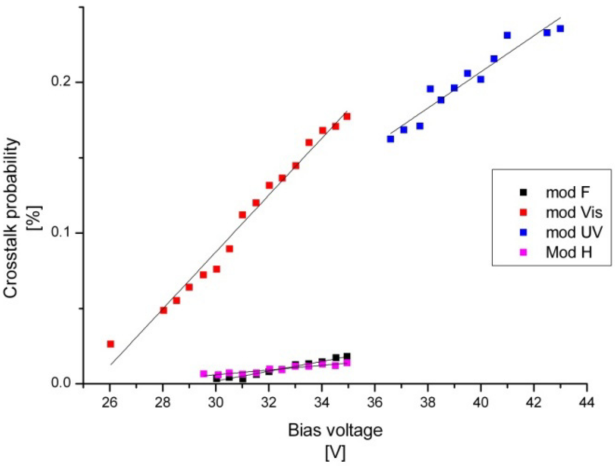

Figure 3. Comparison of theoretical (fitted lines) with experimental (square points) cross-talk probability as a function of the bias voltage for all the SiPM models.

CONCLUSIONS

In this contribution some aspects of the main sources of dark noise, i.e. the thermal generation of electron-hole pairs in the depletion layer and the optical cross-talk (which limit the performance of SiPMs) were analyzed and characterized, describing the response of SiPMs (produced with different manufacturing techniques) to different bias voltages.

A custom-written code to post-process readings taken directly from an oscilloscope was used for measuring the dark count rate and estimating the cross-talk probability for different SiPMs. The algorithm used in the code works well, even for high overvoltage regimes. Noise peaks are successfully identified and separated down to 7 ns in more than 99% of cases.

In addition, measurements of peak height give a clear indication of the linear response of the detector and allow a comparison between theoretical and experimental results. Cross-talk probability was also measured, and shows a linear increase with bias voltage, as expected.

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