In-depth study of single photon time resolution for the Philips digital silicon photomultiplier

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Abstract: The digital silicon photomultiplier (SiPM) has been commercialised by Philips as an innovative technology compared to analog silicon photomultiplier devices. The Philips digital SiPM, has a pair of time to digital converters (TDCs) connected to 12800 single photon avalanche diodes (SPADs). Detailed measurements were performed to understand the low photon time response of the Philips digital SiPM. The single photon time resolution (SPTR) of every single SPAD in a pixel consisting of 3200 SPADs was measured and an average value of 85 ps full width at half maximum (FWHM) was observed. Each SPAD sends the signal to the TDC with different signal propagation time, resulting in a so called trigger network skew. This distribution of the trigger network skew for a pixel (3200 SPADs) has been measured and a variation of 50 ps FWHM was extracted. The SPTR of the whole pixel is the combination of SPAD jitter, trigger network skew, and the SPAD non-uniformity. The SPTR of a complete pixel was 103 ps FWHM at 3.3 V above breakdown voltage. Further, the effect of the crosstalk at a low photon level has been studied, with the two photon time resolution degrading if the events are a combination of detected (true) photons and crosstalk events. Finally, the time response to multiple photons was investigated.

Keywords: Photon detectors for UV, visible and IR photons (solid-state) (PIN diodes, APDs, Si-PMTs, G-APDs, CCDs, EBCCDs, EMCCDs etc); Solid state detectors

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1 Introduction

The digital silicon photomultiplier (SiPM) concept has been firstly commercialised by Philips as an innovative technology combining photon detection and readout in a simple detector device with the possibility to access single photon avalanche diodes (SPADs). A SiPM consists of an array of SPADs operated in Geiger mode and is capable of detecting single photons to multi-photons. In the case of the digital SiPM, complementary metal-oxide-semiconductor (CMOS) electronics is integrated into the SiPM chip, resulting in a fully digital readout. The number of SPADs fired will be counted by an on-chip counter [1]. In the ideal case of a digital SiPM, each SPAD would be connected to a TDC, therefore very high single photon time resolution could be obtained due to efficiently suppressing trigger network skew influences by skew correction from TDC calibration. However, such a device has not yet been realised. The commercial available Philips digital SiPM, has a pair of time to digital converters (TDCs) connected to each array of SPADs. To better understand the low photon time response of the Philips digital SiPM, detailed measurements with low level light have been performed and the results are presented here.

2 Basic characteristics of the Philips digital photon counter

The digital SiPM developed by Philips is also called Philips digital photon counter (PDPC). The PDPC evaluation kit consists of two DPC-3200-22 sensors together with the data acquisition (DAQ) computer and the voltage supply. Each DPC-3200-22 sensor consists of 16 independent dies that are arranged in a $4 \times 4$ matrix. Each die contains four pixels in the form of a $2 \times 2$ matrix as indicated in figure 1. Each pixel consists of 3200 SPADs and the dimension of a pixel is $3.8775 \times 3.2 \text{ mm}^2$ [2]. One die sensor has a pair of TDCs generating a single timestamp per die where as the trigger signals are generated by pixels when one pixel of the die reaches a set threshold. The trigger
network can be configured to register the TDC time information of the first photon detected or, alternatively, at higher photon thresholds. The available time trigger settings are 1, 2, 3 and 4, with each trigger setting corresponding to different logic connections between the 4 sub-pixels of one pixel [2]. The organization of sub-pixels in pixel 1 of die 0 is shown in figure 2. For instance, when the trigger is set at 1 photon level, any sub-pixel detecting a photon can generate the trigger signal. The dark counts can be suppressed by carefully choosing an optimal trigger scheme to record more useful events [3]. In our study, the trigger level 1 was used for all measurements, in order to be sensitive to single photons.

The pixel 2 of die 0 in both sensors were used for the laser measurement, where one sensor was selected as the reference sensor. The noise performance of both pixels were measured and the dark count rate (DCR) for pixel 2 in die 0 of the test sensor and reference sensor is 6.3 MHz and 6.1 MHz at 3.3 V over-voltage (T=18 °C), respectively. The DCR of pixel 2 of the test sensor was measured as a function of the over-voltage. As shown in figure 3, the DCR increases slightly with the over-voltage. The digital SiPM from Philips offers the possibility to reduce the DCR by disabling some hot SPAD cells. For instance, the DCR is half the value of the whole pixel when only 5% of SPAD cells are inhibited, as can be seen in figure 3.

Optical crosstalk happens when a photon generated in the avalanche process of one SPAD is triggering a secondary avalanche in one of the neighbouring SPADs. The probability of crosstalk is directly related to the charge density in the junction of the SPAD. Hence, the bias voltage applied

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Figure 1. Layout and dimension of the Philips digital SiPM [2].

Figure 2. Layout and dimension of a single die composed of 4 pixels. Each pixel consists of 3200 SPAD cells.
Figure 3. The DCR as a function of the over-voltage. All measurements were performed at 18 °C.

Figure 4. The crosstalk probability map with the centred SPAD acting as light generator.

Figure 5. The crosstalk as a function of the over-voltage. All the measurements were performed at 18 °C.
to the SPAD as well as the geometry of the arrangement of the SPADs will affect the crosstalk. In order to characterise the crosstalk, we followed the same method as presented in [1]. The advantage of activating only selected SPAD cells allows directly to measure the crosstalk. A SPAD with high DCR in a low noise environment is selected as the photon source to investigate crosstalk in neighbouring SPADs. DCR values of each SPAD are measured to calculate the probability of random coincident dark counts for the correction. Every time the high DCR SPAD and one of the neighbour SPAD cell are activated. After subtracting the calculated randomly coincident dark counts, the crosstalk probability of that SPAD is calculated by the ratio:

$$P_{\text{crosstalk}} = \frac{\text{Two photon events}}{\text{One photon events}}$$ (2.1)

A $5 \times 5$ array of SPADs surrounding the high DCR SPAD were measured and the results for each SPAD are shown in figure 4. As seen from the figure, the crosstalk probability is unsymmetric, due to the designed geometry of the SPADs. We summed all the crosstalk probabilities of the 24 SPADs, which can be seen in figure 5. The crosstalk is linearly increasing with the over-voltage, with the same trend as observed for the analog SiPM [4].

3 Single photon time resolution setup

A temperature controlled light tight box houses the digital SiPM. A Picosecond pulsed laser from PICOQUANT with 405 nm wavelength was used [5], with a temporal width of 48 ps full width at half maximum (FWHM). We used a repetition rate of 100 kHz for the laser, since the maximum transmission rate between the field-programmable gate array (FPGA) and each die of the sensor is 120 kHz. The laser spot has a diameter of 4 mm and a good uniformity of the light was obtained by placing a diffuser after the laser beam. The scheme of the setup is shown in figure 6. The light from the laser was split by a beam splitter, where one beam of the light was sent to the reference sensor, while the other went to the PDPC under test. In all measurements the trigger threshold level was kept at the level of 1 photon to validate all events. We measured a coincidence time resolution of 47 ps (FWHM) between the two sensors when over 500 photons were detected in both sensor, defining the reference sensor time resolution to $\frac{47}{\sqrt{2}}$ ps. The coincidence time resolution between two sensors under high flux of light varies little by changing the over-voltage from 2 V to 3.3V. To
Figure 7. Histogram of the photon count for low intensity laser light (left), the single photon time resolution (middle) and the two photons time resolution (right). 20% of SPAD cells in the pixel were inhibited in this measurements. The over-voltage was 2.5 V and the temperature was 18 °C.

Figure 8. SPTR of the pixel as a function of over-voltage in dependence of different illuminated areas. The temperature was 18 °C.

reduce the dark count rate of reference sensor, the over-voltage of the reference sensor was hold constant at a value of 2 V in the following study. The laser light impinging the test sensor can be attenuated to the single photon level using a set of neutral density filters. For our study, only 80% of the SPAD cells of pixel 2 of die 0 in the reference sensor have been activated in order to keep the total DCR below 2.0 MHz, mainly to decrease the system dead time.

4 Single photon time resolution results

The SPTR of the digital SiPM is the convolution of all the jitter sources, mainly the SPAD jitter, the SPAD non-uniformity and the trigger network skew [6]. To study the effect of the jitter sources, we measured the timing performance of the digital SiPM on a single SPAD level and on a pixel level.

Figure 7 shows the histogram of the photon counts for an attenuated laser pulse, together with the timing distribution after an offline selection of the 1st photo-electron or 2nd photo-electron...
events. A SPTR of 105 ps (FWHM) was extracted from the sigma of the Gaussian fit of the time distribution, shown in figure 7. The time resolution of multi-photons can also be measured by selecting events with a given number of the photons and extracting the sigma of a Gaussian fit to the time distribution. The SPTR of the pixel 2 (3200 SPAD cells) as a function of over-voltage at different illuminating spot sizes was also measured, as shown in figure 8. It can be observed that the SPTR improves with decreasing area illuminated. This is due to the non-uniformity of the response of each SPAD cell electronics and the trigger network skew.

The trigger network of Philips digital SiPM is built to propagate the trigger signal from all cells to the TDC. However, the signal propagation time of each SPAD cell is different. This different relative signal path between different SPAD cells to the TDC is called trigger network skew [6].

Firstly, we measured the SPTR at different over-voltages for 9 different SPAD cells. To ensure the light intensity hitting the SPAD in single photon level, the Poisson expected value of detected photon distribution for the enable SPAD cell is around 0.02. The result of 9 SPAD cells is shown in figure 9. As can be seen in the figure, for these SPAD cells, the SPTR would not be improved more when the over-voltage is higher than 3 V. The SPTR of each SPAD cell in pixel 2 of die 0 has been measured at 3.3 V over-voltage. The distribution of the SPTR for the 3200 SPAD cells in pixel 2 is shown in figure 10. The mean value of the SPTR for these SPAD cells is 85.6 ps (FWHM). Only few SPAD cells have SPTR values exceeding 90 ps (FWHM). The relative signal propagation time of each SPAD cell was extracted and the skew distribution of the 3200 SPAD cells is shown in figure 11. For these 3200 SPAD cells, the difference between the maximum skew and the minimum skew is less than 150 ps. The root mean square (RMS) of the distribution is 23.8 ps.

The SPTR we got when most of the SPAD cells of the pixel were illuminated is worse than the SPTR of a single SPAD. The SPTR FWHM value when only a spot with 0.5 mm diameter of the digital SiPM was illuminated is 88.6 ps, which is comparable to the SPTR value of a single SPAD. The mean value of the SPTR sigma for all the 3200 SPAD cells in pixel 2 is represented as $\sigma_{\text{SPAD}}$ and the skew variation of all the SPAD cells is expressed as $\sigma_{\text{skew}}$. From our measurement, the $\sigma_{\text{SPAD}}$ can be estimated to 36.4 ps and the $\sigma_{\text{skew}}$ to 23.8 ps. By simply using a jitter transfer calculation:

$$\sigma_{\text{pixel}} = \sqrt{\sigma_{\text{SPAD}}^2 + \sigma_{\text{skew}}^2} \quad (4.1)$$

a value for $\sigma_{\text{pixel}}$ of 43.5 ps is calculated, which is close to the SPTR sigma of 43 ps measured at
Figure 10. SPTR distribution for 3200 SPAD cells in one pixel. The SPTR value of all SPAD cells was measured at 3.3 V over-voltage and temperature was 18 °C.

Figure 11. Skew (transit time spread) distribution for 3200 SPAD cells in one pixel. The measurements were performed at 3.3 V over-voltage and at 18 °C.

3.3 V, when the whole pixel of the digital SiPM is illuminated. We can conclude that the single photon time resolution of a pixel is mainly structured by the contribution of the SPAD jitter and further by the signal skews between the SPADs to the TDC.

5 Low photon intensity time resolution and crosstalk

The direct effect of optical crosstalk in the SiPM on the timing performance was studied with attenuated laser light, using a set of neutral density filters, and the over-voltage of the test sensor was set to 3.3 V. The number of detected photons from the low light flux of the laser pulse should follow the Poisson distribution [7]. Therefore we set the photon level to match different Poisson expectation values (λ) of 0.015, 0.34 and 3.5, for which the ratios of a two photon event to an one photon event were 0.008, 0.17 and 1.75, respectively.

We selected a 3×3 array of SPAD cells, which have similar signal propagation time, as can be seen in figure 12 (the difference is 15 ps between the earliest and the latest). The mean value of the SPTR of these SPAD cells at 3.3 V over-voltage is 85 ps FWHM. We can therefore conclude that these 9 SPAD cells have almost homogenous response.
Figure 12. Distribution of the mean value of the delay time (skew) of selected 9 SPAD cells in the SPTR measurements. The measurements were performed at 3 V over-voltage and at 18 °C.

Figure 13. Time resolution measured at different photon intensities at 18 °C and 3.3 V over-voltage.

Figure 14. Delay time at different photon levels at 18 °C and 3.3 V over-voltage.
The time resolution and the mean value of the delay time of these 9 SPAD cells for different intensities of the laser light are shown in figure 13 and figure 14. In the measurement, 9 SPAD cells selected were turned on while the rest of the SPAD cells in the sensor were inhibited. Concerning the response of the photon detector, N simultaneous detected photons should improve the time resolution by $\sqrt{N}$ compared to the first photon time resolution [8]. However, as shown in figure 13, the time resolution only improves for events that are not mixed with crosstalk events. The delay time shifts to earlier times as the detected number of photons increases. When the Poisson expected value is 0.015, nearly no two photons would arrive to the SiPM in the same time. For very low $\mu$ (Poisson mean) events with 2 or 3 detected photons are mostly “corrupted” by a high number of crosstalk or random coincidences. This is confirmed by the plot of figure 14, where one can see that the delay time does not depend on the number of photons for low $\mu$ intensities. When the Poisson expected value is 3.5, the detection of two photons is then indeed dominated by photons impinging and not crosstalk anymore, leading to an improved timing in the SPTR. The degrading of timing of the two photons events at $\mu = 0.34$ can be explained due to the crosstalk degrading by the overlap of two different types of time distribution, as can be seen in figure 15.

Factors affecting the timing response are the rise time of the signal as well as the trigger network skew. This is the same for the analog SiPM; for example the 2-photon timing can be 200 ps earlier...
compared to the 1 photon event [9]. In order to understand better the influence of these factors on
the performance of the digital SiPM, we performed measurements at the SPAD level as described
below. The laser light intensity was kept constant. We changed the neutral density filters to achieve
a light level of 9 photons arriving to the 3×3 SPAD cell area of the test PDPC sensor. The timing
performance for each SPAD cell was measured individually. The 9 time spectra of these 9 SPAD
cells we normalized and summed as depicted in figure 16. It can be seen that for these 9 SPAD
cells the earliest timestamp is around 0 ps and the mean value of all SPAD cells is 95.0 ps. Further
we enabled all 9 SPAD cells together and measured the timing. The time response of the 9 SPAD
cells together is shown in figure 17. Now the mean value of delay time of the 9-photon events is
-64.2 ps and almost all timestamps are much earlier than 0 ps. This indicates that the rise time of
the signal seen by the TDC changed, because more than one signal arrived to the TDC in the same
time giving to a timestamp earlier, as compared to the individual SPAD cell.

6 Time resolution from single photon to multiple photons

The light intensity was changed using different neutral density filters and was set to different levels of
photons impinging to the digital SiPM. Figure 18 shows the results of measurements with different
numbers of detected photons. As shown in the figure, the time resolution improves with increasing
number of photons detected from 1 to 110 (93 to 54 ps). The time resolution is getting better by the
combination of sharper rise time and a higher photon statistics. This is similar to the analog SiPM.
The delay time, which is the mean value of the time spectra is shown in figure 19. As expected, the
delay time moves to earlier times with increasing number of photons detected.

7 Conclusion

An evaluation for the DCR performance, optical crosstalk and single photon time resolution was
performed. We have characterised the timing performance of the Philips digital silicon photomulti-
tipler with the trigger threshold of 1. The timing performance at the SPAD level has also been
studied. A mean SPTR of 85 ps FWHM was obtained for single SPADs. Mainly due to the signal
skew from each SPAD cell to the TDC in the trigger network, the SPTR of a pixel (3200 SPADs)
Figure 18. Time resolution with different level of detected photons. The sensor is operated at 3.3 V over-voltage and at 18°C.

Figure 19. Delay time with different level of detected photons. The sensor is operated at 3.3 V over-voltage and at 18°C.

degrades to 102 ps FWHM. In [10], the trigger network skew can be efficiently suppressed (4ps RMS) by proper alignment of the TDC lines for the further product. The measurement with very weak laser-light shows that the SPTR value does not depend on the crosstalk if triggering on the first photon. However, if more than 1 photon is detected the timestamp registered in the TDC will be earlier than timestamp of a single photon, and the time profile will depend on the difference of arriving time and number of photons detected. The time resolution of a pixel of the Philips digital SiPM from single photons to multiple photons is getting better, i.e. 93 ps to 54 ps.

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