AND9776/D

Linearity of the Silicon Photomultiplier

At low optical signal levels the output of the SiPM is proportional to the incident photon flux. However, a side-effect of the SiPM's structure is that as the photon levels start to increase, the detector response will start to deviate from linearity. This document discusses the issue of linearity and how it is affected by microcell number and detector size.

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APPLICATION NOTE

INTRODUCTION

The silicon photomultiplier (SiPM) is composed of a 2D array of microcells whose summed output gives the detector signal. Each microcell operates in the Geiger mode and so acts like a binary switch, in either a HI (photon detected) or LO (no photon detected) state. With a large number of these independent and identical microcells in parallel, a quasi-analog output can be achieved. (More information can be found in the Application Note 'Introduction to the Silicon Photomultiplier')

The dynamic range of the SiPM is therefore limited by the number of microcells within the active area. At low optical signal levels, where the number of photons is much less than the number of microcells, the output of the SiPM is proportional to the incident photon flux (assuming that the optical signal is uniformly distribution across all microcells of the SiPM). As the illumination is increased, more and more microcells are involved in the detection event. A non-linear response occurs when the density of incident photons is a significant fraction of the microcell density. At this point there is a reasonable probability that two or more photons will interact in a single microcell simultaneously. Since each microcell can only give binary information, the detection of two or more photons only result in a signal of '1'. In this situation, the detector is no longer linear and starts to saturate.

This non-linear behavior depends on several factors, primarily: the total number of microcells and the light pulse duration compared to the microcell recovery time. These factors are discussed in the following sections.

EFFECT OF MICROCELL NUMBER

The SiPM response to a given number of incident photons (N_{ph}) can be estimated using Equation 1 which gives the number of fired microcells (N_{fired}), or Equation 2 which describes the same behavior in terms of instantaneous charge output (Q),

$$N_{fired} = M\left(1 - e^{\frac{-N_{ph} \cdot PDE}{M}}\right) \qquad \text{(eq. 1)}$$

$$Q = q \cdot M\left(1 - e^{\frac{-N_{ph} \cdot PDE}{M}}\right) \qquad \text{(eq. 2)}$$

where q is the charge from one microcell, M is the number of microcells and PDE is the photon detection efficiency.

It can be seen that when $N_{ph} \cdot PDE << M$ the response is essentially linear:

$$N_{fired} = M\left(1 - e^{\frac{-N_{ph} \cdot PDE}{M}}\right) \approx N_{ph} \cdot PDE \qquad \text{(eq. 3)}$$

$$Q = q \cdot M\left(1 - e^{\frac{-N_{ph} \cdot PDE}{M}}\right) \approx q \cdot N_{ph} \cdot PDE \qquad \text{(eq. 4)}$$

that is because $e^{-x} \approx 1 - x$ when $x << 1$.

Table 1. CALCULATED PHOTON LEVEL AT WHICH THERE IS A 10% DEVIATION FROM LINEAR RESPONSE

Sensor Type	M (Number of microcells)	PDE	Photon Level at which the Output Deviates 10% from Linear Response
10020	1296	8%	3500
10035	576	14%	750
10050	324	22%	300
10100	90	28%	65
30035	4774	14%	7000
60035	19096	14%	29000

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Figures 1 and 2 are generated using Equation 1 and values for the PDE and microcell number for each device that are summarized in Table 1. Also included in Table 1 are the approximate signal levels at which the SiPM response deviates more than 10% from linearity.

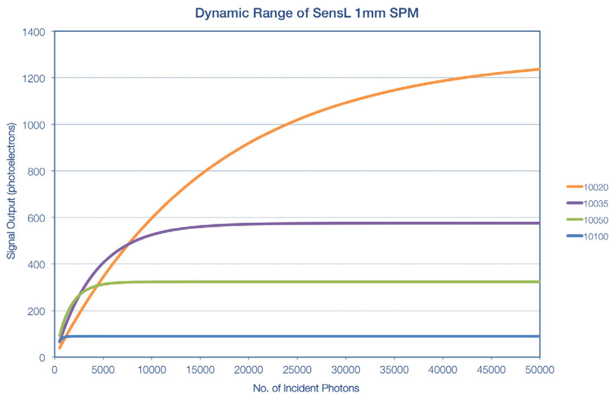

Figure 1. Calculated Values for the Signal Output for Varying Numbers of Incident Photons, for Differing Microcell Sizes (20 μm, 35 μm, 50 μm and 100 μm) on a 1 mm Sensor

EFFECT OF RECOVERY TIME

It should be noted that the description of linearity and saturation from the 'Introduction' section describes the instantaneous situation. That is, photons that arrive within a time window equal to the recovery time of the device. After the duration of the recovery time, any given microcell is returned to its charged and sensitive state. If the optical signal is longer in duration than the recovery time of the microcells, then the saturation effects will be less than predicted by Equations 1 and 2.

Taking into account the recovery time ($\tau_{recovery}$) and the pulse duration (τ_{pulse}) we can define an effective number of microcells (M_{eff}) available for detection,

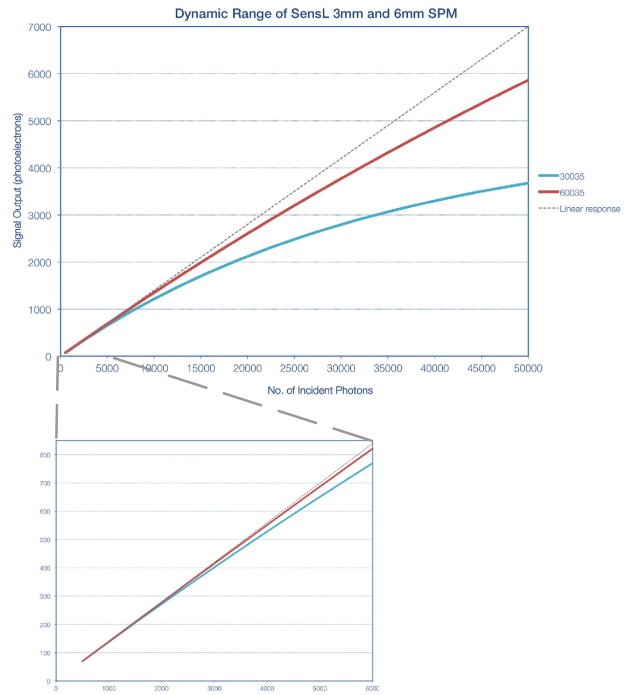

Figure 2. Calculated Values for the Signal Output for Varying Numbers of Incident Photons, for 3 mm and 6 mm Sensor with a 35 μm Microcell Size

$$M_{eff} = M \cdot \frac{\tau_{pulse}}{\tau_{recovery}} \qquad \text{(eq. 5)}$$

in the case of $\tau_{pulse} > \tau_{recovery}$ and $M_{eff} = M$ for $\tau_{pulse} < \tau_{recovery}$.

Recovery times for the various sensor types mentioned in the previous section are listed in Table 2. It can be seen that a smaller microcell size also has a shorter recovery time (due to its smaller capacitance), which in turns extends the linear detection range of these detectors.

Table 2. THE EFFECTIVE NUMBER OF MICROCELLS AVAILABLE FOR DETECTION OF LIGHT PULSES OF VARYING DURATION

Sensor Type	M (Number of microcells)	$\tau_{recovery}$*	M_{eff} (40 ns pulse)	M_{eff} (300 ns pulse)	M_{eff} (1000 ns pulse)
10020	1296	30 ns	1728	12960	43200
10035	576	130 ns	576	1329	4430
10050	324	320 ns	324	324	1012
10100	90	1800 ns	90	90	90
30035	4774	130 ns	4774	11016	36723
60035	19096	130 ns	19096	44067	146892

*These are illustrative values that are typical of a previous generation of SiPM that is now discontinued. Currently available ON Semiconductor SiPM sensors tend to have much shorter recovery times.

It should be noted that Equation 5 simplifies the situation, and assumes the photon density is uniform throughout its duration (square pulse). In reality, pulse shapes can be exponential decays, like those from scintillation crystals, with the greatest concentration of photons emitted in the first part of the pulse, and only small numbers in the latter part.

SUMMARY

This document has shown how the response of the SiPM to a given illumination can be estimated using data for the number of microcells, the PDE and the recovery time. From Equations 1 and 2 it can be shown that a detector with a larger number of microcells will always have a greater linear range. A larger number of microcells can be achieved by either having a larger detector or smaller microcells. A shorter recovery time increases the linear range as each microcell can recover faster and be sensitive to subsequent photons.

Additional effects that can affect the linearity that are not taken into account here are the dark counts and the cross-talk. In both cases the presence of these effects will increase the non-linearity.

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