AND9794/D

Silicon Photomultiplier (SiPM) Signal to Noise Ratio

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APPLICATION NOTE

The ability to detect single photons represents the ultimate sensitivity in optical detection. To achieve such sensitivity a number of technologies have been developed and refined to suit particular applications. Until recently, the traditional vacuum−based PMT has been the detector of choice for many applications. However, since its release into the market over the last decade, the so−called silicon photomultiplier (SiPM) has offered a real alternative to the PMT, achieving a similar performance in terms of gain, photon detection efficiency and timing. In addition the SiPM has all the benefits of silicon technology such as compactness, magnetic insensitivity and high volume CMOS production.

When assessing the suitability of a detector for a given application, a key metric is the signal to noise ratio (SNR). This is defined as the ratio of the signal current (photocurrent) or voltage to the inherent noise produced by the detector. This application note presents the SNR for ON Semiconductor SiPM detectors at a variety of signal levels.*

OVERVIEW

The equation used to calculate the signal to noise ratio in an SiPM is given in Equation 1 below.

$$\frac{S}{N} = \frac{I_S}{\sqrt{2qFBG(I_S + (2I_D + I_B))}} \qquad \text{(eq. 1)}$$

where,

$$I_S = \frac{P_\lambda \cdot PDE \cdot \dot{G}q}{hc/\lambda} \qquad \text{(eq. 2)}$$

- S/N is the signal to noise ratio
- I_S is the SiPM signal current
- F is the excess noise factor
- B is the bandwidth
- G is the SiPM gain
- I_D is the dark current
- I_B is the background noise

In addition, the following assumptions are used,

- Continuous measurement of current
- Bandwidth B = 1 Hz
- Background current $I_B = 0$
- $\lambda = 500$ nm
- $I_D = 0.4\ \mu A$ (1 mm SiPM), $3\ \mu A$ (3 mm SiPM) @ $V_{BR}+2$ V
- F = 1.1 @ $V_{BR}+2$ V
- $G = 2.4 \times 10^6$

Equation 1 is used to plot SNR as a function of the optical power (light intensity) and is shown in Figure 1.

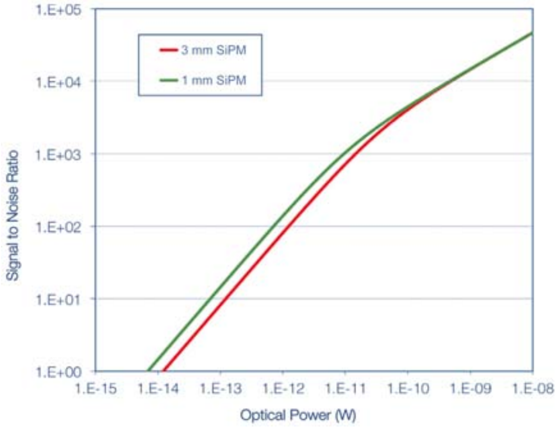

Figure 1. Signal to noise ratio as a function of optical power at 2 V above the breakdown voltage.

Equation 1 can also be used to plot the SNR for a given light level as a function of the applied bias voltage. In the case of Figure 2, this is shown for 2pW on a 1 mm SiPM. The breakdown voltage (V_{BR}) of the device is 27.5 V.

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*The data used in this application note refer to a previous generation of sensors with poorer performance than current devices. The figures are therefore for illustrative purposes only.

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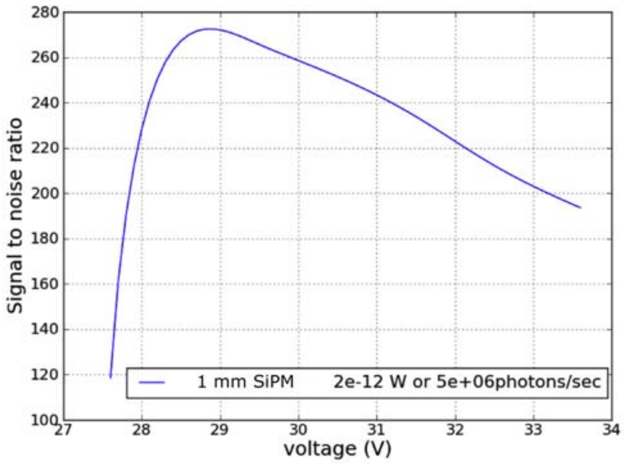

Figure 2. Signal to noise ratio as a function of bias voltage for a 1 mm SiPM.

Certain SiPM parameters are a function of SiPM bias, and so this must be incorporated into the calculation.

- F and I_D have a square dependence on bias
- G has a linear dependence on bias
- The PDE as a function of bias is plotted in Figure 3 below.

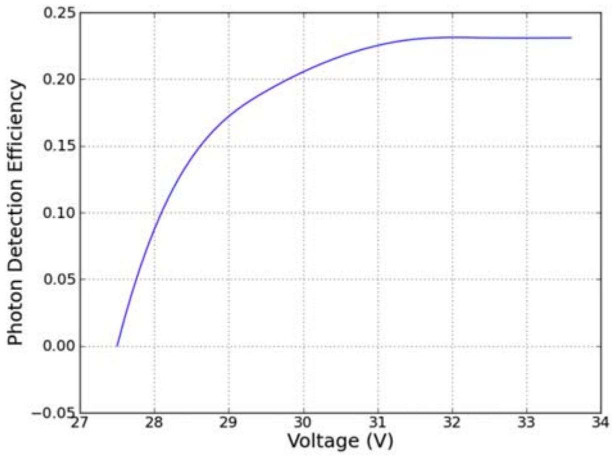

Figure 3. PDE as a function of bias voltage.

Figure 4 shows the same type of plot as in Figure 2, but repeated for a variety of incident light levels. The light levels are shown as both optical power and photons per second. (See Appendix A for more information on converting optical power into photons/sec).

It can be seen, that as the light level increases, the curve flattens off at higher bias voltages. This effect is more clearly seen if the plots are normalized to their maximum levels, as shown in Figure 5. This means that at higher light levels, there is a broader range of bias voltages that can set to achieve a near−optimal SNR.

The same plots are shown for a 3 mm SiPM in Figures 6 to 8.

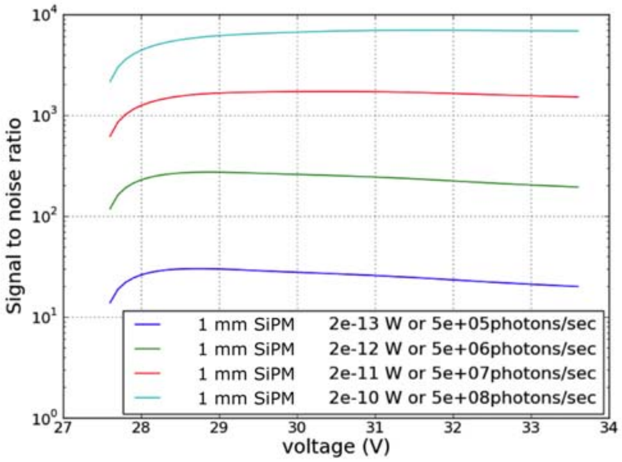

Figure 4. Signal to noise ratio as a function of bias voltage for different light intensities incident on a 1 mm SiPM.

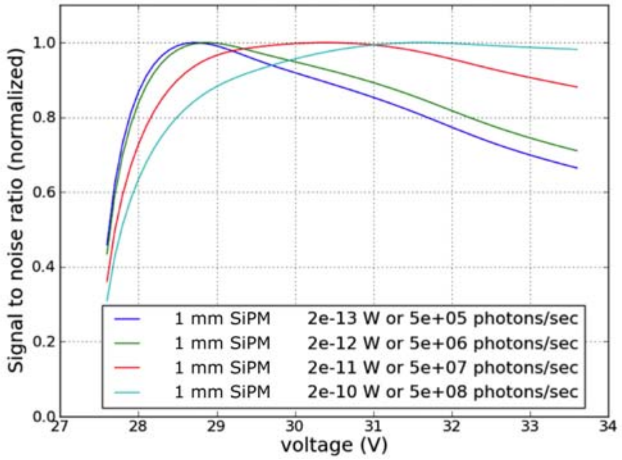

Figure 5. Normalized signal to noise ratio as a function of bias voltage for different light intensities incident on a 1 mm SiPM.

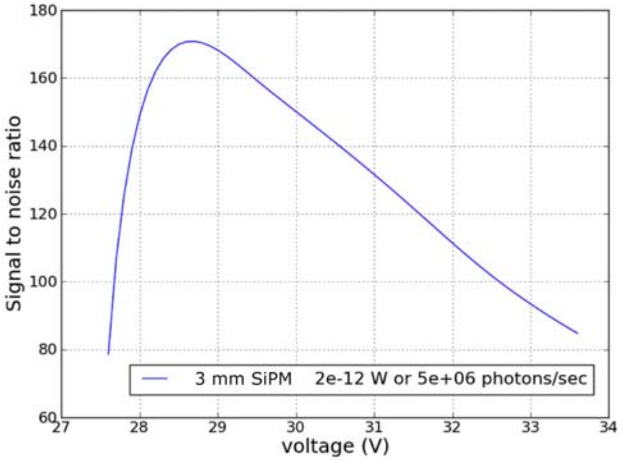

Figure 6. Signal to noise ratio as a function of bias voltage for a 3 mm SiPM.

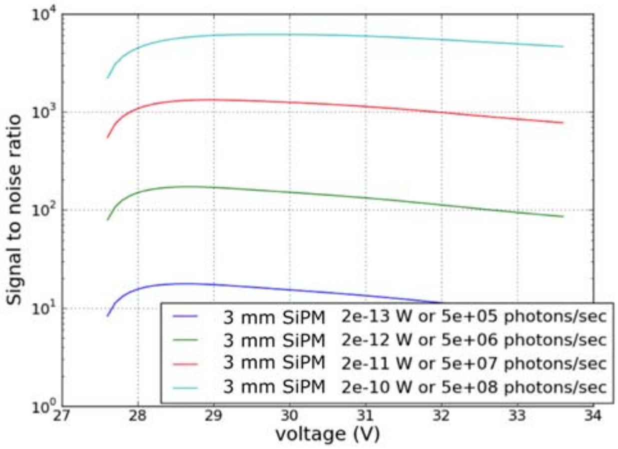

Figure 7. Signal to noise ratio as a function of bias voltage for different light intensities incident on a 3 mm SiPM.

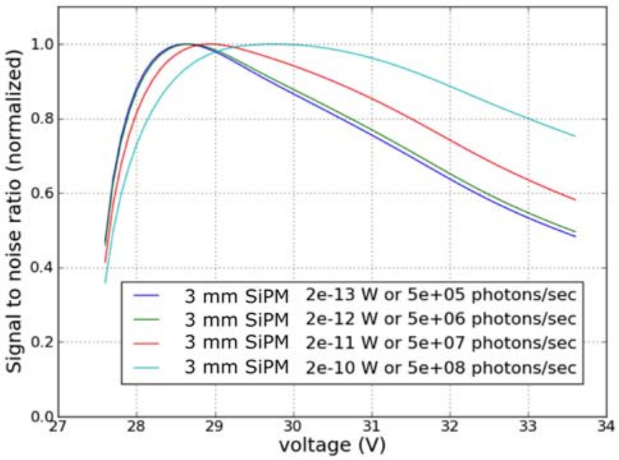

Figure 8. Normalized signal to noise ratio as a function of bias voltage for different light intensities incident on a 3 mm SiPM.

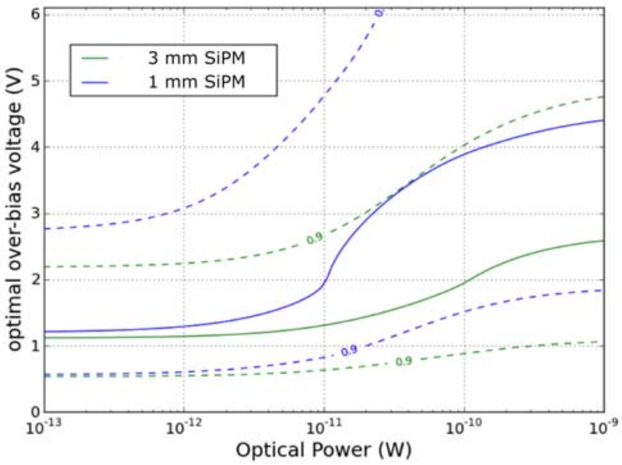

Figure 9. Optimal bias for various light levels for both 1 mm and 3 mm SiPMs. The dashed lines denote 90% of peak SNR values.

Figure 9 summarizes the results, by showing the optimal bias voltage (above breakdown) for both 1 mm and 3 mm detectors. In addition, the dashed lines denote 90% of the peak SNR, showing that the 1mm can achieve a very high SNR over a wide range of bias values. The 3 mm SiPM on the other hand is slightly more constrained, due to its higher noise levels.

APPENDIX

In order to calculate the number of photons that are equivalent to a given optical power, one can use Equation 3, below, to give the energy of each photon of a given wavelength (λ),

$$E = hc/\lambda \tag{eq. 3}$$

where,

- E is the energy in Joules
- h is Plancks constant (6.6×10^{-34} J · s)
- c is the speed of light (3.0×10^{8} ms^{-1})

A watt of power is equivalent to a joule per second, so a given optical power (in watts) can be divided by the power of one photon at a given wavelength (Equation 3) to give the number of photons, e.g) 2pW at 500 nm,

$$2 \times 10^{-12} \div 4 \times 10^{-19} = 5 \times 10^{6} \text{ photons/sec}$$

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