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Noise Equivalent Power NEP Measurements and Calculation of SiPM Device

AND90240/D

Introduction

The Noise Equivalent Power *NEP* is widely used metric [1] to define photodetector or avalanche photodetector sensitivity for light detection. Typically, the *NEP* is defined as power of input signal at which signal to noise ratio *SNR* is equal to 1 in a 1 Hz output bandwidth [2] and is given in Watts per square root of Hertz (W/√Hz). Since light detector sensitivity changes with light wavelength the *NEP* is a function of light wavelength λ.

This application note presents the methods for analytical and experimental calculation of *NEP(λ)* for SiPM devices. The analytical method calculates the *NEP(λ)* from SiPM performance parameters (i.e. photon detection efficiency, correlated and uncorrelated noise [3]), while the experimental measurements method allows to calculate the *NEP(λ)* from reverse IV measurements in the dark, if the SiPM photon detection efficiency is known. Since, the proper measurement of SiPM correlated noise (i.e. prompt and delayed optical crosstalk and after pulses) could be time and instrument consuming process, the approximation of analytical calculation is presented too. Proposed approximation allows to calculate the *NEP(λ)* for a given SiPM device knowing only its dark count rate, photon detection efficiency and first and second breakdown voltages. Good agreement was found between all proposed methods for *NEP(λ)* calculation. Also, the *SNR* ratio was calculated from *NEP(λ)* for different light intensities and pulse durations.

Theoretical Calculation

From the *NEP* definition, it might be calculated from minimum detectable light power $P_{min}(\lambda)$ for a given light wavelength λ as:

$$NEP(\lambda) = \frac{P_{min}(\lambda)}{\sqrt{B}} \qquad \text{(eq. 1)}$$

where *B* is measurement bandwidth. The incident signal power *P(λ)* can be calculated from SiPM signal current *Is* as:

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

where *PDE* is SiPM photon detection efficiency, *G* is SiPM gain and *q* is the electron charge, λ is light wavelength, *c* is speed of light in vacuum (2.997E8 m/s), *h* is Plank constant (6.626E−10 J/Hz). Therefore, *NEP* can be calculated as:

$$NEP(\lambda) = I_S \times \frac{hc/\lambda}{PDE(\lambda) \times G \times q \times \sqrt{B}} \qquad \text{(eq. 3)}$$

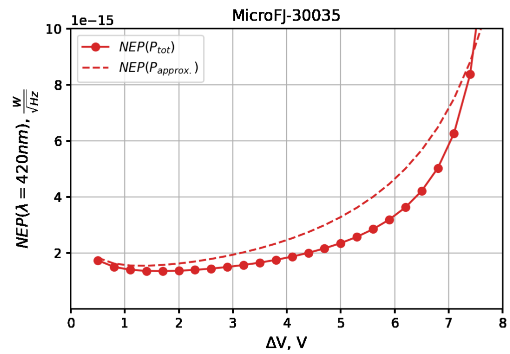

Figure 1. NEP a Function of Overvoltage at λ = 420 nm for MicroFJ−30035 Device calculated from Measured (solid line) and Approximated (dashed line) Correlated Noise

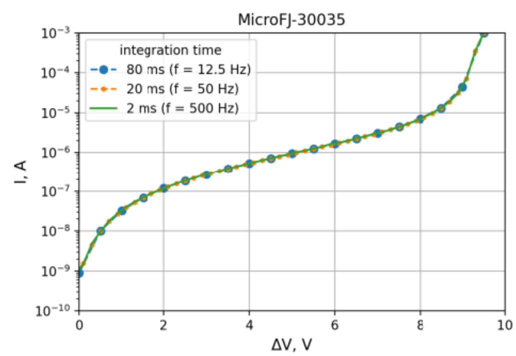

Figure 2. Reverse IV for MicroFJ−30035 device, measured at different integration time: 2ms, 20 ms and 80 ms

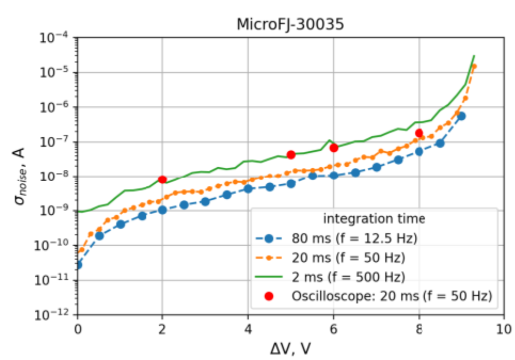

Figure 3. Noise standard deviation as a function of SiPM overvoltage for MicroFJ−30035 measured at different integration times: 2, 20 and 80 ms

The signal to noise rate *SNR* for SiPM devices is defined [4] [5] as:

$$\mathrm{SNR} = \frac{I_S}{i_o} = \frac{I_S}{\sqrt{2qGBF \times (I_S + I_D)}} \quad \text{(eq. 4)}$$

where i_0 is overall shot noise RMS current, F is SiPM excess noise factor, I_S and I_D are signal and dark currents respectively. Since, at *NEP* the *SNR* = 1, the signal current can be calculated from Eq. 4 as:

$$I_S = qGBF \times \left(1 + \sqrt{1 + \frac{2I_D}{qGBF}}\right) \quad \text{(eq. 5)}$$

SiPM I_D is dominated by dark count rate *DCR* enhanced by corelated noise (i.e. optical crosstalk and afterpulses). Therefore, the dark current generated by SiPM can be approximated as:

$$I_D = DCR \times q \times G \times F \quad \text{(eq. 6)}$$

Finally, by combining Eq. 3, Eq. 5 and Eq. 6 the *NEP(λ)* can be calculated as:

$$\mathrm{NEP}(\lambda) = \frac{hc}{\lambda} \times \frac{F \times \sqrt{B}}{PDE} \times \left(1 + \sqrt{1 + \frac{2 \times DCR}{B}}\right) \quad \text{(eq. 7)}$$

Following the Ref. [6], the SiPM excess noise factor F can be calculated as:

$$F = \frac{1}{1 + \ln(1 - P_{tot.})} \quad \text{(eq. 8)}$$

where $P_{tot} = P_{ct} + P_{dct} + P_{ap}$ is a sum of prompt P_{ct} delayed P_{dct} optical crosstalks and afterpulses P_{ap} probabilities(1). In this equation we neglect the probability that crosstalk and afterpulses can generate each other, also we neglect the fact that afterpulses have reduced charge with respect to typical 1 p.e. charge due to not fully recovered microcells.

The measured (solid line) and approximates (dashed line) values for a SiPM correlated noise was used to calculate *NEP(λ)* for MicroFJ−30035 device at λ = 420 nm and *NEP(V)* is presented in Figure 1. Even if approximation of correlated noise slightly overestimates the *NEP(λ)* values, it still might be used for fast and easy estimation of *NEP(λ)* for a given SiPM at a given wavelength.

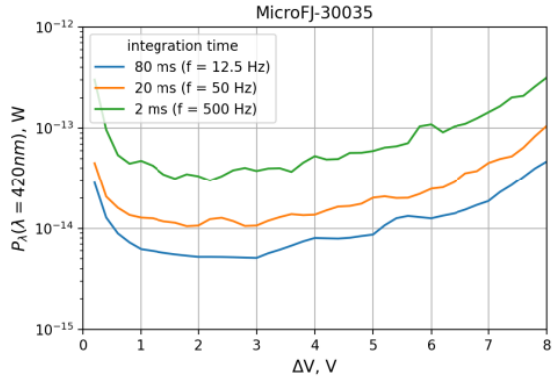

Figure 4. Light Power (λ = 420 nm) at which SNR = 1 as a Function of Overvoltage

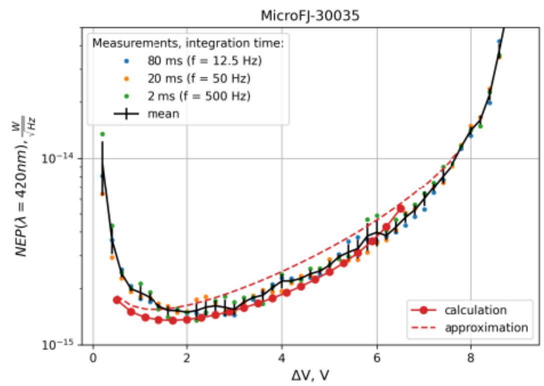

Figure 5. NEP (λ = 420 nm) as a Function of Overvoltage

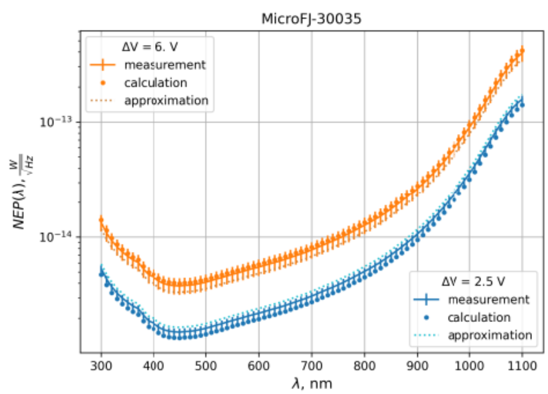

Figure 6. NEP as Function of Light Wavelength for MicroFJ−30035 Device at 2.5 and 6 V Overvoltage

1. If the P_{ct}, P_{dct} and P_{ap} are unknown, the total correlated noise probability could be approximated [7] as: $P_{approx.} = \Delta V / (V_{BD-2nd} - V_{BD})$, where V_{BD} and V_{BD-2nd} are the first and second breakdown voltages.

Measurements

The NEP can be measured experimentally from minimal light power P_{min} at which SNR = 1, as:

$$NEP^{meas.}(\lambda) = \frac{P_{min}}{\sqrt{B}} = \frac{hc}{\lambda}\frac{I_S}{PDE(\lambda)\times G\times q\times\sqrt{B}} \quad \text{(eq. 9)}$$

where I_S is signal photocurrent generated by SiPM. Since, from NEP definition SNR = 1, the I_s should be equal to noise standard deviation σ_{noise}.

The σ_{noise} was measured experimentally during the reverse IV measurements (Figure 2). At each bias voltage V_{bias} 100 dark current I_{dark} measurements were taken and σ_{noise} was calculated as standard deviation of those I_{dark}. The I_{dark} was measured at three different integration times of 2, 20 and 80 ms which corresponds to 12.5, 50 and 500 Hz measurement frequency. The σ_{noise} is presented in Figure 3. As expected, independent of overvoltage σ_{noise} decreases with increasing integration time. Also, σ_{noise} increases with increasing ΔV due to increasing SiPM gain, correlated and uncorrelated noise. At $\Delta V = 0$, the SiPM internal noise should be equal to zero too (i.e. DCR = 0, $Gain$ = 0, optical crosstalk and afterpulses = 0), however we can observe $\sigma_{noise}(\Delta V = 0\ V)$ in ranges from 10 pA to 1 nA (depending of measurement frequency). Those values should correspond to a sum of noise generated by device below breakdown voltage (i.e. Shockley−Read−Hall thermal generation carriers enhanced by trap−assisted and band−to−band tunneling) and instrumentation noise.

The σ_{noise} might be also measured from waveform analyses by connecting the SiPM directly to the oscilloscope and measuring the amplitude standard deviation. However, since typical oscilloscope has smallest vertical resolution of 1 mV, the lowest σ_{noise} which could be measured with reasonable precision is only around a few uV. Assuming the input impedance of 50 Ω, the smallest σ_{noise} which can be measured with this method is only around $10^{-7} - 10^{-8}$ A. This is almost 4 orders of magnitude worse with respect to current measurement described previously. The sensitivity of oscilloscope method might be improved by increasing the input impedance or by adding an amplifier. However, both those solutions are increasing the noise generated by experimental set−up. The measured σ_{noise} (f = 50 Hz) from waveform analyses is presented in Figure 3 by red dots. We can observe the difference of almost one order of magnitude between waveform method and direct measurements from I_{dark} due to lack of precision.

The light power P_{min} equivalent to SNR = 1 was calculated from σ_{noise} ($I_S = \sigma_{noise}$) at λ = 420 nm as:

$$P_{min} = \frac{hc}{\lambda}\frac{\sigma_{noise}}{PDE(\lambda)\times G\times q} \quad \text{(eq. 10)}$$

P_{min} as a function of ΔV is presented in Figure 4. As expected, independent of ΔV, P_{min} decreases with increasing integration time (i.e. decreasing the measurement frequency). $P_{min}(\lambda = 420\ nm)$ shows fast decrease with ΔV increase at low overvoltage due to fast increase of PDE and starts to increase after ~2.5 V due to optical crosstalk and afterpulses. The local minima of $P_{min}(\lambda = 420\ nm)$ was found around ΔV = 2.5 V.

Figure 5 shows the comparison between calculated from experimental data (Eq.9) and theoretical approximation $NEP(\lambda)$ (Eq.7), both for $\lambda = 420\ nm$. We can observe good agreement between measured and calculated NEP values almost at all overvoltage range. However, the NEP calculated from approximated correlated noise values (dashed line) shows slightly overestimated values.

From the SiPM PDE vs. λ [7], the $NEP(\lambda)$ as a function of wavelength was calculated from Eq.9 (measurements) and Eq.7 (theoretical calculation) at ΔV = 2.5 and 6 V and presented in Figure 6. As expected, the lowest NEP is achieved at 420 nm where MicroFJ SiPM has the highest PDE. Also good agreement, almost within the error bars between theoretical calculations and measurements was found.

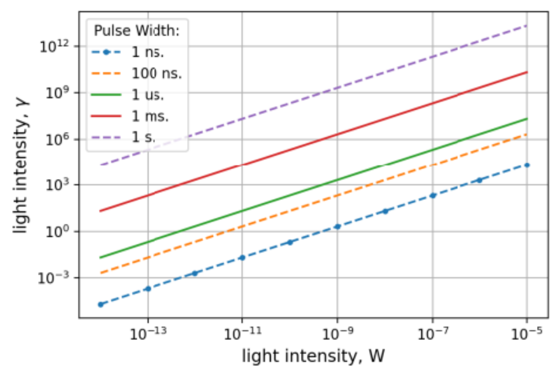

Figure 7. Relation between Incident Light Intensity in Watt and Photons for different Light Pulse Duration from 1 ns up to 1 s

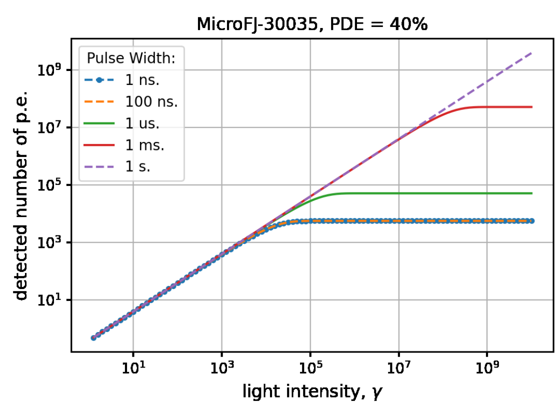

Figure 8. MicroFJ−30035 Linearity as Function of Light Pulse Duration

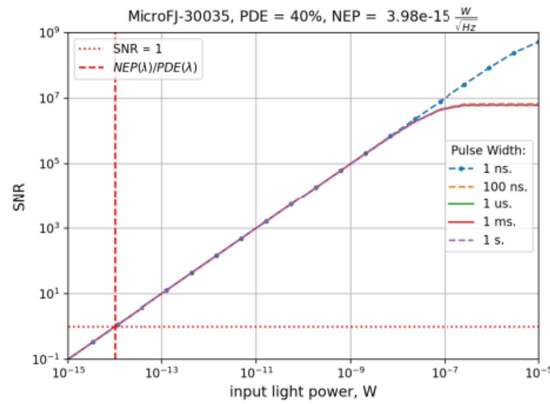

Figure 9. MicroFJ−30035 SNR as a Function of Light Pulse Duration. Also, the Value can be found as Light Power at which SNR = 1.

Signal To Noise Ratio Calculation vs. Light Intensity

The Signal to noise ratio can be calculated from $NEP(\lambda)$ at a given light wavelength λ, as:

$$SNR = \frac{P_{detected}}{NEP(\lambda) \times \sqrt{B}} \quad \text{(eq. 11)}$$

where $P_{detected}$ is light power detected by the SiPM, which can be calculated from number of detected photo electrons $n_{p.e.}$ as:

$$P_{detected} = \frac{n_{p.e.}}{t_{pw}} \times \frac{h \cdot c}{\lambda} \quad \text{(eq. 12)}$$

where t_{PW} is light pulse duration, λ is light wavelength, c is speed of light in vacuum (2.997E8 m/s), h is Plank constant (6.626E−10 J/Hz). The $n_{p.e.}$ is affected by SiPM nonlinearity [8] and can be calculated as:

$$n_{p.e.} = \begin{cases} \frac{N_{pixel} \times t_{PW}}{2.2 \times \tau_{rec.}} \left(1 - e^{-\frac{n_\gamma \times PDE(\lambda) \times 2.2 \times \tau_{rec.}}{N_{pixel} \times t_{PW}}}\right) & \text{for } t_{PW} > 2.2 \times \tau_{rec.} \\ N_{pixel} \left(1 - e^{-\frac{n_\gamma \times PDE(\lambda)}{N_{pixel}}}\right) & \text{for } t_{PW} \le 2.2 \times \tau_{rec.} \end{cases} \quad \text{(eq. 13)}$$

Where N_{pixel} is SiPM number of microcells, $\tau_{rec.}$ is SiPM recovery time constant, PDE is SiPM photon detection efficiency. In this formula we assumed that SiPM microcells effectively recovered within $2.2 \times \tau_{rec.}$ for the full recovery $5 \times \tau_{rec}$ should be used. And finally, n_γ can be calculated from light power as:

$$n_\gamma = P_\gamma \times t_{PW} \times \frac{\lambda}{h \cdot c} \quad \text{(eq. 14)}$$

From Eq. 14, we see that, for a given light power, different pulse widths lead to different numbers of incident photons. This effect is demonstrated in Figure 7. Where the n_γ is presented as function of P_γ generated with different pulse duration (t_{PW}) from 1 ns up to 1 s. This affects the SiPM linearity which is presented in Figure 8. The SNR calculated as a function of incident light power for λ = 420 nm for different light pulse durations is presented in Figure 9. By neglecting the SiPM linearity (which is ideal for light power below 10^{-9} W), the $P_{detected} = P_\gamma \times PDE(\lambda)$. Therefore, from Eq.11 the $NEP(\lambda)/PDE(\lambda)$ can be determined as light power at which $SNR = 1$, which is presented by cross−section of dashed lines in Figure 7.

Conclusions

The SiPM *NEP* was measured and compared with analytical calculation at λ = 420 nm as a function of overvoltage ΔV and as a function of λ at ΔV = 2.5 V and 6 V. Agreement almost within the statistical error bars was found. Slight difference between measured and calculated *NEP* values observed at low overvoltages (ΔV < 3 V). It might be related to the additional noise coming from experimental set−up which is not included in the analytical calculation. Also, the approximation of analytical calculation is presented and it allows to estimate the *NEP* without measuring the SiPM uncorrelated noise. This approximation slightly overestimates the *NEP* values, however it could be used for fast and easy *NEP* estimation. *NEP* value of a few fW/√Hz was found for onsemi MicroFJ−30035 device at λ = *420 nm*. Also, from *NEP* the SiPM Signal to Noise ratio was calculated as a function of incident light power generated with different pulse widths from 1 ns up to 1 s.

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