

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/\sqrt{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 $NEP(\lambda)$ for SiPM devices. The analytical method calculates the $NEP(\lambda)$ from SiPM performance parameters (i.e. photon detection efficiency, correlated and uncorrelated noise [3]), while the experimental measurements method allows to calculate the $NEP(\lambda)$ 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 $NEP(\lambda)$ 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 $NEP(\lambda)$ calculation. Also, the SNR ratio was calculated from $NEP(\lambda)$ 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:

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

where B is measurement bandwidth. The incident signal power $P(\lambda)$ can be calculated from SiPM signal current I_s as:

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

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:

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

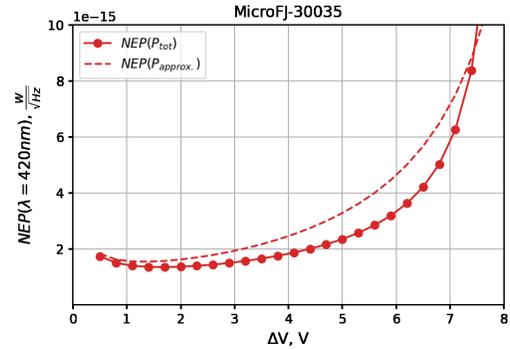


Figure 1. NEP a Function of Overvoltage at $\lambda = 420$ nm for MicroFJ-30035 Device calculated from Measured (solid line) and Approximated (dashed line) Correlated Noise

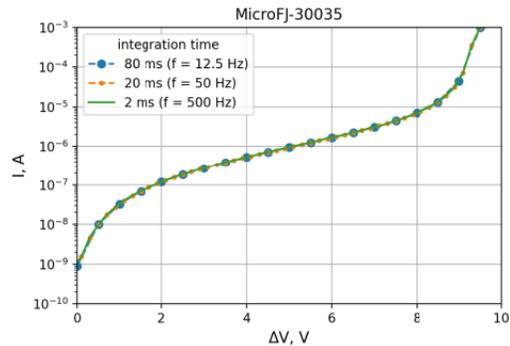


Figure 2. Reverse IV for MicroFJ-30035 device, measured at different integration time: 2ms, 20 ms and 80 ms

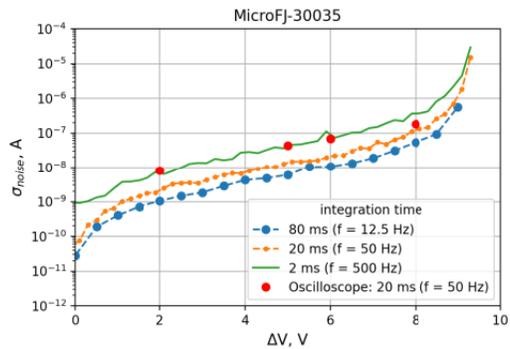


Figure 3. Noise standard deviation as a function of SiPM overvoltage for MicroFJ-30035 measured at different integration times: 2, 20 and 80 ms

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

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

where i_o 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 correlated 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 $NEP(\lambda)$ can be calculated as:

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

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 $NEP(\lambda)$ for MicroFJ-30035 device at $\lambda = 420$ nm and $NEP(V)$ is presented in Figure 1. Even if approximation of correlated noise slightly overestimates the $NEP(\lambda)$ values, it still might be used for fast and easy estimation of $NEP(\lambda)$ for a given SiPM at a given wavelength.

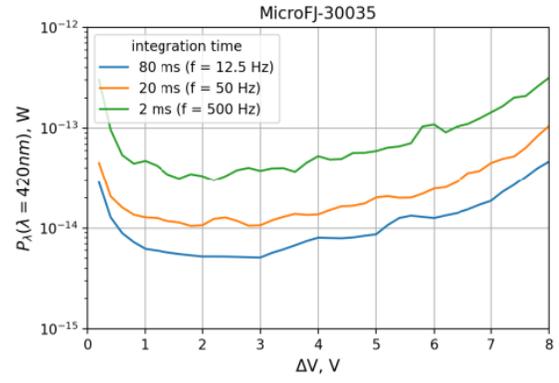


Figure 4. Light Power ($\lambda = 420$ nm) at which $SNR = 1$ as a Function of Overvoltage

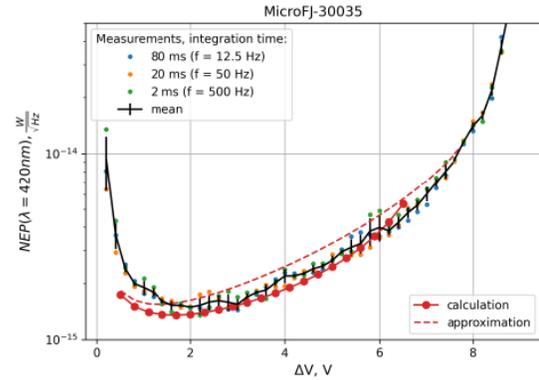


Figure 5. NEP ($\lambda = 420$ nm) as a Function of Overvoltage

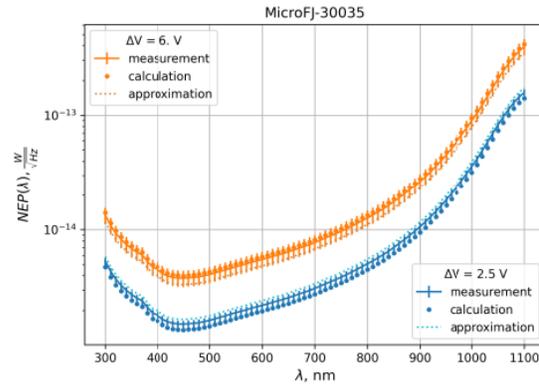


Figure 6. NEP as Function of Light Wavelength for MicroFJ-30035 Device at 2.5 and 6 V Overvoltage

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:

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

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 $\lambda = 420$ nm as:

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

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 $\Delta V = 2.5$ 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 $\Delta V = 2.5$ 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.

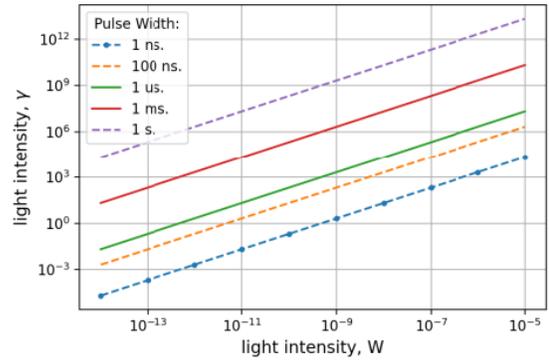


Figure 7. Relation between Incident Light Intensity in Watt and Photons for different Light Pulse Duration from 1 ns up to 1 s

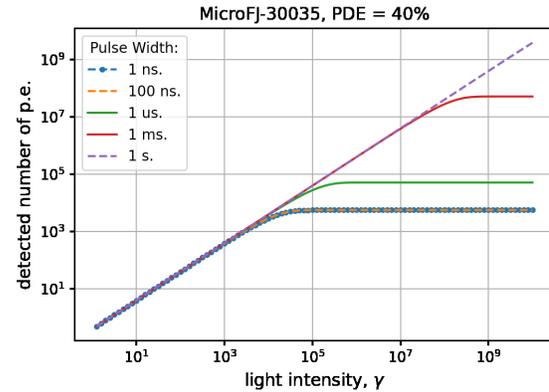


Figure 8. MicroFJ–30035 Linearity as Function of Light Pulse Duration

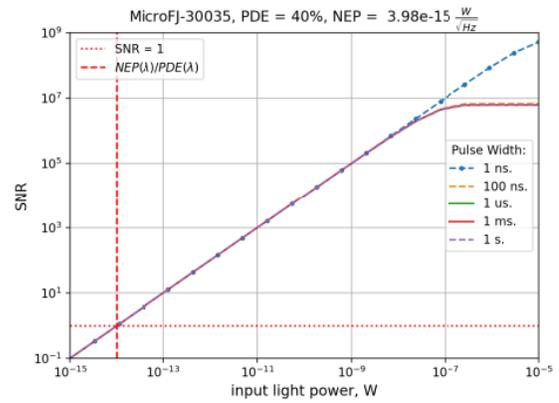


Figure 9. MicroFJ–30035 SNR as a Function of Light Pulse Duration. Also, the Value can be found as Light Power at which SNR = 1.

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:

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

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 $\lambda = 420$ 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 $\lambda = 420$ nm as a function of overvoltage ΔV and as a function of λ at $\Delta V = 2.5$ 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 ($\Delta V < 3$ 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/ $\sqrt{\text{Hz}}$ was found for onsemi MicroFJ-30035 device at $\lambda = 420$ 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.

Bibliography

- [1] V. Mackowiak, J. Peupelmann and A. Gorges, “NEP – Noise Equivalent Power,” [Online]. Available: https://www.thorlabs.com/images/TabImages/Noise_Equivalent_Power_White_Paper.pdf.
- [2] P. L. Richards, “Bolometers for infrared and millimeter waves,” *Journal of Applied Physics*, vol. 76, no. 1, 1994.
- [3] onsemi, “Introduction to the Silicon Photomultiplier (SiPM),” July 2021. [Online]. Available: <https://www.onsemi.com/pub/Collateral/AND9770-D.PDF>.
- [4] V. Kitsmiller, C. Campbell and T. O’Sullivan, “Optimizing sensitivity and dynamic range of silicon photomultipliers for frequency-domain near infrared spectroscopy,” *Biomed Opt Express*, pp. 5373–5387, 2022.
- [5] onsemi, “Silicon Photomultiplier (SiPM) Signal to Noise Ratio,” 8 2018. [Online]. Available: <https://www.onsemi.com/pub/Collateral/AND9794-D.PDF>.
- [6] S. Vinogradov, “Probabilistic analysis of solid state photomultiplier performance,” *Proceedings of SPIE – The International Society for Optical Engineering*, vol. 8375, pp. 83750S–83750S, 05 2012.
- [7] onsemi, “J-Series SiPM Sensors,” onsemi, [Online]. Available: <https://www.onsemi.com/download/data-sheet/pdf/microj-series-d.pdf>.
- [8] onsemi, “Linearity of the Silicon Photomultiplier,” September 2018. [Online]. Available: <https://www.onsemi.com/pub/Collateral/AND9776-D.PDF>.
- [9] S. Vinogradov, “Analytical models of probability distribution and excess noise factor of solid state photomultiplier signals with crosstalk,” 2012.
- [10] A. Nagai, N. Dinu and A. Para, “Breakdown voltage and triggering probability of SiPM from IV curves,” in *2015 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC)*, 2015.

onsemi, Onsemi, and other names, marks, and brands are registered and/or common law trademarks of Semiconductor Components Industries, LLC dba “onsemi” or its affiliates and/or subsidiaries in the United States and/or other countries. onsemi owns the rights to a number of patents, trademarks, copyrights, trade secrets, and other intellectual property. A listing of onsemi’s product/patent coverage may be accessed at www.onsemi.com/site/pdf/Patent-Marking.pdf. onsemi reserves the right to make changes at any time to any products or information herein, without notice. The information herein is provided “as-is” and onsemi makes no warranty, representation or guarantee regarding the accuracy of the information, product features, availability, functionality, or suitability of its products for any particular purpose, nor does onsemi assume any liability arising out of the application or use of any product or circuit, and specifically disclaims any and all liability, including without limitation special, consequential or incidental damages. Buyer is responsible for its products and applications using onsemi products, including compliance with all laws, regulations and safety requirements or standards, regardless of any support or applications information provided by onsemi. “Typical” parameters which may be provided in onsemi data sheets and/or specifications can and do vary in different applications and actual performance may vary over time. All operating parameters, including “Typicals” must be validated for each customer application by customer’s technical experts. onsemi does not convey any license under any of its intellectual property rights nor the rights of others. onsemi products are not designed, intended, or authorized for use as a critical component in life support systems or any FDA Class 3 medical devices or medical devices with a same or similar classification in a foreign jurisdiction or any devices intended for implantation in the human body. Should Buyer purchase or use onsemi products for any such unintended or unauthorized application, Buyer shall indemnify and hold onsemi and its officers, employees, subsidiaries, affiliates, and distributors harmless against all claims, costs, damages, and expenses, and reasonable attorney fees arising out of, directly or indirectly, any claim of personal injury or death associated with such unintended or unauthorized use, even if such claim alleges that onsemi was negligent regarding the design or manufacture of the part. onsemi is an Equal Opportunity/Affirmative Action Employer. This literature is subject to all applicable copyright laws and is not for resale in any manner.

ADDITIONAL INFORMATION

TECHNICAL PUBLICATIONS:

Technical Library: www.onsemi.com/design/resources/technical-documentation
onsemi Website: www.onsemi.com

ONLINE SUPPORT: www.onsemi.com/support

For additional information, please contact your local Sales Representative at www.onsemi.com/support/sales