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APD's excess noise measurements using
spectral analysis (FFT)

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Abstract

In high energy physics, the measurement of APD's excess noise factor is essentially made by histogram method. Another method used mainly in telecommunication field is to measure the noise spectral density using a transresistance amplifier from which the output signal is analysed by FFT (Fast Fourier Transform). The main advantage of this spectral method is the capability to separate the different domain of the whole noise spectrum. In addition, it is easy to use and is more sensitive at low bias voltage. This method also allows one to detect the generation and recombination noises if they exist. For certain type of APDs, this method gives an opportunity to measure the primary photocurrent. We have measured the excess noise of two types of APDs with this spectral method as well as histogram method. The result by the spectral method coincides well with the histogram method.

1 Introduction

The measurement of some APD parameters is not always simple as it has been shown in our previous technical note [1]. In high energy physics, the histogram method is mainly used although the spectral method start to be used [2]. In telecommunication field, APDs of small size have been used for a long time. The characterisation of these APDs has been made by analog spectral methods, and from the beginning of 1980's with digital spectral analysis FFT¹⁾ [3, 4].

One of the most difficult parameter to measure is the primary photocurrent. The group of Montpellier²⁾ has published numerous results on the APD (Si, HgCdTe, AsGa) characterisation using spectral methods for the measurement of the noise and primary photocurrent [5, 6].

To compare the excess noise factor obtained by the pulsed method (histogram method) with the one by spectral analysis and continuous light, this study is devoted to two APDs already investigated [1]. One APD from Hamamatsu (low capacitance type S5345, 5 mm in diameter) is based on the epitaxial growth technology. And the second, from EG&G, is a "reverse reach-through" APD (type C30626E, $5 \times 5 \text{ mm}^2$) based on ion implantation and diffusion technology. The assumed electric field profile and the internal structure of these two APDs are shown in Fig. 1.

Figure 1: Electric field profile and internal structure of the two APDs tested.

¹⁾ Fast Fourier Transform.

²⁾ C.E.M. : Centre d' Electronique de Montpellier.

2 Noise in avalanche photodetector

Here we focus only on the noise generated by APDs. The total noise due to the overall setup of measurement will be discussed in the section 3.2.

In silicon photodetectors such as PIN junctions, the noise associated with the detector is given by its spectral density:

$$S_{I_{inj}}(f) = 2qI_{inj} \quad (\text{A}^2/\text{Hz}), \quad (1)$$

where f is the frequency, q is the electronic charge and I_{inj} is the injected primary current in the junction. This noise is considered as Poisson distribution noise. In APDs, the multiplication process of the photocarriers under an electric field introduces a noise so called multiplication noise which is characterized by the excess noise factor, F . The noise spectral density of such photodetectors is then:

$$S_i(f) = 2qI_{inj}M^2F \quad (\text{A}^2/\text{Hz}), \quad (2)$$

where M is the multiplication factor (gain) defined by the ratio between the photocurrent I_{ph} (delivered by the photodetector) and the primary photocurrent. It can be shown from (2) that the signal to noise ratio is then given by:

$$\frac{\text{Signal}}{\text{Noise}} = \sqrt{\frac{N}{F}}, \quad (3)$$

where N is the number of the primary photocarrier.

One can observe that if there was no multiplication noise, the noise spectral density would be written like:

$$S_i(f) = 2qI_{inj}M^2 \quad (\text{Poisson distribution}). \quad (4)$$

Taking into account of $M = I_{ph}/I_{inj}$, the equation (4) could be rewritten in terms of photocurrent like $S_i(f) = 2qI_{ph}^2/I_{inj}$. Then $S_i(f)$ versus I_{ph} in a log-log scale is a straight line with a slope of 2 (in case of PIN junction, the slope is equal to 1). If one takes into account the excess noise factor, the slope is therefore higher than 2. This gives an opportunity to quickly estimate the APD quality in terms of F . If the slope is near to 2 then F is “small”, and if the slope is larger than 2, F is “high”. In addition, if the slope is equal or higher than 2, it means that carriers undergo multiplication.

The noise spectral density could be measured by two steps, without or with illumination. In the first case the current measured at the output of the APD, as a function of the reverse bias voltage, is the leakage current I_{dark} . This is composed of the surface leakage current I_S and of the bulk leakage current I_b like:

$$I_{dark} = I_S + M_b I_b, \quad (5)$$

where M_b is the gain of the bulk current I_b . This gain could be different from the gain measured under illumination. Injection of generated primary carrier could be dominated by holes or by electrons (see Fig. 1). The noise spectral density under illumination is then measured at the same reverse bias voltage. The total current measured is the sum of the dark current and the photocurrent I_{ph} due to illumination. The photocurrent noise spectral density $S_{I_{ph}}$ versus I_{ph} is calculated from the difference between the total noise under illumination and the dark current noise (assuming that $S_{I_{ph}}$ and $S_{I_{dark}}$ are uncorrelated).

3 Measurement set-up

3.1 Devices

All external sources of noise must be carefully avoided in the setup¹⁾. As is shown in Fig. 2, the APD is biased by a set of electric battery in order to avoid noise coming from the DC power supply (50 Hz), and is directly connected to a Brookdeal current amplifier. The gain of this amplifier can be set to 10^8 , 10^6 and 10^4 V/A with a bandwidth of 1 kHz at the maximum gain. Noise of the APD plus the current amplifier will be considered in the next subsection. Voltage signal is sent to a digital spectrum analyser from ANRISTU MS430A (DC-10 MHz). This digital spectrum analyser uses a 12 bits converter and calculates the Fourier transform of the signal by means of an FFT algorithm. To increase the accuracy of the noise spectral density measurement, an average of 256 spectra is performed by the digital spectrum analyser. It is then possible to obtain the noise spectral density in A^2/Hz by using a PC-computer (up to 100 kHz). The voltage signal given by the current amplifier is also sent to a DC voltmeter in order to measure the continuous component of the signal which is proportional to the current delivered by the APD under the test. At high gain, the current preamplifier has a limited bandwidth (see Fig. 4). The measurement is therefore performed at low frequency (~ 1 kHz to 100 kHz). In addition, this region of analysed frequency gives an opportunity to detect some defects in APDs linked to the technics (contact, interface etc.).

The continuous light source for the noise measurement is a broad band tungsten halogen lamp filtered by a interferometric filter at a wavelength of 492 ± 10 nm. The stability of light is very high (better than $\pm 1\%$ [1]) and its fluctuation have no effect on APDs noise measurement.

There are no control and monitoring of the temperature during the measurement. But as we try to measure not the gain of APDs but the excess noise factor, a very good stability of temperature is not needed because we can consider that the multiplication noise is linked with the total current delivered by the APDs, which defines at that time the gain. It is nevertheless desirable to measure the noise and the signal delivered by APDs in relative short time to have the smallest variation of temperature between the two measurement. (The measurement room is nevertheless air-conditionned at $21^\circ C$).

Figure 2: Measurement setup.

¹⁾ Installed at Centre d'Electronique de Montpellier

3.2 Noise consideration

We suppose that the open loop transfer function of the amplifier is (see Fig. 3):

$$A(s) = \frac{-A}{1 + \tau s}. \quad (6)$$

Figure 3: Electrical preamplifier scheme.

Typical values are $A \simeq 2 \times 10^5$ and $\tau = 1.6 \times 10^{-3}$ s. It can be shown that [7]:

$$\frac{V_{out}}{I_{det}} = \frac{-A(s)}{\frac{A(s)-1}{Z_f(s)} - \frac{1}{Z_{in}(s)}}, \quad (7)$$

$$Z_{in} = \frac{R_{in}}{1 + sC'_{in}R_{in}}, \quad (8)$$

where $C'_{in} = C_a + C_{det}$. C_a is the input capacitance of the amplifier without feedback. In our measurements, the detector capacitance C_{det} is larger than the input capacitance of the amplifier. ($C_a \sim 2$ pF and $C_{det} > 30$ pF). The feedback impedance is:

$$Z_f(s) = \frac{R_f}{1 + sC_fR_f}. \quad (9)$$

If we define C_{in} as $C_{in} = C'_{in} + C_f = C_a + C_{det} + C_f$, then the overall transfer function is:

$$\frac{V_{out}}{I_{det}} = \frac{-R_f \left[\frac{AR_{in}}{(A+1)R_{in}+R_f} \right]}{1 + s \left[\frac{\tau(R_{in}+R_f)+R_{in}R_f(C_{in}+AC_f)}{(A+1)R_{in}+R_f} \right] + s^2 \left[\frac{\tau R_{in}R_fC_{in}}{(A+1)R_{in}+R_f} \right]}. \quad (10)$$

This is a second order transfer function which can exhibit a bump in its frequency response (See Fig. 4 on PSpice simulation). For a given C_{det} and R_f , it is possible to adjust C_f to have a flat Butterworth frequency response. In our measurements, we use the flat part of the frequency response in order to get the noise power spectral density.

Now taking into account the noise of such current amplifier, the noise formula (in A^2/Hz) is given by:

$$i_{nt}^2 = i_{ndet}^2 + \frac{4kT}{R_f} + i_{np}^2 + e_{ns}^2 \left[(2\pi f)^2 (C_{det} + C_a + C_f)^2 + \frac{1}{R_f^2} \right]. \quad (11)$$

Typical values are $i_{np}^2 = 2.25 \times 10^{-30}$ A^2/Hz and $e_{ns}^2 = 64 \times 10^{-18}$ V^2/Hz . In the case of APD, $i_{ndet}^2 \gg i_{np}^2$ and $C_{det} + C_a + C_f \simeq C_{det}$. At a frequency of 1 kHz, $R_f = 10^7 \Omega$ and $C_{det} = 30$ pF, the values for each component in the equation (11) are:

$$i_{nt}^2 = \underbrace{i_{ndet}^2}_{2qI_{det}} + \underbrace{\frac{4kT}{R_f}}_{1.66 \times 10^{-27}} + \underbrace{i_{np}^2}_{2.25 \times 10^{-30}} + \underbrace{e_{ns}^2 \left[(2\pi f)^2 (C_{det} + C_a + C_f)^2 + \frac{1}{R_f^2} \right]}_{2.9 \times 10^{-30}}. \quad (12)$$

Figure 4: Frequency response of the current amplifier for different values of R_f .

It is clear that the predominating term in comparison to the noise of the APD (i_{ndet}^2) is $4kT/R_f$. All the other terms are negligible. During the measurement, we just need to subtract the noise (due to the feedback resistance) which depends on the gain of the current amplifier. From the point of view of noise, the feedback resistance acts like an equivalent leakage current of the detector given by $2qI_{det} = 4kT/R_f$. See table (1).

R_f in Ω	$4kT/R_f$ in A^2/Hz	Equivalent leakage current of the detector
10^4	1.66×10^{-24}	$5 \mu A$
10^6	1.66×10^{-26}	$50 nA$
10^8	1.66×10^{-28}	$0.5 nA$

Table 1: Noise spectral density of R_f and equivalent leakage current of the detector.

4 Experimental results

4.1 Hamamatsu APD (S5345, low capacitance type)

The noise spectral density of the dark current versus the dark current is shown in Fig. 5, where the Schottky noise part is clearly seen (slope $2qI$). The first points are not on the $2qI$ line. This is probably due to the flicker noise of the setup. We also observe more or less a straight line with a slope equal to 2.10 of amplified dark current. The value of the slope is near to two which means that the dark current is amplified with a small excess noise factor.

Shown in the Fig. 6 is the noise spectral density of the Hamamatsu low capacitance APD versus the photocurrent in a log-log scale. For this measurement, due to the lower limitation of APD bias voltage (at least 10.2 V), it was not possible to reach the shot noise region ($2qI$). All the points measured are in the region of amplification (slope greater than two). To calculate the excess noise factor from $S_{I_{ph}}$, we need to know the values of the primary photocurrent. Due to short time allowed for this measurement, we don't have enough data to perform a reliable measurement of it. We therefore use our previous data [1] (gain versus bias voltage) to estimate the primary photocurrent. The excess noise

Figure 5: Noise spectral density of Hamamatsu APD without illumination.

factor is then given by:

$$F = \frac{S_{I_{ph}}}{2qI_{inj}M^2}. \quad (13)$$

The new result shown in Fig. 7 is in good agreement with the previous one.

4.2 EG&G APD (C30626 type)

The Fig. 8 shows the dark noise spectral density of this EG&G APD. We see clearly the $2qI$ noise (no amplification) and also another straight line with a high slope of 15.4. It means that this slope is due to the amplification of holes generated in the π region. For this APD, the leakage current is mainly a surface current which does not undergo multiplication. The noise spectral density in that case is given by:

$$S_{I_{ob}} = 2q(I_s + I_b M_b F_b). \quad (14)$$

The noise due to the surface leakage current is typically a Schottky noise. So the noise due to the bulk leakage current becomes predominant when the slope of the curve in the log-log scale becomes higher than one. At a bias level of 285 V, the value of the slope is approximately 15, which means that the excess noise factor for the bulk leakage current (F_b) is about 13. The gain¹⁾ of the bulk leakage current, calculated by the ratio between the leakage current measured at 285 V and the value of the “primary leakage current” given by the interception of the two straight lines (see Fig. 8), is about one. It is then possible to assume that the noise spectral density of the bulk leakage current becomes predominant when $I_b \simeq I_s/F_b = I_s/13$.

The high value of the excess noise factor, starting at a bias level of 285 V, will probably deteriorate the signal to noise ratio for low level of light signal (this effect will be probably more visible after irradiation due to the increase of the bulk leakage current).

¹⁾ Gain of the bulk leakage current (M_b) is different from the pure gain of the holes amplification (M_h).

Figure 6: Noise Spectral density of Hamamatsu APD under illumination.

Figure 7: Excess noise factor with spectral and with histogram method.

Figure 8: Noise spectral density of EG&G APD without illumination.

The EG&G APD is a reverse reach-through type. The “reach-through” is reached at 160 V bias level which corresponds to the point C in Fig. 9. For higher bias, this device acts like “PIN with gain”. Of course CD is the region of interest and the slope is equal to 2.37 (Slightly higher than the Hamamatsu device). Below “reach through” bias, the device acts like three junctions in serial mode ([1] p. 28). The surprising fact in the region AB is the that the noise spectral density is lower than the $2qI$ noise. We recall that was obtained with continuous light, but in pulsed mode no signal is observed.

As for the Hamamatsu photodiode, the excess noise is calculated using the measurement of $S_{I_{ph}}$ (from Fig. 9) and the data (gain versus bias) from [1]. Values of excess noise factor, shown in Fig. 10, are in good agreement with the previous one.

5 Conclusion

The initial goal of our collaboration with C.E.M. was to investigate APDs with a different method from those used in high energy physics in order to compare the results. We also wanted to test other methods to see the opportunity to use it in quality control of a large number of APDs. The results found for the excess noise factor (using the gain calibration of [1]) are in good agreement for the two types of APDs (Hamamatsu low capacitance type S5345 and EG&G type C30626E) investigated. In addition, it is easy to obtain values of F for small values of gain as well.

The method of primary photocurrent determination (given by the interception of the “gain slope” with the “ $2qI$ slope”) could not be used with good accuracy. In fact if we use this method, we obtain a large disagreement for the evaluation of the primary photocurrent; about -30% for the Hamamatsu APD and in the case of EG&G APD, the complexity of the curve (see Fig. 9) does not allow us to calculate the reliable value. This is why we propose to make another set of measurements to understand this disagreement.

In addition, the spectral analysis method gives some information on the spectrum from DC to 100 kHz. People in telecommunication field prefers to investigate this part of the spectrum in order to check the quality and the reliability of devices because, in this

Figure 9: Noise spectral density of EG&G APD under illumination.

Figure 10: Excess noise factor with spectral and with histogram method for the EG&G APD.

range of frequency, it is possible to see the noise linked to the technology like flicker noise, popcorn noise and generation-recombination noise [8].

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References

- [1] A. Karar, Y. Musienko, R. Tanaka, J.C. Vanel,
“Investigation of Avalanche Photodiodes for EM Calorimeter at LHC”,
CMS-TN/95-095.
- [2] C. De la Taille,
“Electronique très bas bruit pour détecteur à liquide organométallique”,
Thesis, Ecole Polytechnique, Dec. 1989.
- [3] C. Maille,
“Modélisation à l’obscurité et sous éclaircissement des photodétecteurs à avalanche $N^+\pi P\pi P^+$ au silicium”,
Thesis, Académie de Montpellier, July 1980.
- [4] B. Orsal,
“Analyse numérique des spectres basses fréquences”,
Thesis, Académie de Montpellier, June 1982.
- [5] R. Alabedra, C. Maille, D. Ratsira and G. Lecoy,
“Utilisation des mesures de bruit pour la détermination du photocourant primaire dans des photodiode à avalanche $N^+\pi P\pi P^+$ au silicium”,
Revue Phys. Appl., July 1980, p.1201.
- [6] B. Orsal, M. Decker and R. Alabedra,
“Chaine numérique d’analyse spectrale basse fréquence (1 kHz-1 100kHz) pour la caractérisation des composants opto-électroniques d’extrémité”,
OPTO N° 16, October 1983.
- [7] M. Abraham,
“Design of butterworth-type transimpedance preamplifier”,
IEEE Trans. on Circuits and System N° 6 June 1982 p. 375-382.
- [8] “Noise in physical systems”,
Proceedings of the fifth international conference on noise,
Springer-Verlag, March 13-16, 1978 p. 13-24.