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Low-temperature performance of a large area avalanche photodiode

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Abstract

A Large Area Avalanche Photodiode was studied, aiming to access its performance as light detector at low temperatures, down to $-80°C$. The excess noise factor, F, was measured and found to be approximately independent of the temperature. A linear dependence of F on the APD gain with a slope of 0.00239 ± 0.00008 was observed for gains > 100. The detection of low intensity light pulses, producing only a few primary electron–hole pairs in the photodiode, is reported.

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Keywords: Photodetectors; Excess noise factor; Avalanche photodiode; LAAPD

1. Introduction

Large Area Avalanche Photodiodes (LAAPD) are of great interest for high efficiency detection of low intensity light pulses from scintillators. In spite of some drawbacks, they can compete successfully with photomultiplier tubes (PMT) in many applications that require very compact detector packaging (in Positron Emission Tomography, for instance), low sensitivity to magnetic fields (as in some space applications and accelerator experiments) or low intrinsic radioactivity as required for the low background experiments (e.g., dark matter search). Very good time and energy resolutions have been achieved with LAAPDs with various scintillators, namely inorganic crystals [1,2] and liquid xenon [3].

Operation at low temperature can be not only a necessity, as in the case of liquid xenon [3], but also a favorable option. In fact, to operate the LAAPD at low temperature has two advantageous effects: (1) the dark current noise decreases dramatically, (2) the voltage required to achieve a certain gain becomes lower. In our previous work [4], both effects were investigated as a function of the temperature between 25°C and −100°C.

In a detector with a LAAPD readout, the noise and the fluctuations of the avalanche gain contribute to the energy resolution of the system. The later is usually expressed in terms of the excess noise factor, F [5]. Previous measurements of the energy resolution in liquid xenon excited with alpha-particles [3],

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indicated a value of F significantly larger than that usually reported for room temperature.

In this paper, we report on measurements of the excess noise factor as a function of the gain at low temperatures (down to $-80°C$). The results of observation of very low intensity light pulses that produce only a few primary electron–hole pairs in the photodiode are also presented.

2. Experimental set-up

In our measurements we used a windowless LAAPD, 5 mm in diameter, from Advanced Photonix, Inc. [6]. This photodiode, manufactured using beveled-edge technology, has low dark current and relatively small capacitance (typically, about 30 nA and 25 pF, respectively, at room temperature and a gain of 200).

The set-up used for the measurements is schematically depicted in Fig. 1. The APD connected to a low-noise charge sensitive preamplifier (Cremat CR-101D) was mounted inside a metallic cage and placed into a liquid nitrogen cryostat.

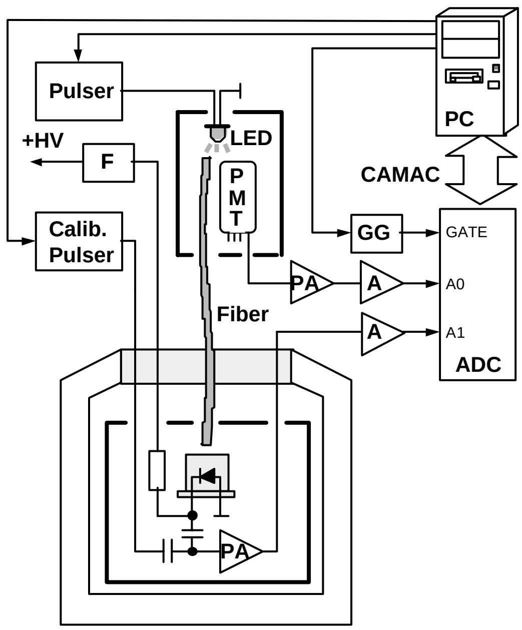

Fig. 1. The experimental set-up for studying the low-temperature performance of APDs: PA—charge sensitive preamplifier; A—spectroscopy amplifier; GG—gate generator; F—RC filter.

Light pulses of 0.5 μs in duration were produced by a green LED driven by a pulse generator. The LED was mounted in a black box outside the cryostat and optically connected to the APD through an optic fiber. The intensity of light pulses generated by the LED was monitored by a PMT (Hamamatsu R1668). The output signal of the APD was amplified by a charge sensitive preamplifier followed by a spectroscopy amplifier (Canberra 2021). Semigaussian shaping with shaping time of 1 μs was used. The amplified and shaped signals from both the APD and the PMT were digitized by a peak ADC (LeCroy 2259B) and stored in a PC-based multichannel analyzer. The PC also controlled the LED and calibration pulsers and, synchronously, provided a gate for the ADC. The linearity, amplification, pedestal (offset) and the electronic noise of the whole spectrometric channel were measured using calibration pulses from a high precision pulser fed to the input of the preamplifier through a capacitance of 2.4 pF. The calibration was verified by observing the pulse height spectrum due to direct conversion of 60 keV γ-rays (from an ^{241}Am source) in the photodiode at unitary gain.

For precise measurement of the excess noise factor it is very important to maintain the stability of the APD gain during the acquisition. This requires stable bias voltage and temperature as the gain strongly depends on both of them, especially at high gain values.

In our measurements, the stability of the bias voltage was better than 0.1 V. To reduce the ripples from the HV power supply (CAEN N471), an RC-filter with a time constant of 1 s was used. The variations of the temperature were measured with a precision of 0.02°C using a platinum thermoresistor fixed directly on the photodiode. During the acquisition of a single data point, the temperature variation did not exceed 0.2°C.

3. Experimental methods and results

3.1. Measurement of gain

For each value of the bias voltage, the amplitude distribution of the APD charge signals was recorded. The gain was then found as the ratio of the mean amplitude found from the distribution to that measured at low voltage ($V_{bias} = 400\,V$), where the gain is unitary [7]. Some results are plotted in Fig. 2.

3.2. Measurement of excess noise factor

In an avalanche photodiode, the random character of the multiplication process of the electron–hole pairs under an electric field introduces the so-called multiplication noise, which is characterized by the excess noise factor, F, defined as

$$F = \frac{\langle m^2 \rangle}{\langle m \rangle^2} = \frac{\langle m^2 \rangle}{M^2} \quad (1)$$

where m is the gain of an avalanche in the photodiode and $M = \langle m \rangle$ [8].

By considering the statistical nature of the avalanche formation, it was shown that F can be approximated to

$$F \approx k_{\text{eff}} M + \left(2 - \frac{1}{M}\right)(1 - k_{\text{eff}}) \ \text{for}\ M \gg 1 \quad (2)$$

where k_{eff} is the effective ionization rate ratio [9].

The fluctuations of the amplitude of the charge signal of an APD illuminated with light pulses can be expressed as [5]:

$$\frac{\sigma^2}{A^2} = \left(\frac{\sigma_n}{MN_0}\right)^2 + \frac{F-1}{N_0} + \delta^2 \quad (3)$$

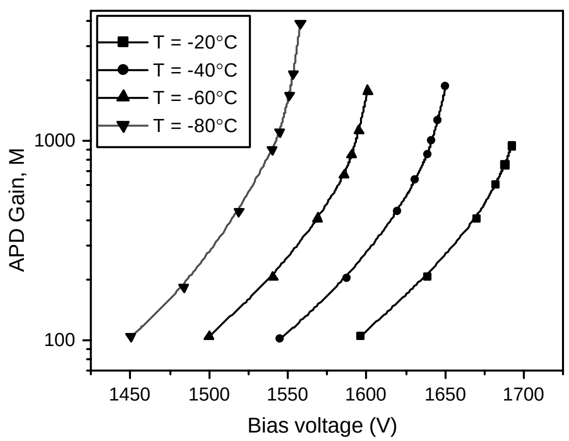

Fig. 2. Dependence of the APD gain on the bias voltage at different temperatures.

where $A \equiv MN_0$ is the average amplitude of the pulses at the photodiode output expressed in number of electrons, N_0 the average number of primary electron–hole pairs created by a single light pulse, σ^2 the variance of the signal amplitude distribution (in number of electrons), σ_n the electronic noise at the input of the preamplifier (r.m.s. in number of electrons), and δ^2 is the relative variance in N_0 and can be written as

$$\delta^2 = \frac{1}{N_0} + \varepsilon^2 \quad (4)$$

where ε^2 includes all the non-Poisson contributions to the fluctuations in N_0. In the present measurements, the contribution to ε^2 is only due to the fluctuations of the intensity of the light source and the gain non-uniformity in the photodiode. Replacing Eq. (4) in Eq. (3), one gets

$$\sigma^2 = \sigma_n^2 + M^2 N_0 F + \varepsilon^2 M^2 N_0^2. \quad (5)$$

If the light source is stable and the fluctuations due to the gain non-uniformity are not relevant such that $\varepsilon \ll \sqrt{F/N_0}$, the last term in Eq. (5) can be neglected (in our measurements, the lowest value of $\sqrt{F/N_0}$ is obtained at $F \approx 2$ and $N_0 \approx 5000$, which gives $\varepsilon \ll 0.02$) and the excess noise factor determined from the expression:

$$F = \frac{\sigma^2 - \sigma_n^2}{M^2 N_0} \quad (6)$$

or, more conveniently,

$$F = \frac{\sigma^2 - \sigma_n^2}{M^2 N_0^2} N_0 = \frac{\sigma^2 - \sigma_n^2}{A^2} N_0. \quad (7)$$

For measuring the excess noise factor, the amplitude distribution of the APD output signals, as well as the distribution of the calibration pulses, were acquired for different values of the gain. A typical pulse height spectrum is shown in Fig. 3. From these distributions, the following values were determined: σ^2 and A as the variance and the mean of the APD signal distribution and σ_n^2 as the variance of the distribution of the calibration pulses. The value of N_0 was measured at $M = 1$ as the mean charge signal amplitude expressed in number of electrons. In the beginning of each run, N_0 was set approximately to 4000 e and was kept constant as long as the output signal did not saturate the preamplifier. Then, the amplitude of

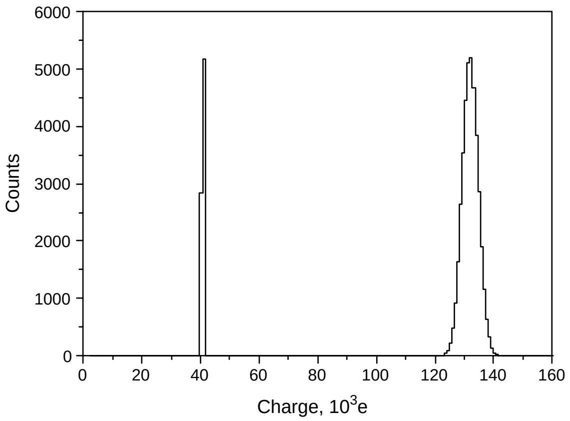

Fig. 3. A typical pulse height spectrum due to the LED (at the right) and calibration pulses (at the left). The horizontal axis shows the charge at the preamplifier input. Temperature is $-60°C$, APD gain is 33, $N_0 = 4000$ electrons.

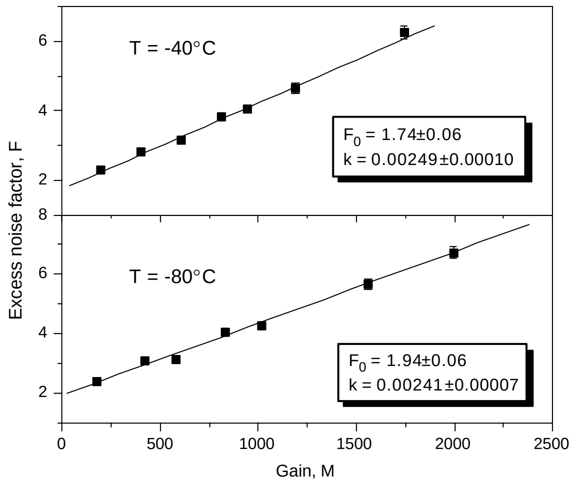

Fig. 4. Dependence of the excess noise factor on the APD gain at $-40°C$ and $-80°C$. The straight line $F = F_0 + kM$ is fitted to the experimental results with F_0 and k as adjusted parameters.

the light pulse was decreased and a new value for N_0 was calculated from the ratio of PMT signals.

These measurements were carried out for gains up to 2000 in the temperature range from 0°C down to $-80°C$. The results for $-40°C$ and $-80°C$ for $M > 100$ are represented in Fig. 4, as examples. In all the cases, the excess noise factor increases linearly with gain, i.e.,

$$F = F_0 + kM. \tag{8}$$

No temperature dependence of F_0 and k was observed within the experimental errors (Fig. 5). Averaging the values of F_0 and k obtained by fitting the data for different temperatures with Eq. (8), one gets $F_0 = 1.87 \pm 0.02$ and $k = 0.00239 \pm 0.00008$. These results are consistent with those presented in Ref. [10].

Fig. 6 shows the electronic noise, σ_n, as a function of the APD gain for different temperatures. For $T \leqslant -40°C$ and $M \geqslant 5$, the noise is approximately constant and ≈ 250 electrons (r.m.s.). At higher temperatures ($T = -20°C$), the noise increases dramatically for large gains due to the increase of the dark current.

3.3. Low-intensity signal detection

The reduction of the dark current at low temperature allows the detection of light signals

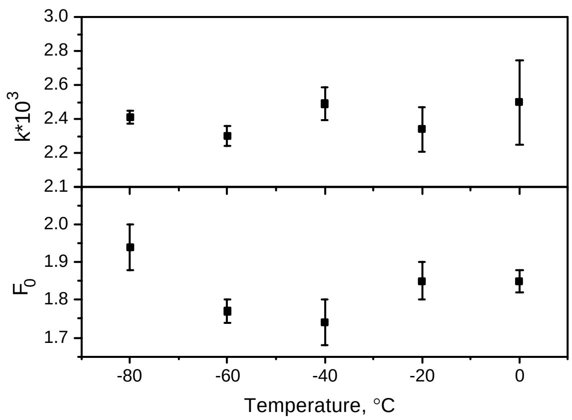

Fig. 5. F_0 and k obtained at different temperatures.

of very low intensity, which produce just a few primary electron–hole pairs in the photodiode. In Fig. 7, it is shown the spectrum corresponding to $N_0 = 4.3$, N_0 being the mean number of electron–hole pairs per light pulse (we observed similar spectra for N_0 varying from 3 to 7 electron–hole pairs). For these measurements, the light pulse amplitude was set initially rather high and N_0 was measured with the APD at $M = 1$. Then, the light intensity was reduced and N_0 re-calculated using the PMT signals as reference.

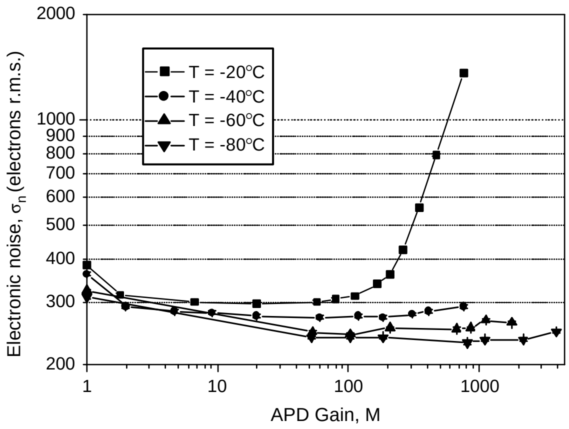

Fig. 6. Dependence of the electronic noise at the preamplifier input on the APD gain and temperature (the preamplifier was connected to the APD).

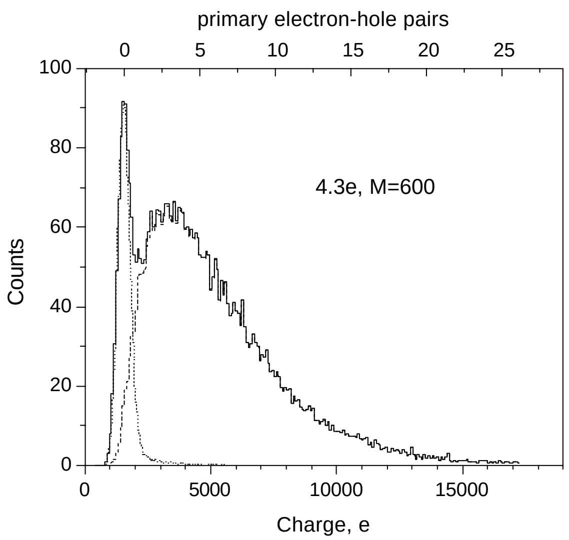

Fig. 7. A spectrum of the APD output signals corresponding to a mean number of primary electron–hole pairs equal to 4.3. Temperature is $-40°C$, APD gain is 600.

To avoid possible non-linearity in the first channels of the ADC, an offset was added by sending a test pulse of fixed amplitude and duration to the preamplifier input simultaneously with the light pulse. The value of the offset was equivalent to 1500 electrons at the photodiode output. Hence, the broad pulse distribution in Fig. 7 corresponds to the offset light pulses while the sharp peak at the left is due to the test pulses only and is acquired with the LED turned off. The upper axis in Fig. 7 was scaled to the number of primary electron–hole pairs by dividing the charge measured at the photodiode output by the APD gain, M. Similar spectra were observed in Ref. [10].

4. Conclusions

The excess noise factor of a LAAPD was measured as a function of gain and temperature. For the APD gains >100, it was found to be linear with gain and practically independent on temperature in the range from $0°C$ down to $-80°C$. The amplitude distributions of the signals with the average number of primary electron–hole pairs as small as 3 to 7 were measured, thus showing the possibility of detection of very low intensity light pulses.

Acknowledgements

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