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The gain, photon detection efficiency and excess noise factor of multi-pixel Geiger-mode avalanche photodiodes

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Abstract

In this work we propose a method to characterize multi-pixel Geiger-mode (MPGM) avalanche photodiodes (APDs) and present systematic studies of new devices from three different manufacturers. The basic properties of MGPM APDs such as gain, photon detection efficiency, excess noise factor and noise, as well as their dependence on operating voltage have been measured. Spectral response was measured in the range 350–800 nm. It was shown that despite very good pixel-to-pixel gain uniformity, the excess noise factor of these APDs can be significantly greater than 1.

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Keywords: Silicon avalanche photodiodes; Light detection; Pixellated detectors

1. Introduction

Recently developed multi-pixel Geiger-mode avalanche photodiodes (MPGM APDs [1–3]) are very promising candidates for many HEP, astrophysical and medical applications [4]. They have many advantages over conventional photosensors (such as photomultiplier tubes (PMTs), APDs and normal photodiodes) because of their compact size, low power consumption, high gain, reasonably high QE in the green and red regions of the optical spectrum, non-sensitivity to magnetic field, etc. However, the measurement techniques for characterization of these devices have not been well developed. In this work we propose a method to characterize MPGM APDs and present systematic studies of new devices from three different manufacturers.

2. MPGM APDs studied

For this paper we have studied the performance of three MPGM APDs which were developed by three different groups.

The APDs from MEPhI/PULSAR and Center of Perspective Technologies and Apparatus (CPTA) are both based on the n^+-p-p^+ structure. They have 1 mm^2 sensitive area, which is subdivided into 576 (MEPhI/PULSAR) and 556 (CPTA) separate pixels, respectively. Each of these pixels is quenched by an individual resistor.

The structure of these APDs was optimised for green-red light detection. In the case of the CPTA devices, pixels are separated by grooves, which are filled with an optically non-transparent material. This is a new development based on the structure described in Refs. [2] and [5]. The third device (from Dubna) is made on an n-type silicon substrate. It has a 0.5 mm^2 sensitive area, which is subdivided into 10,000 separate avalanche regions-micro-wells (for more details see Ref. [6]). The structure of this APD was optimised for the blue-UV part of the light spectrum.

3. Dependence of gain and photon detection efficiency on the bias voltage

One can assume that the MPGM APD gain is equal to the charge (Q_1) stored in a pixel capacitance when a single pixel is fired [2,4]:

$$Q_1 = C_{\mathrm{pix}}(V - V_{\mathrm{B}}) \qquad (1)$$

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where C_{pix} is the equivalent pixel capacitance, V is the APD operating voltage and V_{B} is its breakdown voltage.

However, it was found [7] that light emitted during the pixel breakdown penetrated adjacent pixels due to optical cross-talk and fired these pixels. Thus the average number of pixels fired by a primary photoelectron is typically more than 1. Then the real APD gain (M_{APD}) is equal to the charge Q_1 multiplied by the average number of fired pixels (N_{pix}):

$$M_{\text{APD}} = N_{\text{pix}} Q_1. \tag{2}$$

Fig. 1 shows a single electron spectrum (SES) of the MEPhI/PULSAR APD measured at reduced temperature (with the MPGM APD placed inside a commercial freezer). The "pedestal" events were carefully subtracted from this plot. The green LED ($\lambda = 515\,\text{nm}$) pulse amplitude was reduced to the level of $\ll 1$ photon/pulse using neutral density filters.

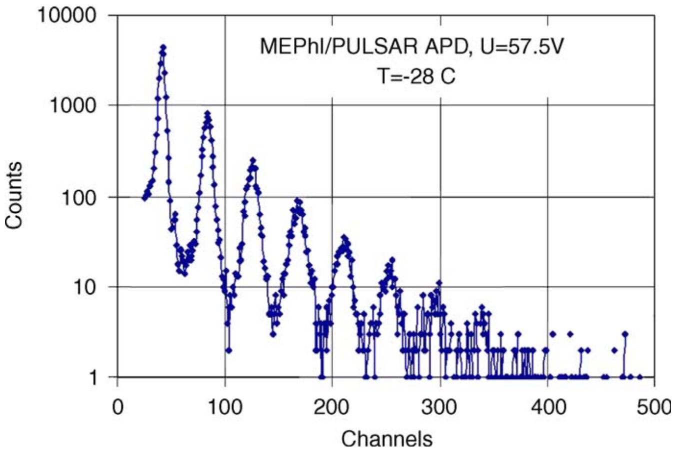

Fig. 1. Single electron spectrum of the MEPhI/PULSAR APD.

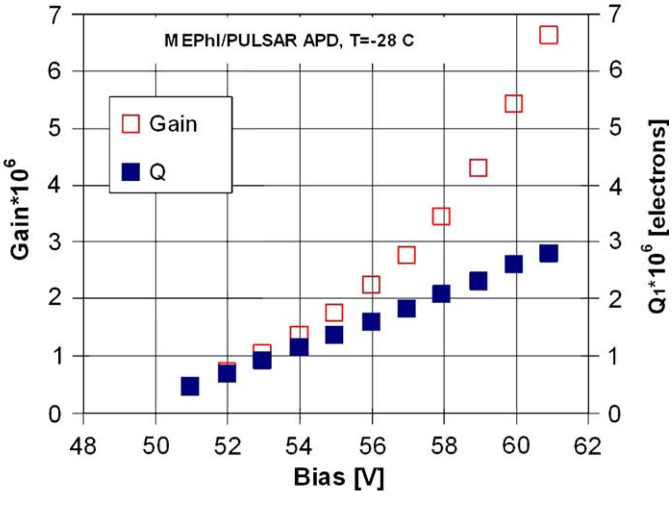

Fig. 2. Gain and Q_1 of the MEPhI/PULSAR APD as a function of voltage measured at $T = -28\,^\circ\text{C}$.

From Fig. 1 one can see that there is a significant probability that 2 or more pixels are fired by an absorbed photon. From the measurements of the SES at different voltages one can calculate the MPGM APD gains, corresponding to these voltages. Fig. 2 shows the MEPhI/PULSAR APD gain and Q_1 charge as a functions of the bias voltage measured at $T = -28\,\text{C}$. One can see that at $U = 61\,\text{V}$ the average number of fired pixels is more than 2.

The gain of the MPGM APD can also be measured in a different way. The charge Q measured by the ADC in response to the LED pulse is related to the MPGM APD gain by:

$$Q = N_{\text{pe}} G_{\text{amp}} M_{\text{APD}} \tag{3}$$

where N_{pe} is the number of photoelectrons and G_{amp} is the gain of the amplifier.

If the APD noise is small, the measured low light LED amplitude spectra (see, for example, Fig. 1 from Ref. [8]) can be compared with the Poisson distribution and the mean, N_{pe}, can be calculated using the well-known property of this distribution:

$$N_{\text{pe}} = -\ln(P(0)). \tag{4}$$

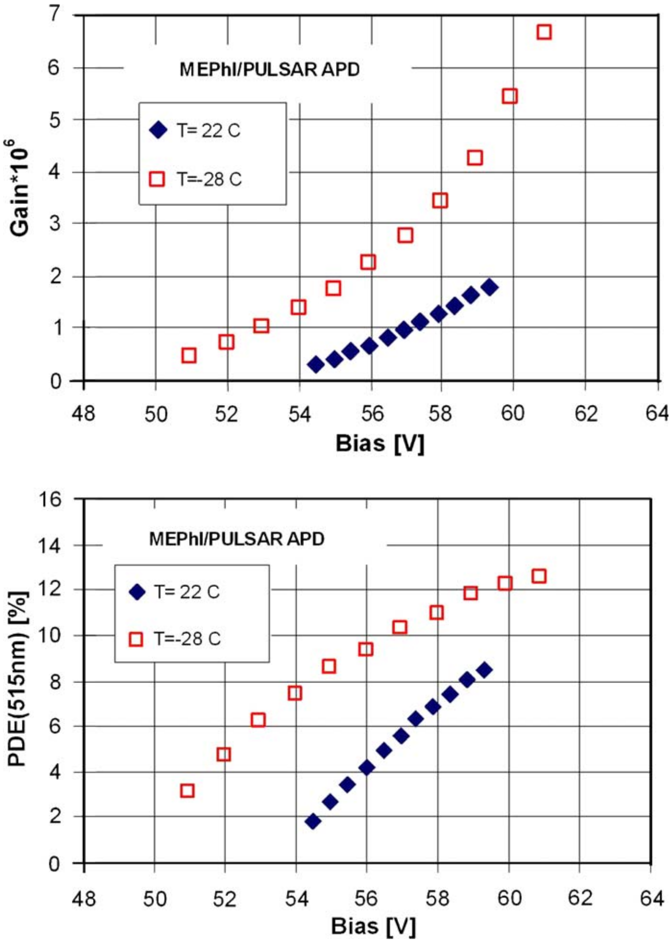

Fig. 3. Gain (top) and PDE (bottom) as a function of voltage for the MEPhI/PULSAR APD measured at two temperatures.