JOURNAL OF OPTOELECTRONİCS AND ADVANCED MATERİALS Vol. 9, No. 4, April 2007, p. 810 - 813

Excess noise in silicon avalanche photodiodes

F. KOÇAK, I. TAPAN*
Department of Physics, Uludag University, 16059, Bursa, Turkey

The mean avalanche gain and the excess noise factor are important parameters characterizing the performance of an Avalanche Photodiode. These parameters vary with electric field strength and the position of the primary electron-hole pairs generated in the APD depletion layer. In the present paper, the mean avalanche gain and the excess noise properties have been investigated for the Hamamatsu S8148 APD structure for different distribution of photo-generated electron-hole pairs in the depletion region. Calculations were made with a Single Particle Monte Carlo simulation technique. Based on this work, the performance of the Hamamatsu S8148 APD as a photodetector for the $PbWO_4$ scintillation light has been discussed.

(Received November 2, 2006; accepted February 28, 2007)

Keyword: Avalanche photodiodes, Monte Carlo simulation, Gain, Excess noise

1. Introduction

Hamamatsu S8148 Silicon Avalanche Photodiode (APD) structure, working in proportional mode has been chosen as photodetector for the lead tungstate ($PbWO_4$) crystals in the barrel of the CMS electromagnetic calorimeter (ECAL) at the Large Hadron Collider at CERN [1]. The ECAL of the detector will be a hermetic full energy calorimeter [2] made of 61,200 $PbWO_4$ crystals mounted in the central ‘‘barrel’’ part, closed by 7324 crystals in each of the two end-caps [3]. The $PbWO_4$ crystals emit light in the wavelength region of 320 nm to 600 nm peaking at around 420 nm as shown in Fig. 1.

APDs have the big advantage that they can be produced in standard fully automated processes and therefore can be cheap, that they can be tailored to individual needs in a short time of few months and they open new areas of applications because of their low mass and their very small space consumption [4]. In addition APDs have the advantages of an high quantum efficiency and internal gain; moreover they are able to operate in a strong magnetic field and high radiation levels [2]. The gain is, however, accompanied by excess noise that arises from the randomness of the avalanche multiplication process. The quantum efficiency, gain and the excess noise factor are important parameters for the energy resolution of the crystal-APD system [5].

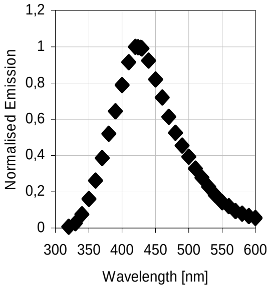

Fig. 1. $PbWO_4$ emission spectrum as a function of wavelength.

2. APD Structure and Quantum Efficiency

The Hamamatsu APD type S8148 is a silicon avalanche photodiode that consists of successive layers of p^+, p, n, n^- and n^+-type silicon layers, as shown in Fig. 2. Here w is the depletion region in which is established an electric field. On either side of the depletion region are quasi-neutral diffusion regions. They extend over a distance from the boundaries of the depletion region that is of the order of a diffusion length for the minority carriers. The depletion region is divided into a low field drift region and a high field avalanche region. One where photo-generated charge carriers are created and then drift into the narrow avalanche region where avalanche multiplication takes place. The p-n junction of the device, where the avalanche gain takes place, is located around 5 μm from the light entry surface to minimize the sensitivity to ionizing radiation. The n^- layer was introduced to increase the thickness of the depletion region. This decreased both the capacitance and the sensitivity of the gain to changes in the applied bias. The 30 μm deep V- shaped grooves around the cathode were found to be necessary to reduce surface currents, especially important after the APD has received a large radiation dose [1,6].

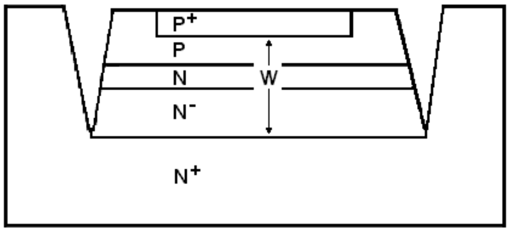

Fig. 2. Hamamatsu S8148 Silicon APD structure.

The effective quantum efficiency of an APD when operating without internal gain, expressed in terms of the number of electrons out per photon in. It depends on the position of the photo-conversion point, on whether this is inside or outside the depletion region. Fig. 3 shows the effective quantum efficiency as a function of wavelength for the APD structure.

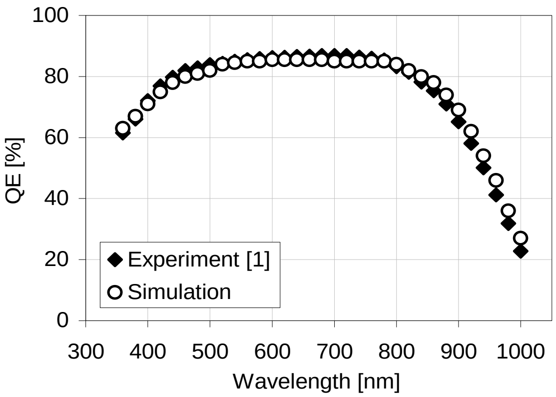

Fig. 3. Quantum efficiency variation with wavelength for the S8148 APD structure.

The quantum efficiency is 72% for the emission of $PbWO_4$ crystals at 420 nm and reaches more than 80% at wavelengths between 500 and 900 nm. It has lower values at shorter wavelengths less than 450 nm. At these wavelengths the photon absorption coefficient in silicon is considerably high, as shown in Fig. 4, and so photo-absorption and electron–hole pair production take place earlier, mostly in the p+ layer. From such conversions the minority carriers, the electrons, can reach the depletion region via much slower diffusion processes.

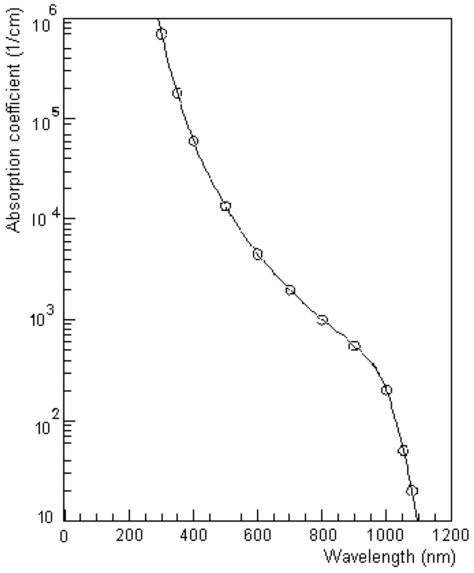

Fig. 4. Optical absorption coefficient versus wavelength for silicon [7].

3. APD contribution to the energy resolution

The ECAL performance is expressed in terms of the energy resolution which is parametrised by the following quadratic sum,

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E} \tag{1}$$

where $\oplus$ denotes a quadratic sum, a is the stochastic term, b is the constant term, c is the noise term and E is the energy per incident particle. The APD contribution to the stochastic term is due to the photo-electron statistics that depend on the sensitive area and the quantum efficiency of the APD, and avalanche gain fluctuation. The deterioration of the stochastic term in the energy resolution due multiplication noise can be significant if the light yield, coming from the calorimeter, is relatively small as is the case for $PbWO_4$ crystal, for example. In this case, by neglecting the intrinsic resolution, the stochastic term for the CMS ECAL can be expressed as follows [5]:

$$\left(\frac{\sigma}{E}\right)^2 = \frac{F}{N} \tag{2}$$

where N is the number of primary photo-electrons which depends on the APD quantum efficiency, E is the energy per incident particle and F is the excess noise factor of the APD.

Avalanche gain is defined as the ratio of the number of charge carriers which pass between the contact electrodes to the number of photo-carriers generated initially. Excess noise factor is a measure of the avalanche gain fluctuations. Random fluctuations in the distance traversed by carriers between successive ionizing collisions give rise to fluctuations in the total number of secondary charge carriers generated for each primary photocarrier entering into the high-field avalanche region. The avalanche gain and its fluctuations are the same for any charge-carrier entering into the highfield avalanche region that has been generated optically outside it and the excess noise is given by

$$F = 1 + \frac{\sigma_M^2}{M^2} \tag{3}$$

where M is the avalanche gain and σ_M is the avalanche gain fluctuation. According to the model developed by McIntyre, the excess noise factor is a function of the ratio $k = \alpha_h / \alpha_e$, where α_h and α_e are the ionization coefficients for holes and electrons. This theory assumes that the region of the gain is very long, or, equivalently, that the number of ionizing collisions per primary carrier transit is very large, and that the electric field is more or less uniform in the avalanche region [5]. The values of α_h and α_e, along with the length of the field region and the carrier-injection conditions, determine the magnitude of the avalanche gain. For the charge carriers injected into the avalanche region, the excess noise factor (when the multiplication is initiated by electrons) is given by [8]

$$F = k_{eff} M + (2 - 1/M)(1 - k_{eff}) \tag{4}$$

For $M > 10$

$$F = 2 + k_{eff} M \tag{5}$$

$$k_{eff} \approx k = \alpha_h / \alpha_e$$

The k ratio and thus the excess noise factor is a strong function of the electric field profile across the high-field avalanche region. For the APD structure, the behavior of the excess noise factor F versus the mean avalanche gain M without the generation of dark current is illustrated in Fig. 4 with k as a parameter [9]. F takes lower values at the same mean avalanche gains in the silicon APDs which have wider avalanche region and lower electric field in it.

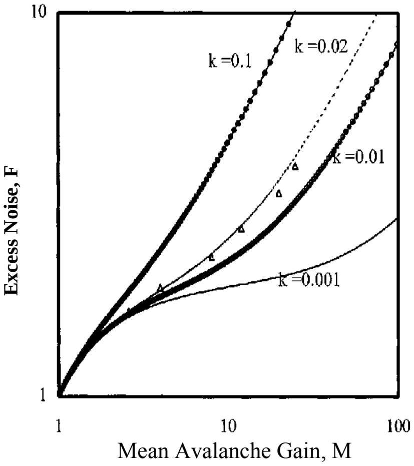

Fig. 5. Variation of excess noise factor as a function of mean avalanche gain at different k values.

Excess noise factor is the same for any photo-carrier entering into the avalanche region that has been generated outside it. Some of the incident photons may penetrate sufficiently far to be absorbed in the avalanche region. The absorption in the avalanche region decreases the avalanche gain, because there is a shorter path across the high field within which the avalanche may develop. These instances of reduced gain lead to additional gain fluctuation σ_{MA} and cause an increase of the excess noise factor which is now given by [10]

$$F^* = F + \frac{\sigma_{MA}^2}{M^2} \tag{5}$$

4. Simulation and results

Simulation has been performed by using Single Particle Monte Carlo technique[11] in order to see the variation of the gain in the Hamamatsu S8148 APD structure for an indiviual incident single photons in the wavelength region of 360 nm to 800 nm. Fig. 6 and Fig. 7 show the simulated avalanche gain and excess noise as a function of wavelength for the APD structure, with the same avalanche gain of 50. It is clear that photons with shorter wavelengths of less than 500 nm will be fully absorbed before the avalanche region and generated carriers will all have the same multiplication value and excess noise factor. At shorter wavelengths of less than 500 nm, the excess noise factor was obtained as 2. This value corresponds well to the experimental measurements at a gain of 50 [1].

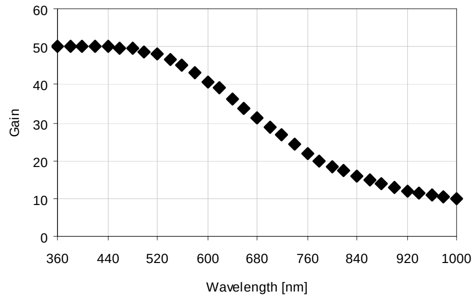

Fig. 6. Gain variation versus wavelength.

As the photons absorption length in silicon increases with the wavelength, the incident photons with wavelengths longer than 500 nm will be absorbed not only before the avalanche region but also partly inside and even behind it [12]. Therefore, the mean avalanche gain is seen to be smaller for the longer wavelength photons, causing an increase of the excess noise factor as indicated in Section 3. The variation of the excess noise versus wavelength is consistent with the simulation result presented by Pauchard et al. [13].

Simulation shows that the Hamamatsu S8148 APD has been optimised for the photons with around the peak wavelength of the $PbWO_4$ emission spectrum. In the case of the entire emission spectrum of $PbWO_4$ crystal, as one part of the $PbWO_4$ photons in the wavelength region of 320-450 nm cause a decrease of the N_i, the other part of them in the wavelength region of 520-600 nm cause an increase of the F for the S8148 APD structure.

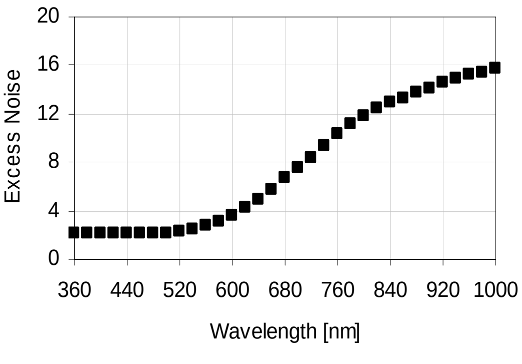

Fig. 7. Excess noise variation versus wavelength.

5. Conclusions

The investigations of the APD made by Hamamatsu Photonics have shown that this APD is well-suited for the electromagnetic calorimeter of CMS. They have an excess noise factor which is close to the theoretical limit.

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*Corresponding author: ilhan@uludag.edu.tr