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Investigation of Shot Noise in Avalanche Photodiodes

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$PbWO_4$ crystal-Hamamatsu S8148 avalanche photodiode (APD) assembly has been used in the barrel section of the CMS electromagnetic calorimeter. The shot noise of the photodiode is one of the important parameters for the energy resolution of the crystal-APD system. The major source of this noise is the statistical variations in the rate at which primary charge carriers are generated and recombine. Thus, the shot noise varies with position of the primary charge carriers generated in photodiode. In this work, the shot noise properties of the Hamamatsu S8148 APD structure and zinc sulfide-silicon (ZnS-Si) isotype heterojunction APD structure have been compared for the $PbWO_4$ photons. Calculations were made with a Single Particle Monte Carlo simulation technique.

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1. Introduction

The scintillation light detection using crystal-avalanche photodiode (APD) system is an important technique in high-energy physics experiments. As an example, Hamamatsu S8148 silicon APD working in proportional mode has been chosen as readout device 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 performance of the $PbWO_4$ crystal-APD combination depends on the light intensity of the crystal and the noise of the photodetector. The noise of the APD contains the avalanche gain fluctuation (excess noise) and the shot noise. The aim of this work is to compare the shot noise contribution to signal fluctuations for the Hamamatsu S8148 APD and a zinc sulfide-silicon (ZnS-Si) isotype heterojunction APD structures.

2. APD limitation to the energy resolution

The energy resolution of a detector based on the APD readout strongly depends on statistical limitation determined by the shot noise and the excess noise. The shot noise or quantum noise arises from the statistical nature of generation-recombination of the primary charge carriers. As stated by Miyamoto and Knoll [2], the relative fluctuation of the mean signal in the proportional mode operation can be expressed as follows,

$$\left(\frac{\sigma_s}{S}\right)^2 = \left(\frac{\sigma_N}{N}\right)^2 + \frac{1}{N}\left(\frac{\sigma_M}{M}\right)^2, \tag{1}$$

where M is the APD gain, N is the number of primary charge carriers which are electron and hole pairs, σ_N is the standard deviation of the primary charge carriers and σ_M is the standard deviation of the single charge gain. The APD excess noise factor, F, is used instead of the fluctuations in the avalanche gain:

$$F = 1 + \sigma_M^2/M^2. \tag{2}$$

Then the statistical fluctuation of the signal from the APD, Eq. (1), can be rewritten as

$$\left(\frac{\sigma_s}{S}\right)^2 = \left(\frac{\sigma_N}{N}\right)^2 + \frac{(F-1)}{N}. \tag{3}$$

For the light pulse detection the fluctuation of primary charge carriers, (σ_N/N), and the excess noise factor, F, vary with position of the primary charge carriers generated in the APD. The excess noise factor of the APD was investigated in our previous work [3]. Single Particle Monte Carlo simulation code was developed in order to determine the gain and the excess noise factor as a function of wavelength for the APD structure at a constant gain value of 50. The emission weighted APD excess noise factor was calculated as 2.2 for the $PbWO_4$ emission spectrum [4]. Now, we are focused on the fluctuation of primary charge carriers.

3. Structures of the investigated APDs

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. An electric field is established in the depletion region. 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. Charge gain is obtained in the avalanche region by accelerating the primary photocarriers in a high electric field so that they acquire energy greater than the threshold needed to generate secondary charge carriers by impact ionisation. The properties and working principles of the structure were given in [5, 6].

The photon detection mechanism for an APD can be explained as follows [7]. Electron-hole pairs are generated by the absorption of incident photons. The electrons and holes separate as they drift in opposite directions in an electric field. The majority carriers will recombine while the minority carriers may drift to the avalanche region

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(unless the pair creation has in fact occurred within the avalanche region). In the high field of the avalanche region, the charge carriers will gain energy and they may produce further charge by impact ionisation. They may on the other hand be lost by recombination. The surviving charge carriers are carried from the avalanche region by drift and diffusion to become majority carriers in the n-or p-type layer and collected by contact electrodes. The fluctuation of primary charge carriers depends on the position of the photo-conversion point, on whether this is inside or outside the depletion region. The spatial distribution of photon absorption inside the APD follows an exponential law. For shorter wavelength photons less than 450 nm, the absorption coefficient in silicon is considerably higher and so photo absorption and electron-hole pair production take place earlier, mostly in the p^+ layer in the Hamamatsu S8148 APD structure. In this region the impurity concentration is high and there is essentially no electric field, so the generated photoelectrons almost all recombine. Any absorption of light in this region has a negative effect on the number of primary charge carriers.

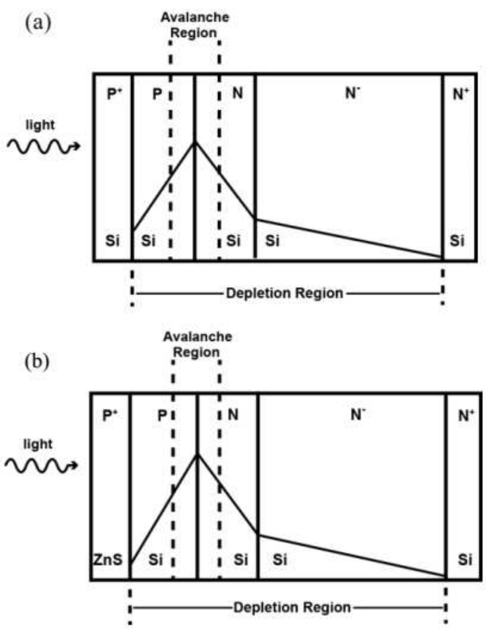

Fig. 1. Sketches of the Hamamatsu S8148 silicon APD structure (a) and the ZnS-Si APD structure (b).

APD noise can be significant if the light yield, coming from the calorimeter, is relatively small as is the case for the $PbWO_4$ crystal, for example. In order to keep the energy resolution reasonably high, high-quantum efficiency, low excess noise factor and low shot noise factor in the region of the $PbWO_4$ photons are needed for the APDs. For this reason, a zinc sulfide-silicon (ZnS-Si) isotype heterojunction APD structure has been developed [8]. Absorption before the depletion region was eliminated by making p^+ region transparent to the incident light. The ZnS has been chosen as surface layer for the transmission of incident light into the Si depletion layer. Figures 1a and b show the Hamamatsu S8148 APD structure chosen by the CMS and the ZnS-Si APD structure, respectively. The electric field distributions in the depletion regions can be seen for these structures.

4. Simulation and results

The primary charge carrier generation process was simulated by tracking a large number of individual incident photons and following the generated charge carriers in well-defined Hamamatsu S8148 APD and ZnS–Si APD geometries using a Single Particle Monte Carlo technique [7]. In the Monte Carlo method for device simulation, the motion of particles is spatially restricted in a device model. The boundary of the regions depends on temperature, doping concentrations and applied bias voltage. The numerical solution of the Poisson equation gives the electric field variation in the depletion region.

The $PbWO_4$ crystals chosen for the ECAL of the CMS detector emit scintillation photons in the wavelength region from 320 nm to 600 nm peaking at around 420 nm. For this reason, simulation has been performed in order to compare the Hamamatsu S8148 and the ZnS-Si APD structures for incident photons up to 600 nm. 1000 incident photons were sent to the APD structures and the mean number of primary charge carriers, N, and its fluctuation σ_N/N, were calculated and plotted in Figs. 2a and b, respectively.

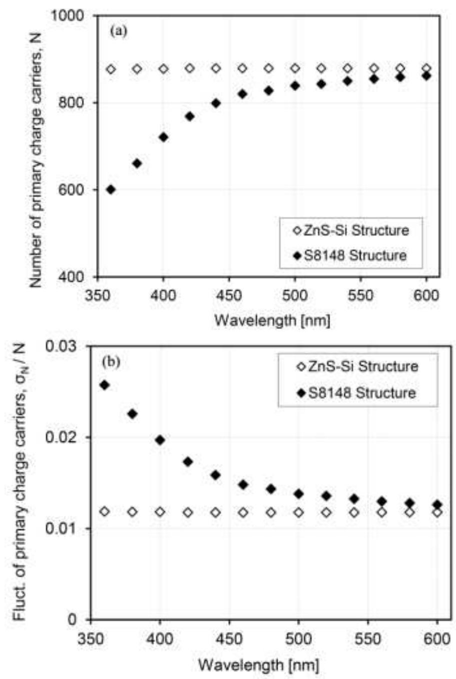

Fig. 2. Number of primary charge carriers as a function of wavelength for both the Hamamatsu S8148 and the ZnS-Si APD structures (a). Fluctuations in the number of primary charge carriers as a function of wavelength for two APD structures (b).

The loss of photoelectrons by recombination in the p^+ is significant at shorter wavelengths. The simulation shows that, a part of the $PbWO_4$ photons up to 500 nm are absorbed in the p^+ surface layer of the Hamamatsu S8148 APD structure. This causes a decrease of the N and an increase of the primary charge carriers fluctuation or the shot noise.

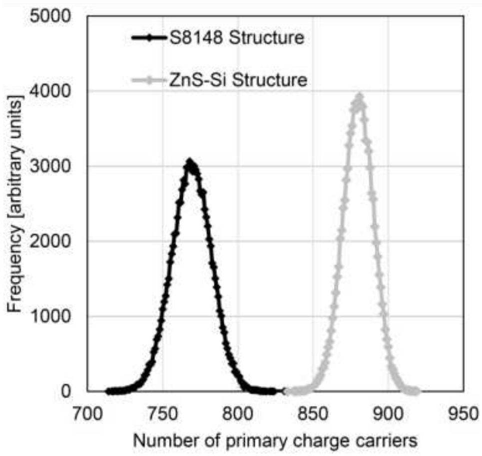

Fig. 3. Primary charge carriers distributions for both the Hamamatsu S8148 and the ZnS-Si APD structures.

For the ZnS-Si APD structure, incident photons easily penetrate ZnS surface layer and create electron-hole pairs in the depletion layer. Thus the resultant number of primary charge carriers is the bigger as well as the smaller fluctuation. Figure 3 shows the simulated number of primary charge carriers distributions of two different APD structures for 1000 incident photons at 420 nm which is the peak wavelength of the $PbWO_4$ crystals. As the mean number of the primary charge carriers is 769 and its fluctuation is 0.017 for the S8148 APD, these values are 879 and 0.012 for the ZnS-Si APD structure. Signal fluctuation values for 1000 incident photons have been obtained using Eq. (3) for two different APD structures and are shown in Fig. 4. The results are similar to that obtained for single particles in [8].

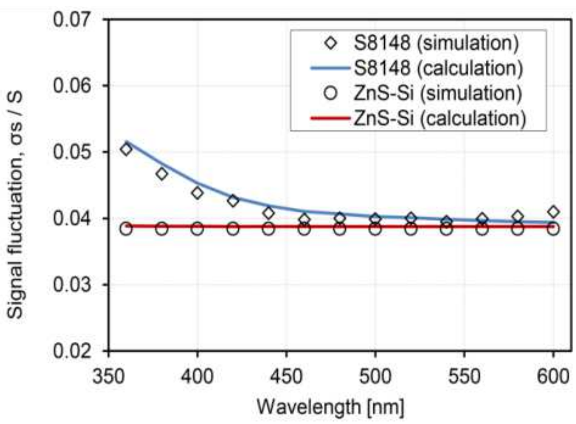

Fig. 4. Signal fluctuations for two APD structures.

5. Conclusions

Increase in fluctuation of the number of the primary charge carriers, or shot noise, corresponds to an increase in the signal fluctuation. This gives a negative effect on the ECAL energy resolution. Thus low shot noise makes the ZnS-Si APD structure a good choice for $PbWO_4$ light detection.

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