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Avalanche photodiodes for electromagnetic calorimeters

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Abstract

Hamamatsu S8148 silicon avalanche photodiode (APD) working in proportional mode has been chosen as readout device for the $PbWO_4$ crystals in the barrel of the CMS electromagnetic calorimeter (ECAL). High hadron fluences strongly affect the main parameters of both the scintillation crystals and the silicon detectors. In this work, we offer a new zinc sulfide–silicon (ZnS–Si) isotype heterojunction APD structure that is able to operate in high-radiation levels. A Monte Carlo simulation code has been performed in order to compare the Hamamatsu S8148 and the ZnS–Si APD structures for the photons emitting from $PbWO_4$ crystal during 10 years of CMS operation. Based on this work, the performance of these two APD structures has been investigated.

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Keywords: Avalanche photodiodes; Monte Carlo simulation; Radiation damage

1. Introduction

The CMS electromagnetic calorimeter (ECAL) [1] is a homogenous scintillating crystal detector designed for high precision energy measurement of photons and electrons. The $PbWO_4$ crystals used for the ECAL emit light in the wavelengths from 320 to 600 nm peaking at 420 nm.

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

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

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, as well as on the avalanche gain fluctuation or excess noise factor (F). In order to keep the stochastic term of the energy resolution reasonably low, high-quantum efficiency and low excess noise factor in the region of $PbWO_4$ light emission are needed for the APDs [2]. For this reason, a zinc sulfide–silicon (ZnS–Si) isotype heterojunction APD structure has been developed [3]. Fig. 1 shows the variation of quantum efficiencies for the Hamamatsu S8148 APD structure [4] chosen by the CMS and the ZnS–Si APD structures.

The neutron exposure of the APDs in the ECAL is estimated to be about $2 \times 10^{12}\,\mathrm{n/cm^2/year}$ of the CMS operation. This causes a degradation of the performance of the ECAL.

2. Radiation damage on APDs

A detailed understanding of all radiation damage effects on APD performance is necessary. The results of such effects on Hamamatsu S8148 APD were reported in Refs. [5,6]. This paper reports an investigation of the radiation damage in the ZnS–Si APD structure.

By high energetic neutrons irradiation, atoms are displaced from their equilibrium position in a crystal. These displaced atoms cause a change in the effective doping concentration. As the magnitude of the electric field in the detector depletion region is related with the effective doping concentration, high neutron fluences would affect the APD properties [7].

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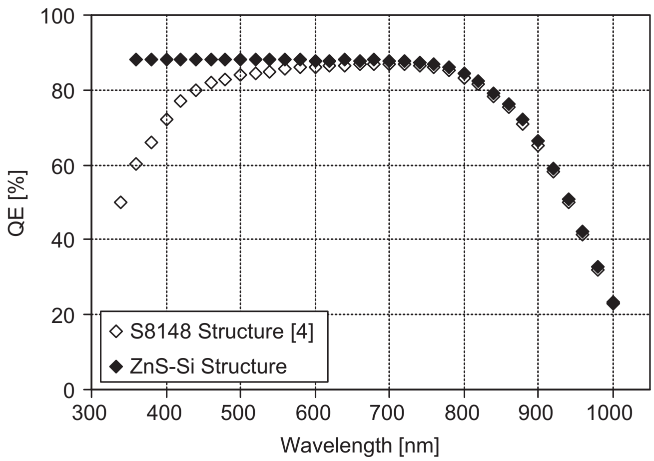

Fig. 1. Quantum efficiency as a function of wavelength for both the S8148 and the ZnS–Si APD structures [3].

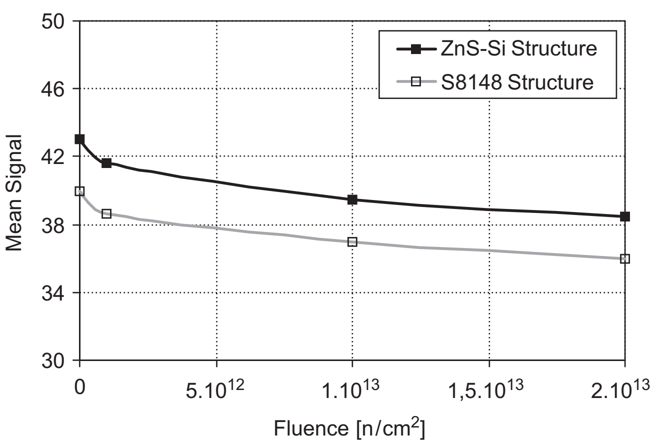

Fig. 2. Signal variation as a function of irradiation for two APD structures.

Studies showed that ZnS is very effective at trapping charge, so neutron-induced permanent degradation become more important than displacement damage. Both electrons and holes could be trapped in the ZnS depending on the applied bias voltages. At higher voltages for a gain value of 50, the net-trapped charge is only a few percent of the total charge in the ZnS [8].

3. Simulation and results

The signal generation process was simulated by tracking a large number of individual incident photons and following the generated charge carriers in well-defined APD geometries using a Single Particle Monte Carlo technique [9]. The simulation code included radiation damage both in the $PbWO_4$ crystals and APD structures

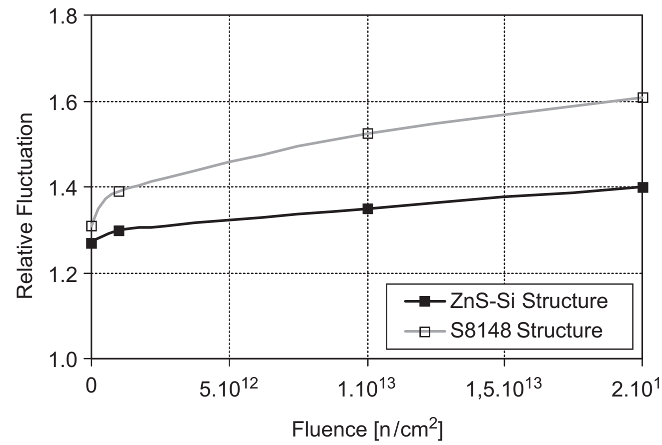

Fig. 3. Relative fluctuation in the signal as a function of irradiation for two APD structures.

for neutron fluences up to $2 \times 10^{13}\,\mathrm{n/cm^2}$ (1 MeV equivalent).

Simulation has been performed in order to compare the Hamamatsu S8148 and the ZnS–Si APD structures for incident $PbWO_4$ photons at a constant gain value of 50. The mean signal values, S, and the relative fluctuations in the signals, σ_S/S, were calculated and plotted in Figs. 2 and 3, respectively, at the different neutron irradiation rates during ten years of CMS operation.

When a particle with energy E creates a signal, then the relative precision of the calorimetric measurement of the energy σ_E/E can be given by the relative fluctuation in the detector signal σ_S/S [10]. Increases in the signal fluctuation, σ_S/S, correspond to an increase in σ_E/E. Low radiation damage makes the ZnS–Si APD structure an excellent photo-detector for the $PbWO_4$ scintillation light detection in CMS ECAL.

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