Wavelength Dependence of Avalanche Photodiode (APD) Parameters

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Abstract

New types of Hamamatsu avalanche photodiodes (APD) have been investigated for the readout of $PbWO_4$ crystals. The results presented cover quantum efficiency measurements of APD prototype A-E, which is passivated by a SiO_2 layer or a Si_3N_4 layer, before and after exposure to a 5.5 Mrad dose of ^{60}Co photons. The measurements of the gain and of the excess noise factor as a function of the wavelength are also presented and compared to analytic calculations based on a simple model for the internal APD structure.

This work was performed within the frame of the CMS ECAL group.

1 Introduction

Avalanche photodiodes (APD) are foreseen for the readout of the $PbWO_4$ crystals chosen for the electromagnetic calorimeter of the CMS [1] detector at the LHC. $PbWO_4$ emits its scintillation light in the wavelength region of 400 nm to 550 nm. It is a birefringent scintillator with relatively low lightyield (50 $\frac{photons}{MeV}$) and a refractive index of n=2.2. Therefore a readout device with an internal gain, a high quantum efficiency and a high refractive index of the surface layer is needed.
The measurements were performed with 6 different types of APDs developed by Hamamatsu (S5345 low capacity version, prototype A-B, A-C, A-E, A-G, A-H).

2 Quantum efficiency

The quantum efficiency is mainly determined by the light loss due to reflection at the APD surface and absorption in the passivation and protective layers. Surface damage is expected from the exposure to gamma radiation. The quantum efficiency measurements were carried out with APD A-E which has a SiO_2 (n=1.5) or a Si_3N_4 (n>1.68) passivation layer. The results (figure 1) show that the quantum efficiency for the Si_3N_4 passivated APD is higher than that for the SiO_2 passivated one. The APDs were exposed to a

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5.5 Mrad dose of ^{60}Co photons (10x the expected CMS lifetime dose). Both kinds of layers are not radiation hard, but the quantum efficiency decrease after gamma-irradiation is less for the Si_3N_4 passivated APD. Remeasuring the irradiated APDs two months later shows a small recovery for the SiO_2 passivated APD and a total annealing of the Si_3N_4 passivated device.

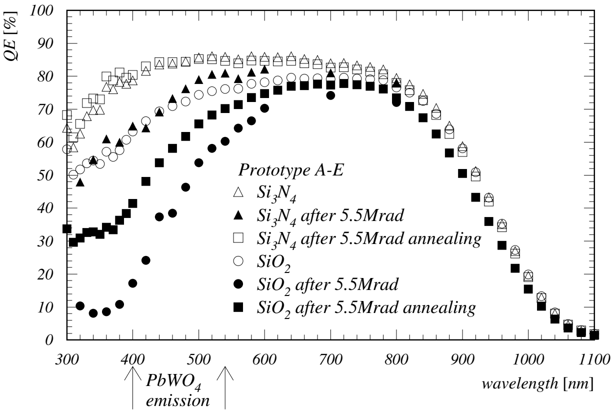

Fig. 1. Quantum efficiency of APDs with different passivation layers before and after gamma-irradiation and annealing.

3 Excess Noise Factor and Gain

The APD consists of a conversion layer followed by the avalanche region (p-n junction) and an intrinsic layer to reduce the capacitance of the device. The thickness of the conversion layer is important for the nuclear counter effect. This is reduced with very thin conversion layers, but leads to an increase of the wavelength dependence of the excess noise factor which describes the statistical fluctuations of the avalanche cascade inside the multiplication region and is an important parameter for the energy resolution of the crystal-APD system. The conversion layer thickness can be determined by measuring the gain as a function of the wavelength. For light absorbed before the avalanche region the gain is constant. The gain decreases for light absorbed inside the avalanche region. By normalizing the measured gain values it is possible to define a limiting wavelength above which light is absorbed inside the avalanche region (figure 2). The thickness of the conversion layer d_{conv} of the investigated APDs is shown in table 1. For light absorbed before the avalanche region, the excess noise factor is defined as $F = 1+\frac{\sigma^2_{M_S}}{M^2}$ where M is the gain and σ_{M_S} the respective fluctuation. The absorption of light inside the avalanche region leads to additional gain fluctuations. Under the assumption of a constant electric field in the avalanche region of width W, the gain M can be calculated to be $M = e^{\alpha(W-x)}$ where α is the ionisation coefficient and x the longitudinal position. The light absorption inside the APD follows an exponential law $N(x) = N_0 \cdot e^{(-k\cdot x)}$ where k is the absorption coefficient. The additional fluctuations can then be calculated analytically:

Table 1
Measured thickness of conversion layer.

APD Prototype	d_{conv} (μm)
A-B	1.2
A-C	3.2
A-G	1.2
A-H	1.6
S5345 1995	5.7

$$\frac{\sigma^2_{M_{LA}}}{M^2} = \frac{e^{(-k\cdot d_{conv})}\cdot\left(\frac{2}{(\frac{k}{\alpha}+1)\cdot(\frac{k}{\alpha}+2)} - \frac{e^{(-k\cdot d_{conv})}}{(\frac{k}{\alpha}+1)^2}\right)}{\left(1-\frac{e^{(-k\cdot d_{conv})}}{(\frac{k}{\alpha}+1)}\right)^2}$$

The dominant parameter is the thickness of the conversion layer d_{conv}. The excess noise factor is then $F^* = F + \frac{\sigma^2_{M_{LA}}}{M^2}$. Measurements of the excess noise factor as

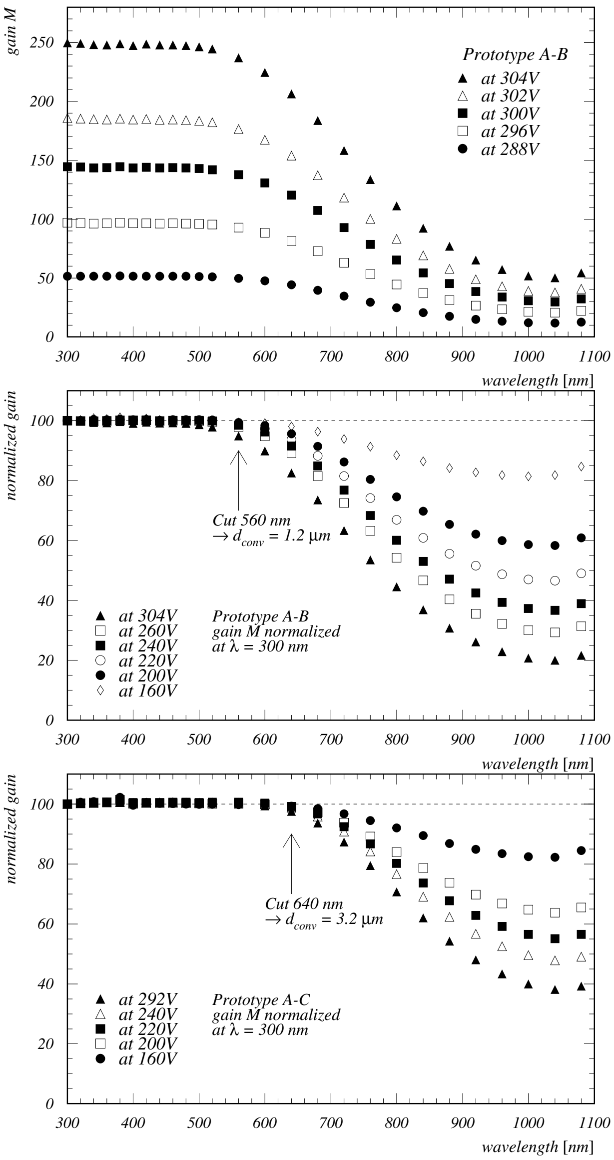

Fig. 2. Wavelength dependence of APD gain. Determination of the thickness of the conversion layer d_{conv} by normalizing the gain.

a function of the wavelength are in good agreement with this simple model (figure 3), which predicts an increase of the wavelength dependence of the excess noise factor for thinner conversion layers.

4 Conclusion

The investigation of Hamamatsu APDs showed that the Si_3N_4 passivated APDs

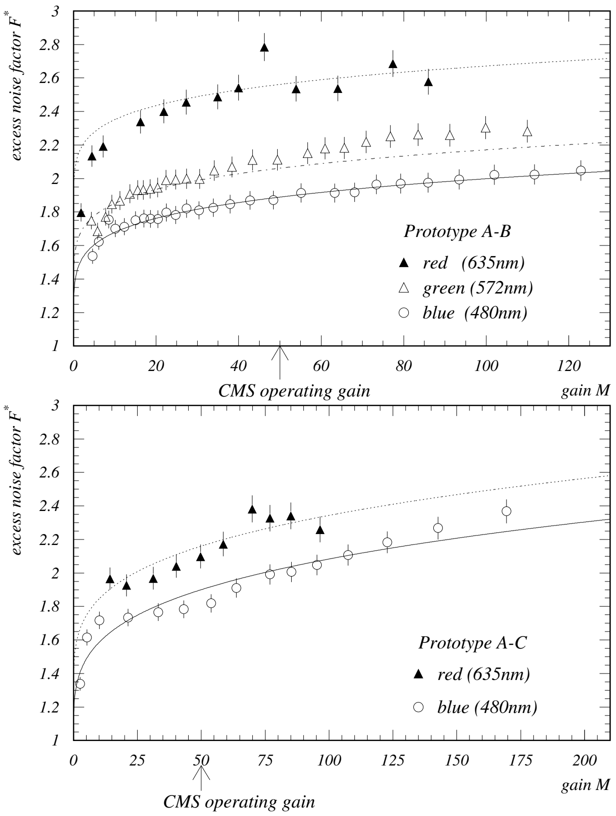

Fig. 3. Excess noise factor for different wavelengths compared to analytical calculations.

have a high quantum efficiency ($\approx$ 80%) in the wavelength region of $PbWO_4$. After exposure to a 5.5 Mrad dose of ^{60}Co photons a decrease of the quantum efficiency by 15% was observed in this wavelength region. After a time period of two months the irradiated APD recovered totally.
A reduction of the thickness of the conversion layer increased the wavelength dependence of the excess noise factor and the gain of the APD. Measurements and analytic calculations based on a simple model are in a good agreement.

References

[1] *Technical Proposal of CMS Collaboration*, CERN/LHCC 94-38, LHCC/P1, 15 December 1994, p. 49-72