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Characterization of the Hamamatsu S8664 avalanche photodiode for X-ray and VUV-light detection

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ABSTRACT

We present the first operation of the VUV-sensitive avalanche photodiode (APD) from Hamamatsu to xenon scintillation light and to direct X-rays of 22.1 keV and 5.9 keV. A large non-linear response was observed for the direct X-ray detection. At 415 V APD bias voltage it was of about 30% for 22.1 keV and about 45% for 5.9 keV. The quantum efficiency for 172 nm photons has been measured to be $69 \pm 15\%$.

1. Introduction

Avalanche photodiodes (APDs) have proven to be a good alternative to photomultiplier tubes (PMTs) in visible and VUV photon detection [1,2]. They are compact, consume small amounts of power and are simple to operate. APDs present also high quantum efficiency, acceptable gain, insensitivity to intense magnetic fields, resistance to high-pressure environments and low degassing properties. In particular, their low radioactivity contamination is attractive for low background experiments based on xenon (Xe), such as direct dark matter searches (XENON [3], ZEPLIN [4]) and neutrinoless double beta decay search (EXO [5], NEXT [6]), where the radiopurity of the photosensors is of critical importance.

High pressure TPCs based on xenon [6–8] are being considered for the detection of the neutrino-less double beta decay. Gas detectors present several advantages over the liquid option. Gaseous xenon detectors have better intrinsic energy resolution [9] than the liquid and the low density media allows to track the electrons emitted from the double beta decay reducing the background contamination from topological constraints. Previous studies show that the operation of the detector in the so-called electroluminiscence regime allows to obtain resolutions close to the ones from the primary electron fluctuations. Electroluminiscence is achieved by accelerating the primary electrons in the xenon to an energy that produces scintillation light without entering into the charge amplification regime. This technique is well established for xenon with photomultipliers [10] and APD [11] readouts. In this paper we evaluate the performance of the Hamamatsu S8664-SPL Avalanche Photodiode sensor. This APD is a special version of the standard product, made sensitive to xenon (172 nm) and argon (128 nm) scintillating light. The APD is available in two different sizes (5×5 mm^2 and 10×10 mm^2). The small size of the sensor allows to explore the possibility of using this technology for energy measurement and tracking when laying them as an array of sensors with independent readouts [12].

In this paper we present an independent measurement of the quantum efficiency for 172 nm photons for these devices and a measurement of their response to direct X-rays of 22.1 keV and 5.9 keV. Although there are some applications of APDs to direct X-ray detection, e.g. Ref. [13], X-ray detection with APDs was mainly investigated to measure the charge carriers produced in light measurements, using the number of charge carriers produced by the X-ray interaction in the APDs as a reference, resulting in a straight forward process to evaluate the number of charge carriers produced in the APD by the light pulse. This method has been

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extensively used to measure the scintillation yield in inorganic crystals [14] and in noble gases [15], as well as to determine the quantum efficiency of APDs [16–18]. However, non-linearities in the APD response to X-rays have to be taken into account. This effect has been studied for the standard S8664 type APDs [19–21]. Therefore, the non-linear response to X-rays has to be investigated for a full characterization of the present type of photodiodes.

2. Experimental setup

Fig. 1 depicts the schematic of the gas proportional scintillation counter (GPSC) used in this work. The detector body has a cylindrical shape of 14 cm in diameter and 5 cm in height, with a 2 mm aluminized Kapton radiation window. A stainless steel cylinder of 60 mm diameter fixes the Mesh G1, and has multiple perforations on its side surface to increase gas circulation in the drift/absorption region. The radiation window is kept at negative high-voltage HV0, while mesh G1 and its holder are kept at -HV1. Mesh G2 and detector body are grounded. Electrical insulation of the radiation window and the G1 holder is achieved using a machinable glass ceramic, Macor®, glued to the detector body and to the window with a low vapor pressure epoxy. The voltage difference between the detector window and G1 defines the reduced electric field in the absorption/drift region, which is kept at 0.5 V/cm/torr, below the xenon scintillation threshold. The scintillation region is delimited by two planar meshes: G1 and G2. In this GPSC prototype, the absorption/drift region and the scintillation region are 2 cm deep and 1.4 cm deep, respectively. The chamber operation parameters are shown in Table 1. X-rays interacting in the drift region produce a primary electron cloud that drifts toward the scintillation region. Upon crossing the scintillation region, each primary electron produces, in average, a known number of scintillation photons [22]. X-ray interactions in the scintillation region will lead to scintillation pulses with lower amplitudes. These pulses result in a distortion of the Gaussian-shape pulse height distribution with a tail toward the low amplitude region. However, the peak of the pulse height distribution is not altered by this tail. A fraction of the X-rays interact in the APD, producing a pulse height distribution that is independent of the electric fields of the GPSC, depending only on the APD biasing.

3. Method for the Q_{eff} determination

The quantum efficiency of the APD was determined by comparison of the VUV-scintillation pulse amplitudes with those resulting from direct interaction of the X-rays in the photodiodes. We follow here the method established in Ref. [22]. The total number of photons produced is computed from the energy released by the ^{109}Cd gamma ray and the value of

$$N_{\gamma}^{total} = N_{elec} G = \frac{E_{\gamma}}{w_{Xe}} G \tag{1}$$

where G is the gain of the electroluminescence phase, and N_{elec} is the number of primary electrons released by the Xe via ionization. This number is obtained from the average energy needed to produce an electron–ion pair, w, and the total energy of the X-rays, E_{γ}. The photon yield per cm and per bar, Y/p, is given by the empirical formula [22]:

$$\frac{Y}{p}\left[\frac{\text{photons}}{\text{cm bar}}\right] = 140\frac{E}{p}\left[\frac{\text{kV}}{\text{cm bar}}\right] - 116\left[\frac{\text{photons}}{\text{cm bar}}\right]. \tag{2}$$

Here, E/p is the reduced electric field in the scintillation region. The gain G is then given by

$$G = \frac{Y}{p} pd \tag{3}$$

whereby d, the gap between the electroluminescence meshes, is given by the geometry of the detector and p is the operation pressure. For ^{109}Cd, $d = 1.4$ cm, $p = 1.07$ bar and a $E/p = 3.75$ kV/cm/bar, the total number of UV photons produced is about 622 000. The number of photons arriving to the APD, N_{obs}, is derived from the total number of photons emitted in 4π and the solid angle, Ω_{APD}, covered by the sensitive area of the APD

$$N_{obs} = N_{\gamma}^{total} \frac{\Omega_{APD}}{4\pi} T. \tag{4}$$

The solid angle Ω_{APD} and the transparency T of the electroluminescence mesh are estimated from a Monte Carlo program described in Section 5. The quantum efficiency Q_{eff}, defined as the number of free electrons produced in the APD, $N_{e,sci}$, per VUV photon, is then given by

$$Q_{eff} = \frac{N_{e,sci}}{N_{obs}} \tag{5}$$

$$Q_{eff} = \frac{A_{UV}}{A_{XR}} \frac{N_{XR}}{N_{obs}}. \tag{6}$$

Here, A_{UV} and A_{XR} are the peak position of the UV and the direct X-ray peak in the pulse-height spectrum and N_{XR} is the number of

Table 1
Description of the chamber operation parameters.

Parameter	Value
Reduced electric field in drift region	150 V/cm/bar
Reduced electric field in scintillation region	3.75 kV/cm/bar
APD bias voltage	415 V
Gas pressure	1.07 bar

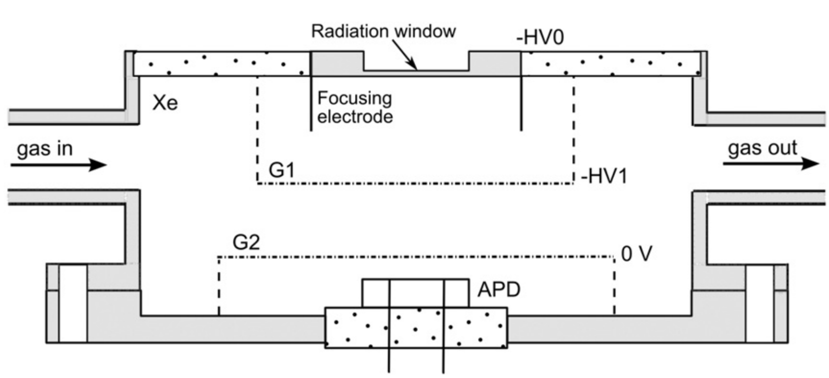

Fig. 1. Schematic drawing of the GPSC used for the EL measurements.