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Study of large area Hamamatsu avalanche photodiode in a γ-ray scintillation detector

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Abstract

We have carried out study of a large area ($10 \times 10\,\text{mm}^2$), reverse-type avalanche photodiode (APD) recently developed by Hamamatsu photonics. It has low dark current of 3 nA at room temperature, and the gain stability was almost the same as prototypical APDs reported in our previous paper. We studied the performance as a γ-ray detector with four scintillators, CsI(Tl), BGO, GSO(Ce), and YAP(Ce) crystals. For example we obtained the best energy resolution of $4.9 \pm 0.2\%$ (FWHM) for 662 keV γ-rays, as measured with a $10 \times 10 \times 10\,\text{mm}^3$ CsI(Tl) crystal. The minimum detectable energy was as low as 10 keV at 20°C and 3.1 keV at −20°C. Thanks to its large effective area, this APD can effectively read out photons from larger size scintillators. When coupling to a $300 \times 48\,\text{mm}^2$ BGO plate of 3 mm thickness, an FWHM energy resolution of $20.9 \pm 0.2\%$ was obtained for 662 keV γ-rays, with the minimum detectable energy of about 60 keV at −15°C. These results suggest that our prototype APD can be a promising device for various applications replacing traditional PMTs such as use in space for Japan's future X-ray astronomy mission *NeXT*.

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1. Introduction

In recent years, avalanche photodiodes (APDs) have attracted considerable attention as X-rays and γ-rays scintillation detectors in nuclear

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physics. Compared with photomultiplier tubes (PMTs), APDs are compact, less sensitive to the magnetic field, and have rugged structures. Moreover, they have an excellent quantum efficiency (QE) ($\geqslant$80%) in the visible and near infrared. In previous works, three types of APDs, beveled edge, reach-through and reverse-type have been intensively studied [1,2], reverse-type APDs are the improved version of reach-through APDs [4]. They have a narrow, high-field multiple region close to the surface, which enables to obtain sufficient internal gain under relatively low bias voltage ($\sim$400 V [12]). In particular, reverse-type APDs have a good advantage of significantly, reducing dark noise, since the thermal electrons do not amplify inside the device. It has also been shown that reverse-type APDs are tolerant of nuclear radiation by CMS calorimeter in CERN [3,11].

In our previous paper, we have reported that Hamamatsu reverse-type APD, S8664-55, works at relatively low bias voltage of 300–350 V and have remarkably low dark current of $\sim$1 nA at room temperature. Their high QE and internal gain allow us to obtain good energy resolutions especially for the low-energy scintillation detection when coupled to CsI(Tl) crystals [5]. For example, the best FWHM resolutions of $9.4 \pm 0.3\%$ was obtained for 59.5 keV γ-rays from a ^{241}Am source. 5.9 keV X-rays were clearly resolved at -20°C with an energy resolution of $32.9 \pm 0.3\%$. In spite of many advantages, APDs have not been used widely because of their small effective area: commercial products of Hamamatsu APDs (S8664-55) have surface of $5 \times 5\,\mathrm{mm}^2$ at the maximum. To increase their effective area facilitates reading out X-rays and γ-rays with larger size scintillators and hence raises new possibilities for further applications.

Recently we have developed larger area, reverse-type APD ($10 \times 10\,\mathrm{mm}^2$) with Hamamatsu photonics. In this paper, we study the basic properties and performance as a γ-ray scintillation detector. In Section 2, we evaluate its basic parameters, such as gain stability and an excess noise factor. In Section 3 we examine the performance as a scintillation detector coupled with four small scintillators, CsI(Tl), BGO, GSO(Ce), and YAP(Ce) crystals. As an application, we use this APD to read out a large BGO plate scintillator ($300 \times 48\,\mathrm{mm}^2$; 3 mm thickness), which we plan to use for Japan's sixth X-ray astronomy mission *NeXT* (New X-ray Telescope) to effectively reject background γ-ray/particle events. Finally, we summarize our results in Section 4.

2. Properties of Hamamatsu APD: S8664-1010N

We have made two samples of large area ($10 \times 10\,\mathrm{mm}^2$) APD with Hamamatsu photonics (S8664-1010N). This APD is developed on the technical base of S8664-55 ($5 \times 5\,\mathrm{mm}^2$), except that the dead layer of S8664-1010N is thinner than that of S8664-55 [5]. These APDs have a narrow multiple region close to the front of the device, with a peak field only 7 μm deep. The Si wafer is placed on a ceramic board and the surface is coated with epoxy resin. The basic parameters of S8664-1010N are shown in Table 1. At a gain of 50, the leakage current is as low as 2.4/3.4 nA at 20°C and decreases to 52/60 pA at -20°C. The detector capacitance is 266/268 pF, which is about three times larger than that of S8664-55 [5]. The QE is more than 80% between 500 and 830 nm and hence most sensitive at visible and near infrared. The QE decreases at ultraviolet due to absorption by the surface window.

2.1. Gain characteristics

As has been reported in the literatures, gain characteristics of APDs depend both on the bias

Table 1
Parameters of Hamamatsu APD (S8664-1010N: 2 pieces)

Surface area	$10 \times 10\,\mathrm{mm}^2$
Window	Epoxy resin
Dark current I_D[a] (at 20°C)	3.4, 2.4 nA
Dark current I_D[a] (at -20°C)	52, 60 pA
Break-down voltage: V_{brk} (at 25°C)	426, 433 V
Bias: $V_{G=50}$[a] (at 20°C)	376, 381 V
Capacitance: C_{det}[a] (at 20°C)	268, 266 pF
Quantum efficiency	$\geqslant$80% (500–830 nm)
	60% (390 nm, 930 nm)

[a]Measured at a gain of 50.