Nuclear Instruments and Methods in Physics Research A 787 (2015) 38–41

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Performance of ultra-small silicon photomultiplier array with active area of 0.12 mm × 0.12 mm

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ARTICLE INFO

Available online 5 November 2014

Keywords:
SiPM
Silicon photomultipliers
Bulk quenching resistor
Positron emission tomography

ABSTRACT

We report the performance of an ultra-small silicon photomultiplier (SiPM) line array with 7 elements of 0.12×0.12 mm^2 in active area, 0.2 mm in pitch and 120 micro cells in one element. The device features an epitaxial bulk quenching resistor concept, demonstrated high geometrical fill factor of 41% and photon detection efficiency (PDE) of 25.4% in the wavelength region between 430 nm and 480 nm while retaining high micro cell density around 10 000 mm^{-2} and ~3 ns FWHM of dark pulses width; it also demonstrated dark count rate of less than 28.7 kHz, optical crosstalk of the order of 2% to 4%, and excellent photon number discrimination. A 0.15 mm × 1.6 mm × 1.6 mm lutetium yttrium oxyorthosilicate (LYSO) crystal, corresponding to the width, length and height respectively, was successfully coupled to the 1×7 SiPM array for possible ultra-highly resolved positron emission tomography (PET) applications. This novel type of device has advantages particularly for small active area since the performances, such as PDE and response speed is one of the best among SiPMs with similarly high density of micro cells. It may pave a way for this type of SiPM as a promising pixel position sensitive device in imaging sensor applications.

1. Introduction

Silicon photomultiplier (SiPM) is a new generation single photon detector with photon number discrimination capability. It is exactly multiple single photon avalanche detectors (SPADs), with passive quenching resistor usually between 200 kΩ and 1 MΩ, integrated monolithically in a single silicon chip. The SiPMs have outstanding advantages such as high gain, excellent timing resolution, insensitive to magnetic fields, low operating voltage, compactness and convenience for integration, etc. For the SiPM applying in HEP calorimeters and positron emission tomography (PET) as readout of the scintillator detector, high photon detection efficiency (PDE) and large dynamic range are both preferred. However, for most SiPMs now commercially available that employ polysilicon as quenching resistor, the trade-off between the dynamic range and the PDE is a problem [1]. The SiPM with epitaxial bulk quenching resistor is a novel concept which is an alternative solution to this problem [2].

The SiPM with bulk quenching resistor has been developed by NDL successfully that employs the bulk silicon structure as quenching resistor [2]. In the past years, with the optimization of the fabrication technology and structure of the device, its active area has been increased from 0.5×0.5 mm^2 to 1×1 mm^2 and 2.2×2.2 mm^2, the peak PDE has been increased from ~8% to more than 12%, while the micro cell density remains to as large as ~10 000 mm^{-2} and the recovery time remains to as low as ~5 ns [3]. The SiPMs with epitaxial bulk quenching resistor have advantages particularly for small active area since the performances, such as PDE and response speed is one of the best among SiPMs while retaining large number of micro cells adequately. It also paves a way for this type of SiPM as a promising pixel position sensitive device in imaging sensor applications in which smaller area of element means better spatial resolution. In addition, the simple technology for the structure allows low-cost volume production, which will promote the applications of SiPMs in PET and other imaging systems. One to one coupling the device of 2.2×2.2 mm^2 with a 2 mm × 2 mm × 10 mm lutetium yttrium oxyorthosilicate (LYSO) crystal yielded an energy resolution of 11.8% by using radiation sources of ^{137}Cs (662 keV photons) without any high speed preamplifiers [3].

In this manuscript, preliminary results of an ultra-small SiPM in 0.12×0.12 mm^2 with epitaxial bulk quenching resistor are reported, including the dark count rate, the single photon detection, the photon detection efficiency and the dynamic range, etc.

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http://dx.doi.org/10.1016/j.nima.2014.10.068
0168-9002/

2. Experimental

The ultra-small SiPM with epitaxial bulk quenching resistor in this study is a 1×7 line array with pixel elements of $0.12 \times 0.12\ \text{mm}^2$ in active area and 0.2 mm in pitch. There are 120 micro cells in one element with geometrical fill factor of 41%. As shown in Fig. 1, the depletion regions in the gap p–n junction isolate the APD cells in order to decrease the electrical crosstalk; the N^{++} channel functions as a common anode to directly collect avalanche signals from each cell; there is no need for contacts and metal lines matrix in the light entrance window. Fig. 2 show the fabricated 127 ultra-small SiPM array and the TO-8 package, in which the 1×7 ultra-small SiPM array was mounted on the TO-8 can. For such an array, all elements were fabricated simultaneously under same conditions to ensure the outstanding uniformity.

For characterizing the ultra-small SiPMs, the negative bias on the detector was offered by a common high voltage power; the avalanche signal and the dark count rate (DCR) were amplified by a high-speed amplifier with the bandwidth of 1.5 GHz (Femto HAS-Y-1-60), and then recorded by a digital oscilloscope (Tektronix TDS1012).

The schematic setup for the pulse height distribution measurement is shown in Fig. 3 consisting of a multi-channel analyzer (MCA) (Canberra Multiport II), a charge sensitive preamplifier and a main amplifier (Ortec 673) with gain 50. The light source employs a pulsed LED (@ 525 nm) driven by a function generator (GFG-3015) with pulse width of 20 ns and repetition frequency of 10 kHz. A delay generator (Ortec 444) connects the MCA and the function generator.

As shown in Fig. 4, a bromine-tungsten lamp, a grating monochromator (BOIF Inc., WMD1-3) and a calibrated PIN photodiode (Hamamatsu Inc., S1227-1010BQ) were employed for the PDE measurement. Within the circular aperture a uniform intensity light from the fiber optic integrating sphere (Ocean Optics Inc., FOIS-1) was attenuated to very low level so that it could be regarded as discrete single photon flux and imposed on the detector. The single photon counting rate recorded by the digital oscilloscope was proportional to the incident photon flux after subtracting the DCR. The method based on single photon counting with subtraction of dark noise could avoid as much as possible cross-talk and afterpulses [4].

The linearity and the dynamic range of SiPM are determined by total number of micro cells and the PDE. The output from a Nd:YAG pulsed laser (@ 532 nm with FWHM of 0.02 nm and pulse width of 7 ns) was calibrated by a commercial PIN (Hamamatsu Inc., S1227-1010BQ). Therefore, the intensity of incident light is expressed by the photoelectric current of the PIN and the pulses height is determined by the number of fired pixels.

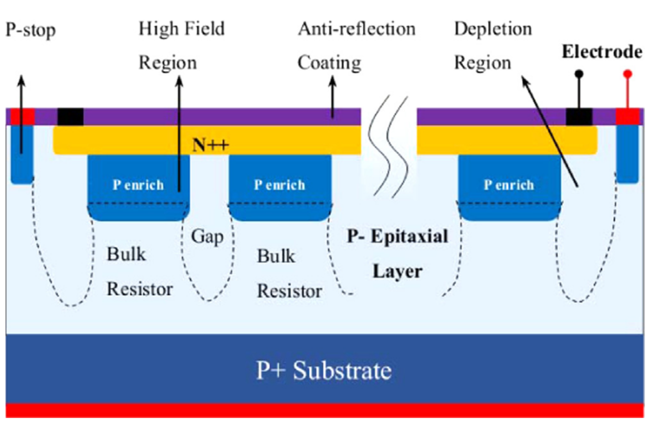

Fig. 1. Schematic structure of the SiPM with bulk quenching resistor developed by NDL.

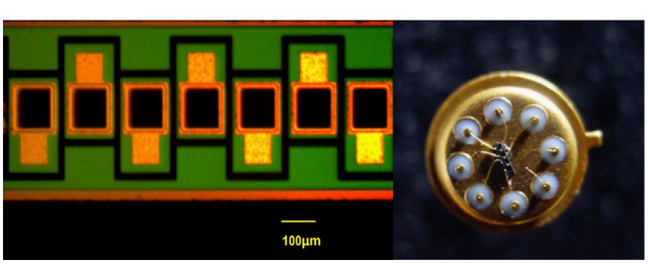

Fig. 2. Micrograph (left) and TO-8 package of the 1×7 ultra-small SiPM array.

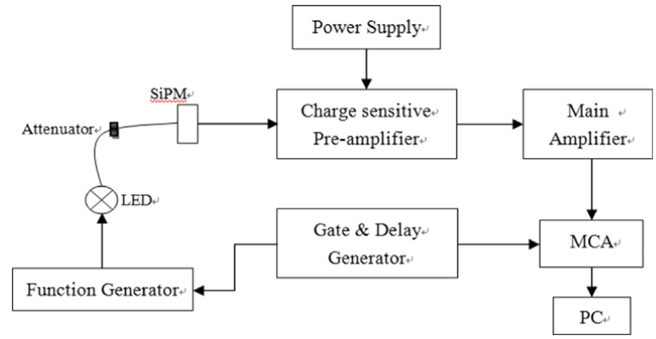

Fig. 3. Schematic setup for the pulse height distribution measurement.

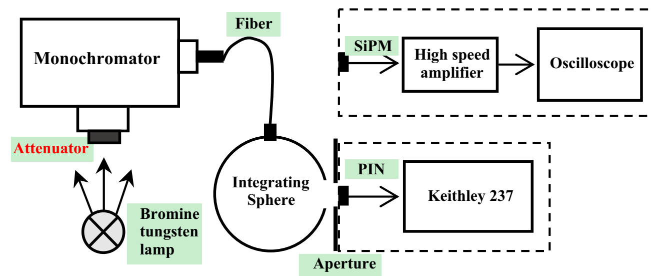

Fig. 4. Schematic setup for the PDE measurement.

3. Results and discussion

3.1. I–V characteristics

Fig. 5 shows the *I–V* characteristics of the ultra-small SiPM element at room temperature ($T = 300$ K). The breakdown voltage (Vb) is 22.9 V and the leakage current is about 0.01 nA. A "second breakdown" like phenomenon was observed. The voltage (VB) at the second inflexion in the curve is 31 V. Thus we obtained the maximum allowable over-voltage ($VB - Vb$) of the ultra-small SiPM in $0.12 \times 0.12\ \text{mm}^2$ as 8.1 V, which is higher than other devices with large active area [2]. The uniformity in the line array was also characterized. As shown in the inset, all elements have almost the same *I–V* characteristics. The SiPMs with good uniformity would have enormous potential in the imaging sensor application which needs a huge number of detectors.

3.2. Dark counting properties

Fig. 6 shows the dark pulse signal from the ultra-small SiPM element reversely biasing at 29 V at room temperature corresponding to 1 p.e. that means pulse with amplitude equivalent to one photoelectron, which is dominated by thermally generated free carriers. The FWHM of the dark pulse is about 3 ns and the DCR is 28.7 kHz at 0.5 p.e.