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Quantum efficiency measurement of n–i–p a-Si:H photodiode array on CMOS circuit for positron emission tomography (PET)

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Abstract

Detection of scintillation light from LSO (Lutetiumoxyorthosilicate) crystals used in positron emission tomography (PET) is traditionally based on photo-multipliers. The proposal is to develop a novel photo-sensor, which is based on vertically integrating an hydrogenated amorphous silicon (a-Si:H) film on a pixel readout chip. The a-Si:H film is deposited with a n–i–p diode structure. The ASIC (Application Specific Integrated Circuit) performs both signal amplification and readout processing. The advantage of such an approach is the extremely compact and low-cost design, together with ultra-low noise signal retrieval. In addition the a-Si:H offers the technological advantage of direct deposition on the wafer thanks to the low deposition temperature. The article presents the results of quantum efficiency measured on different types of a-Si:H photodiodes deposited on glass (DC measurement) and CMOS circuit (AC measurement). Quantum Efficiency (QE) up to 80% has been measured at the wavelength of interest for the optimized photodiodes.
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1. Introduction

Standard a-Si:H diodes exhibit a maximum quantum efficiency around the 550 nm wavelength and most of the a-Si:H based commercial devices (such as solar cells) are actually optimized for this wavelength. However, since the light output of the LSO (Lutetiumoxyorthosilicate) [1] crystal has a peak at 420 nm, the a-Si:H (n–i–p) diodes used for Positron Emission Tomography (PET) applications [2] have to be optimized for this value. The response of a photodiode for this wavelength and down to the UV region is mainly controlled by the top transparent conductive layer and the top doped p-layer. A possibility to decrease the optical loss is thus the reduction and optimization of the thickness of these top layers [3]. An alternative is to increase the optical band gap by alloying amorphous silicon with carbon, but this technique is not described in this paper. The article is organized as follows. Section 2 describes the experimental technique used to determine precisely the number of photons of the laser, which is used as a light source; the way the light source is collimated and aligned with a single pixel is presented as well. Section 3 discusses the experimental results, in particular the measurement of the quantum efficiency around 420 nm for optimized and standard photodiodes deposited on CMOS circuit [4]. Results obtained in AC condition are compared with DC measurements for a-Si:H photodiodes deposited on glass. A measurement of the uniformity of the deposited amorphous silicon sensor is also presented.

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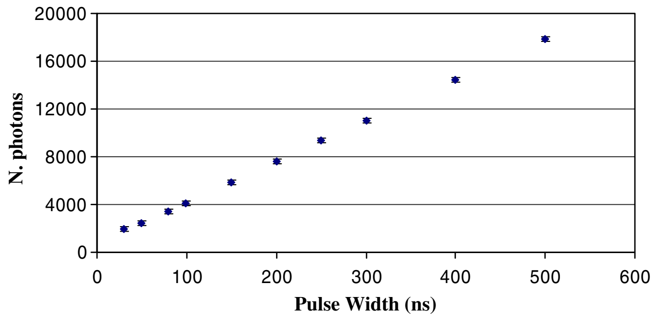

Fig. 1. Number of photons as a function of the pulse width of the laser.

2. Experimental technique

The pixel sensor under investigation consists of a film of hydrogenated amorphous silicon forming a n–i–p diode structure which is directly deposited on top of an integrated circuit. Two photodiodes are analyzed in this paper with thicknesses of 5 μm and 10 μm, respectively. The integrated circuit consists of 48 octagonal pads of about 140 μm width and 380 μm pitch. Each pad is connected to a charge sensitive amplifier followed by a shaper stage [4]. To prove the capability of a-Si:H photodiodes to detect pulsed light equivalent to LSO crystals and to study their competitiveness in comparison to other photodetectors, a laser of a fixed wavelength of (405 ± 5) nm has been used. The laser is triggered with a square wave of fixed amplitude. Its width varies from 30 ns to 500 ns during the calibration, with a frequency of 1 kHz. The light from the laser is first attenuated. Then it is focused into one pixel of the a-Si:H photodiode using a collimator of 100 μm diameter to avoid light dispersion and cross talk with adjacent pixels. The set up used to calibrate the light from the laser consists of an Avalanche Photo Diode (APD) and a calibrated read out chip detailed in [5]. The APD, from Hamamatsu [6] has QE of 75% and a measured gain of 174 ± 5 at a bias voltage of -411 V. The gain and the linearity of the readout chip have been precisely measured [7]. From these quantities the number of photons is obtained in dependence of the pulse width of the laser. The results are shown in Fig. 1. The value used as input light pulse for the quantum efficiency measurement of the a-Si:H photodiodes is 4140 ± 120 photons. During the measurements, the laser, the attenuator, and the 100 μm diameter collimator form a solid assembly. This assembly is aligned with the 140 μm wide pixel of the a-Si:H photodiode by means of micromanipulators.

3. Experimental results

The quantum efficiency of a standard n–i–p a-Si:H photodiode of 10 μm thickness operating at a reverse bias voltage of 70 V and of a 5 μm thick optimized photodiode operating at a reverse bias voltage of 45 V has been measured. The bias voltages are chosen for a full depletion of the diodes. All devices have been deposited by Very High Frequency plasma-enhanced Chemical Vapor Deposition (VHF PE-CVD) [8,9]. The top transparent conductive layer is made of indium tin oxide (ITO). The ITO layer has a thickness of 65 nm corresponding to a deposition time of 1′45″, for standard a-Si:H diodes. Studies [3] performed by the Institute of Micro-Technology (IMT) of Neuchatel on ITO layer samples deposited on glass have shown that by reducing the deposition time to 45″ the quantum efficiency is optimum for wavelengths from 350 nm to 450 nm. This deposition time corresponds to an estimated layer thickness of 28 nm. For the reduction of the optical loss the thickness of the p-layer has to be reduced as well. The optimized photodiodes have a deposition time for the p-layer between 4′ and 5′ compared to 10′ for a standard p-layer. The thickness of the p-layer has been reduced to approximately 20 nm, while the thickness of the n-layer is between 30 nm and 40 nm. Results for standard and optimized a-Si:H photodiodes deposited on CMOS circuits, measured in AC condition for 48 different pixels are presented in Fig. 2. The input light pulse at 405 nm, for a pulse width of 100 ns, corresponds to 4140 ± 120 photons (cf. Fig. 1). The QE at this wavelength lies between 42% and 54% for the standard photodiode. For the optimized photodiode the value of QE in the different pixels is between 69% and 83% with an average value of 77%, as shown in Figs. 2 and 4. The total leakage current of the 48 pixels for both structures, measured at the mentioned bias voltages, is less than 15 nA. The standard deviation on the measurements, mainly due to variation of the output pulse measured on the scope, is less than 3%. Fig. 3 shows the QE of an optimized photodiode of 4 μm thickness, deposited on glass and measured in DC condition, as function of the wavelength. A comparison of the QE measured on the a-Si:H photodiode deposited on glass (Fig. 3) and on CMOS circuit (Fig. 2) at 405 nm shows

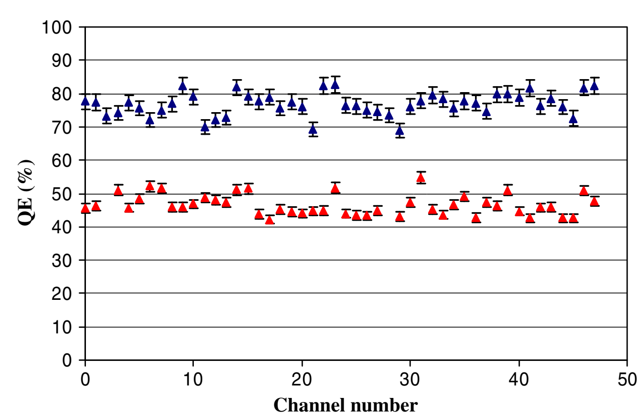

Fig. 2. Quantum efficiency of standard (red) and optimized (blue) a-Si:H n–i–p photodiodes measured at 405 nm for 48 different pixels in AC condition. The average values of the QE are respectively 46% and 77%. (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

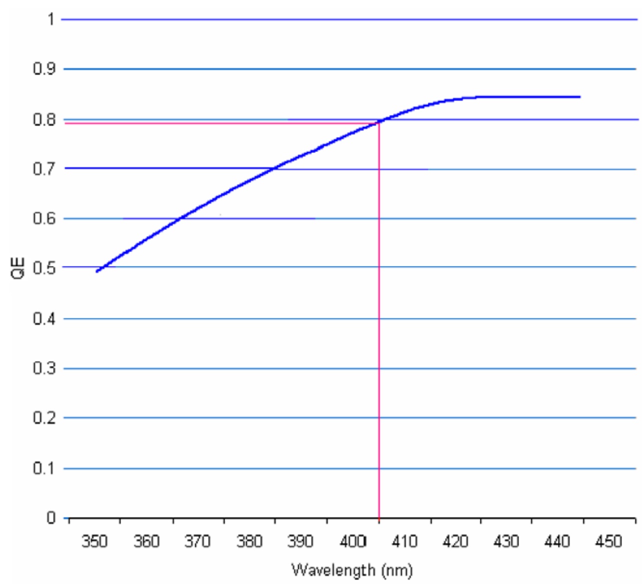

Fig. 3. Quantum efficiency of the optimized a-Si:H photodiodes measured in DC condition as a function of the wavelength. The QE value measured at 405 nm matches well the results obtained in AC conditions for the 48 pixels (Fig. 2). The thickness of the diode is 4 μm.

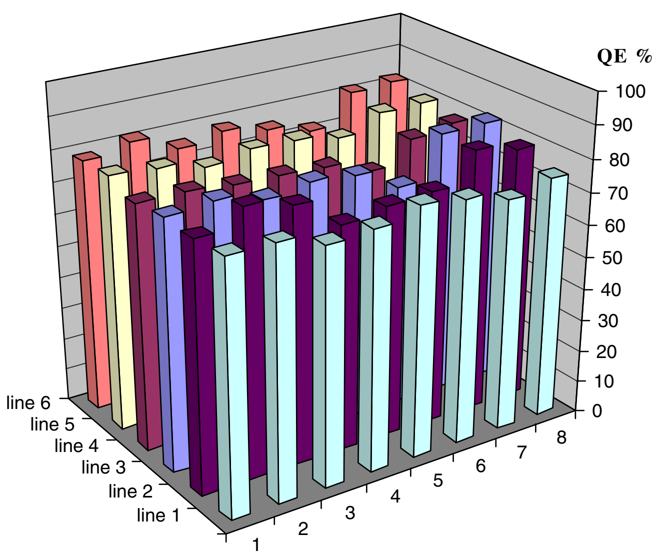

Fig. 4. Quantum efficiency of a 5 μm optimized photodiode as a function of the position of the pixel in the structure. A good uniformity and the absence of degradation of the QE at the borders are achieved (for the error bars refer to Fig. 2).

good agreement. In both cases the QE has a value between 75% and 80%. The value of QE at 420 nm, the peak emission wavelength of the LSO crystal, is slightly higher. In the final design the a-Si:H photodiode, for the readout of the incoming light from a $2 \times 2 \times 15\,mm^3$ LSO crystal, will be segmented into 9 pixels of 600 μm width each. Segmentation will be done by the metal pads integrated in the ASIC. To limit the increase of the sensor capacitance, and therefore the series noise of the read out chip, the thickness of the a-Si:H photodiode has to be at least 10 μm. This study has been performed on a-Si:H photodiodes with thicknesses from 1 μm to 5 μm, to limit the dark current. No major obstacles are expected, for the realization of optimized photodiodes of a thickness around 10 μm.

4. Conclusions

Measurements of a-Si:H photodiodes, optimized for a wavelength of 420 nm, have shown a quantum efficiency up to 80% for samples deposited on glass. The results are confirmed by a-Si:H diodes deposited on ASIC. The dark current of the optimized photodiodes, with thickness up to 5 μm, is not increased in comparison to standard a-Si:H diodes. The noise of the readout electronics is also not influenced by the optimization of the sensor structure. A confirmation of the QE results with thicker diodes, around 10 μm, could allow the design of a low noise readout chip together with an extremely efficient photosensor, competitive with the detectors actually used in PET applications.

Acknowledgments

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