Nuclear Instruments and Methods in Physics Research A ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

Influence of X-ray irradiation on the properties of the Hamamatsu silicon photomultiplier S10362-11-050C

Q1 Chen Xu [a,*], Robert Klanner [b], Erika Garutti [b], Wolf-Lukas Hellweg [b]

[a] DESY, Hamburg, Germany
[b] Institute for Experimental Physics, University of Hamburg, Hamburg, Germany

ARTICLE INFO

Article history:
Received 10 April 2014
Received in revised form
21 May 2014
Accepted 25 May 2014

Keywords:
XFEL
Silicon photomultipliers
MPPC
GAPD
X-ray radiation damage

ABSTRACT

We have investigated the effects of X-ray irradiation to doses of 0, 200 Gy, 20 kGy, 2 MGy, and 20 MGy on the Hamamatsu silicon-photomultiplier (SiPM) S10362-11-050C. The SiPMs were irradiated without applied bias voltage. From current–voltage, capacitance/conductance–voltage, capacitance/conductance–frequency, pulse-shape, and pulse-area measurements, the SiPM characteristics below and above Q3 breakdown voltage were determined. Significant changes of some SiPM parameters are observed. Up to a dose of 20 kGy the performance of the SiPMs is hardly affected by X-ray radiation damage. For doses of 2 and 20 MGy the SiPMs operate with hardly any change in gain, but with a significant increase in dark-count rate and cross-talk probability.

1. Introduction

After more than 30 years of development, silicon-photomultipliers (SiPMs) are now well established high-gain photodetectors [1,2], which already have found numerous applications [3]. A SiPM consists of a matrix of avalanche photodiodes connected in parallel and operated above the breakdown voltage in Geiger mode. Relevant parameters which characterize the SiPM performance are: signal shape, gain, dark-count rate, cross talk, afterpulse rate, breakdown voltage, and their dependencies on voltage and temperature.

As SiPMs detect single charge carriers, radiation damage is a major concern. In numerous investigations [4,5] it has been found that for high-energy radiation the dominant radiation effect for SiPMs is an increase in the dark-count rate due to defects in the silicon crystal. Given that radiation damage presents a serious limitation for many applications, several groups together with the producers of SiPMs are undertaking major efforts to make SiPMs more radiation tolerant.

In contrast to radiation-induced bulk damage, little is known on the effects on SiPMs of surface damage caused by X-rays and ionizing radiation. The authors of Ref. [6] have irradiated a prototype SiPM from Hamamatsu (Type No. T2K-11-100C) under bias up to 240 Gy of ^{60}Co γ-rays and measured dark current, dark-count rate, gain, and cross talk. Whereas gain and cross talk did not significantly change with dose, large dark-count pulses and localized spots with leakage current along the edge of the active region and the bias lines were observed for about half an hour after X-ray irradiation for doses above 200 Gy. As far as we know this study has not been pursued further. In Ref. [1] it is reported that several SiPMs have been irradiated up to 500 Gy by a ^{60}Co-source without applying a bias voltage during irradiation. No evidence for large pulses has been found after the irradiation. The authors of Ref. [7] have irradiated green-sensitive SiPMs (SENSL SSPM-0701BG-TO18) with 14 MeV electrons to fluences between 3.1×10^{7} and 3.8×10^{8} cm^{-2} and observed a large increase in dark-count rate and a decrease in effective gain. In Ref. [8], in which the radiation hardness of Hamamatsu SiPMs was investigated, footnote 1 states: "An early irradiation test on SiPMs using a series of high activity ^{137}Cs-sources in Jefferson Lab showed that SiPMs are insensitive to electromagnetic radiation and there was no significant change in the performance of SiPMs up to 2 krad of gamma irradiation."

This paper first gives a short summary of X-ray radiation effects in silicon sensors, describes the methods used to determine the parameters of the Hamamatsu SiPMs using measurements below and above breakdown voltage, and finally presents the results for doses of 0, 200 Gy, 20 kGy, 2 MGy, and 20 MGy of X-ray irradiation without applied bias voltage. Details of the measurements can also be found in Refs. [9,10]. As we anticipate that X-ray radiation damage depends on the details of the SiPM design, we plan to extend these studies to SiPMs from other producers.

* Corresponding author. Tel.: +49 40 8998 2964.
E-mail address: Chen.Xu@desy.de (C. Xu).

http://dx.doi.org/10.1016/j.nima.2014.05.112
0168-9002/© 2014 Published by Elsevier B.V.

Please cite this article as: C. Xu, et al., Nuclear Instruments & Methods in Physics Research A (2014), http://dx.doi.org/10.1016/j.nima.2014.05.112

2. X-ray radiation damage in silicon sensors

X-rays with energies below 300 keV, which is the threshold energy for the formation of defects in the silicon bulk, generate only defects in the dielectrics, at the Si–SiO_2 interface and at the interfaces between dielectrics. The effects of X-ray radiation damage are discussed in detail in Refs. [11,12]. Here, we only give a short summary.

In SiO_2, X-rays produce on average one electron–hole (eh) pair every 18 eV of deposited energy. Depending on ionization density and electric field, a fraction of the eh pairs recombine. The remaining charge carriers move in the SiO_2 by diffusion and, if an electric field is present, by drift. Most electrons, due to their high mobility and relatively low trapping probability, leave the SiO_2. However holes, which move via polaron hopping, are typically captured by deep traps in the SiO_2 or at the Si–SiO_2 interface, which results in fixed positive charge states and interface traps. We denote the density of oxide charges by N_{ox}, and the density of the Si–SiO_2 interface traps by N_{it}. The interface traps, if exposed to an electric field, act as generation centers for a surface current with density J_{surf}.

Results on N_{ox} and J_{surf} from MOS-Capacitors and Gate-Controlled-Diodes produced by different vendors and for different crystal orientations for X-ray doses between 10 kGy and 1 GGy can be found in Refs. [13–15]. For a dose of 10 kGy the values for N_{ox} are between 0.4×10^{12} and 1.2×10^{12} cm^{-2}, and for J_{surf} between 0.1 and 1 μA/cm^2 at room temperature. Depending on technology and crystal orientation for doses of the order of 1 MGy the values of N_{ox} and J_{surf} saturate at $1.5\text{–}3.5 \times 10^{12}$ cm^{-2} and $2-6$ μA/cm^2, respectively. Before irradiation typical values are a few 10^{10} cm^{-2} and a few nA/cm^2, respectively. We note that in addition to differences due to technology, the values of N_{ox} and of J_{surf} at a given dose depend on the value and the orientation of the electric field in the oxide, and that there are significant annealing effects [14,15].

The depleted Si–SiO_2-interface areas generate surface currents, and therefore we expect a significant increase in dark current below the breakdown voltage. In case a fraction of the charge carriers from the surface current reaches the amplification region, an increase in dark-count rate will also occur above the breakdown voltage. This however depends on the details of the SiPM design.

3. Sensors, measurements, analysis and results

3.1. Sensors and X-ray irradiation

Sensors of the type Hamamatsu S10362-11-050C [16] were used for the studies. They have 400 pixels of 50 μm × 50 μm and a total area of 1 mm × 1 mm. Fig. 1 shows an overall view of the SiPM, Fig. 2 details of the pixel region, and Fig. 3 a schematic cross-section. The biasing contact, which can be seen at the middle right of Fig. 1, is connected to the biasing lines which run horizontally between alternate pixel rows. Fig. 2 shows how the biasing lines are connected to the quench resistors which run up and down in between the pixels. The ends of the quench resistors are connected to square Al rings surrounding the pixels. The connections to the p^+ implants are seen as the square dots at the middle right of every pixel. The readout contact to the n^+ substrate is made from the top side of the SiPM via the bulk. The corresponding Al layer (silvery area) surrounds the entire pixel area, with a contact seen at the lower left corner of Fig. 1.

The Si–SiO_2 interface areas are sensitive to X-ray radiation damage. These and their respective areas, estimated from the photographs, are:

- the region below the Al biasing ring which surrounds the entire pixel area 4×1 mm $\times$ 38 μm $= 15.2 \times 10^{-4}$ cm^2,
- the region below the Al biasing lines in between the pixels: 10×1 mm $\times$ 12 μm $= 12 \times 10^{-4}$ cm^2,
- the region below the quench resistors: 400×40 μm $\times$ 12 μm $=$ 19.2×10^{-4} cm^2, and
- the region in between the pixels not covered by the Al biasing line 9×1 mm $\times$ 10 μm $= 9 \times 10^{-4}$ cm^2.

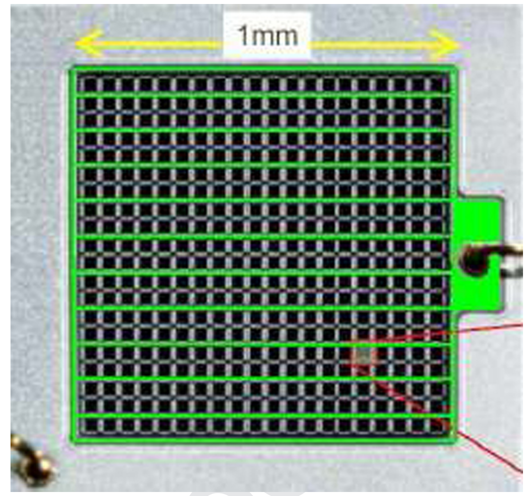

Fig. 1. Photo of the Hamamatsu S10362-11-050C taken from Ref. [1]. One can see 20 × 20 pixels, the biasing contact on the right, which is connected via the biasing lines to the individual pixels, and the readout contact on the bottom left. The pixel size is 50 μm × 50 μm.

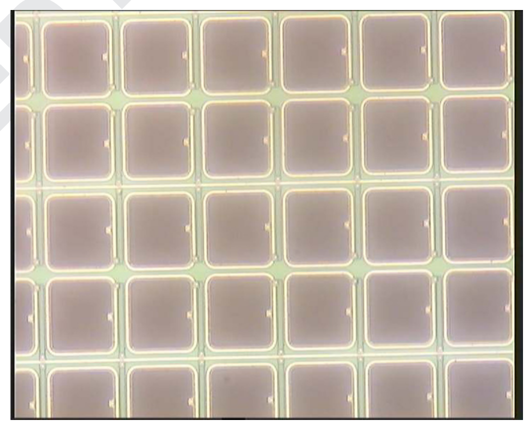

Fig. 2. Photo of the pixels of the Hamamatsu SiPM S10362-11-050C. The pixel size is 50 μm × 50 μm.

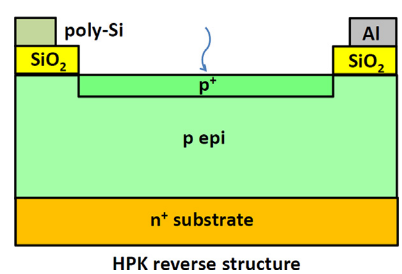

Fig. 3. Schematic cross-section of the Hamamatsu S10362-11-050C after Ref. [18]. Compared to the figure given there, the SiO_2 layer, the Al-contact line, and the poly-Si layer of the quenching resistor have been added. From the capacitance measured above full depletion we estimate a depth of the p-epitaxial layer of about 2.3 μm. We assume that the p^+ implant is covered by an anti-reflection coating, which however should not affect the electrical properties of the SiPM.

Please cite this article as: C. Xu, et al., Nuclear Instruments & Methods in Physics Research A (2014), http://dx.doi.org/10.1016/j.nima.2014.05.112