Nuclear Instruments and Methods in Physics Research A 626–627 (2011) 77–81

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

Computer-aided design (CAD) model for silicon avalanche Geiger mode systems design: Application to high sensitivity imaging systems

K. Jradi [a,b,*,1], D. Pellion [a,b,1], D. Esteve [c,d,2], J.L. Boizard [c,d,3], A. Le Padellec [a,b,4], A.R. Bazer-Bachi [a,b,5]

[a] Université de Toulouse, UPS, Centre d'Etude Spatiale des Rayonnements, 9, avenue du Colonel Roche, 31028 Toulouse Cedex 9, France
[b] CNRS, UMR5187, 31028 Toulouse, France
[c] Université de Toulouse, UPS, Laboratoire d'Analyse et d'architectures des Systèmes, 7, avenue du Colonel Roche, 31077 Toulouse, France
[d] CNRS, UPR 8000, 31077 Toulouse, France

ARTICLE INFO

Article history:
Received 14 April 2010
Received in revised form
9 September 2010
Accepted 27 September 2010
Available online 13 October 2010

Keywords:
APD-Geiger
Noise
VHDL-AMS
Modeling

ABSTRACT

Our consortium CESR-LAAS in Toulouse has developed generic technology for Geiger-APD and SiPM. The main feature of these devices is the high homogeneity in breakdown voltage. The work presented here describes the model that has been used to design these devices. This also includes the integration into micro-systems, with the ambition in the long term, to develop multiple applications in astrophysics, biology, optical sensing, and above all, imaging systems.

The paper is divided as follows:

1. An introduction presents the main issues in the physics of silicon avalanche Geiger mode systems.
2. A section (Geiger mode) divided into two parts. The first part is devoted to the electrical model of the basic device, which provides the response of the Geiger-APD to an incident photon: gain, current, and voltage. The second part presents the production of the model using Simplorer simulation software under VHDL-AMS (VHSIC—Very High Speed Integrated Circuit-Hardware Description Language-Analog and Mixed Signal) [1].
3. A comparison between our model and that used by Otono et al. [5] followed by a discussion with a special emphasis on presenting the noise model based on the real component made and tested by our consortium.
4. A conclusion.

1. Introduction

The technology and use of avalanche photodiodes (APD) have been known for around three decades. The usual gain (electrons/photons) is around one hundred. More recently, new designs have evolved for the mode known as *Geiger*, for which the gain can be as high as 10^7. This allows the use of these Geiger–APDs in photon counting applications, through the design of components known as "silicon photomultiplier" (SiPM). The latter is a matrix of multipixels of Geiger–APDs, where the pixels are connected by the cathodes of the APDs, and only one output of the SiPM is available. While a Geiger–APD represents only one pixel, this technology is being used in a few laboratories and firms worldwide. Unitary samples are commercially available (see the websites of Hamamatsu and SensL).

The CESR, a laboratory specialized in space physics, has been involved in early very high energy (VHE) astrophysics experiments in France, and elsewhere, e.g. Namibia (HESS I and II). The LAAS is a CNRS laboratory working on micro-systems and microelectronics. Four years ago, we started a collaboration within these two laboratories to develop solid state photo-detectors, with the aim of developing sensors for future Cherenkov cameras. It is obvious today that progress in the field will come from progress made in imaging capabilities. At the outset, our

Abbreviations: Geiger-APD, Geiger avalanche photodiode; SiPM, Silicon photomultiplier; PMT, Photomultiplier tube; CESR, Centre d'Etude Spatiale des Rayonnements; LAAS, Laboratoire d'Analyse et d'Architecture de Système; CNRS, Centre National de la Recherche Scientifique; VHE, Very high energy; ZSC, Zone of space charge

* Corresponding author at: Université de Toulouse, UPS, Centre d'Etude Spatiale des Rayonnements, 9, avenue du Colonel Roche, 31028 Toulouse Cedex 9, France. fax: 33 05 61 55 67 01.

E-mail addresses: khalil.jradi@cesr.fr (K. Jradi), denis.pellion@cesr.fr (D. Pellion), esteve@laas.fr (D. Esteve), jlboizar@laas.fr (J.L. Boizard), arnaud.lepadellec@cesr.fr (A. Le Padellec), bazer@cesr.fr (A.R. Bazer-Bachi).

[1] Tel.: +33 5 61 55 75 69.
[2] Tel.: +33 5 61 33 64 03; fax: 33 05 61 55 35 77.
[3] Tel.: +33 5 61 33 79 65.
[4] Tel.: +33 5 61 55 69 47.
[5] Tel.: +33 5 62 25 82 73.

0168-9002/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2010.09.146

challenge was twofold: first catch up with current state of the art technology and second offers better overall performances.

This could only be done by manufacturing an "on the chip" Cherenkov camera. Producing such a camera implies producing a sensor with a uniform sensitivity over the entire chip, and a process maintaining this quality during the whole production phase. Study, modeling, and simulations of this process have been made and the first results are sufficient to answer questions about the photodetection of light. The technology used for this process [2] is based on the n/p junction and the APD is biased beyond its breakdown voltage. This mode of function is called "Geiger mode". A quenching resistor is necessary for this mode because of the overvoltage applied, a method used to protect the APD from the high current passing through it. The quenching resistor is internal to avoid any parasitic effects and its value is around 100 kΩ.

In Geiger mode, amplification of the photoelectron is about 10^7, depending on the difference between the bias voltage and the breakdown voltage. Although the design criteria of an avalanche photodiode are well known, current difficulties in their manufacture are the realization of multi-cell devices (photodiode arrays). This technology remains a serious challenge to the scientific community.

Although equations of Geiger–APD physics are well known, there are some peculiarities when using the Geiger mode, especially regarding thermally generated random noise. During our design phase, physical and electrical simulations were conducted to optimize the process. We report here the details of the model which have been used; keeping in mind, that in addition to the application in very high energy (VHE) astrophysics, there are numerous fields that use a fast, high sensitivity imaging sensor, with around 100×100 pixels (about 30 μm each).

2. Geiger mode

2.1. The electrical model

Prior to this work, a physical and electrical model was achieved in our group [3] to give the desirable behavior of a real Geiger–APD. Taking into account the limitations in this preliminary study, we have built on what was already achieved, to improve the existing model's behavior and to optimize its performance. It should be noted that other models have been developed by other groups to explain the phenomena of avalanches in APDs. Corsi et al. [4] presented the electrical model of a SiPM based on measurements performed on a real detector. Otono et al. [5] focused on the avalanche effect for single APDs using equations describing the physics of semiconductors. Badoni et al. [6] have described a model for both components: first the APD and then SiPM by generalizing the results for one pixel.

All the models reviewed here are electrical and describe an APD biased above the breakdown voltage. This is also the case in the present work, which is the first to use VHDL-AMS code. The latter allows the noise to be taken into account. Our new enhanced model is represented in Fig. 1 (right) with the corresponding components and incorporates the three following elements:

- An open switch in the normal state, which closes when a photon is absorbed.
- A capacitor symbolizing the n/p junction of the considered Geiger–APD, which loads and off-loads with the photon flow cycle.
- A third crucial element of this model is the current generator, which is located and operates in parallel association with the capacitor. This final component represents the avalanche effect following the detection of one photon.

The avalanche mechanism in Geiger–APDs takes place when a photon is absorbed by the sensitive and active area. It is first produced by the creation of one electron–hole pair (photon hitting the silicon) [7]. The separation of this pair due to the presence of a very high electrical field that prevails in the zone of space charge (ZSC), resulting from a high polarization of the Geiger–APD, will successively release electrons present in the structure. A quench resistance is used in series with the Geiger–APD, which has dual roles: it allows Geiger–APD polarization above the breakdown voltage and triggers the decline in the level of polarization with the current passing through it.

The amplification of the current is the result of the multiplication effect of the carrier electron–hole pair. The factor M, i.e. the multiplication of the carriers, is given by the empirical formula obtained by adapting the Miller law [8]

$$M = \frac{1}{1-(\alpha(v/V_G))^m} \tag{1}$$

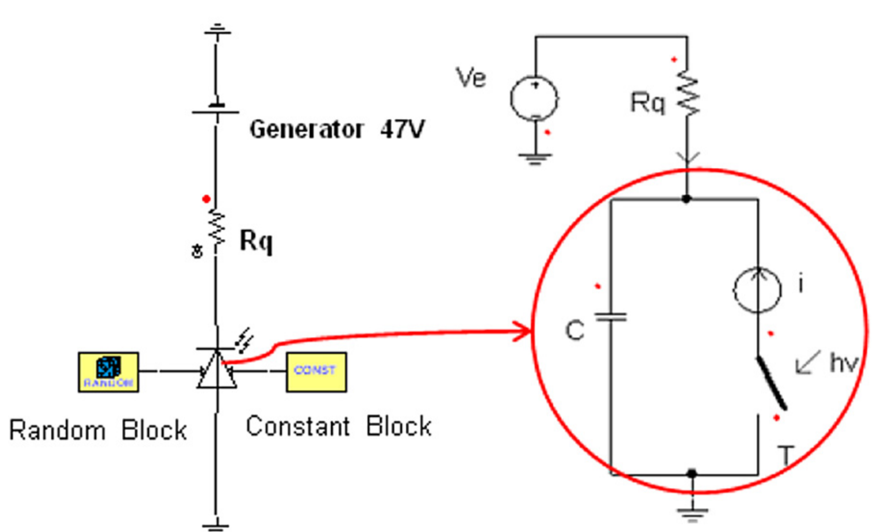

Fig. 1. Electrical scheme with the different elements associated with the VHDL-AMS model.