ECMS 2009
9th International workshop on Electronics, Control, Modelling, Measurement and Signals 2009
8-9-10 July, 2009, University of Mondragon, Spain

Modelization and design of Geiger-APD for applications in astrophysics and biology

K. JRADI[1], D. PELLION[1], A. LEPADELLEC[1], D. ESTEVE[2], T. CAMPS[2], J.L. BOIZARD[2], F. MOUTIER[1], A.R. BAZER-BACHI[1]

[1] Paul Sabatier/Microtec, CESR, Toulouse, France
[2] CNRS, LAAS, Toulouse, France
jradi@cesr.fr

Abstract: *Nowadays, there are two devices to detect low luminous flux: the PhotoMultiplier Tube -PMT- and the Avalanche Photodiodes polarized in Geiger mode -Geiger–APD-. The PMT is a detector designed in the sixties, combining many advantages but also suffering disadvantages such as its large size, expensive cost, heavy weight, sensitivity to magnetic fields and most importantly its very difficult integration for imaging pixels.*
Our consortium CESR-LAAS in Toulouse has developed a generic technology for Geiger–APD and SiPM. The Geiger–APD is designed to detect very low luminous flux and compares well to PMT with many additional advantages. The work presented here consists in the study of modeling and design of a matrix of pixels with high sensitivity for application areas such as space observations, medical imaging and biology.
In this paper, we describe the model which has been used to design these devices. In the first part, we present the model for avalanche mechanism able to take into account electrical and thermal aspects. In the second part, we give the complete model including Noise evaluation and Photon generation for the basic devices which provides the response of the Geiger–APD to an incident photon: current, voltage and gain. This model is investigated by Simplorer using VHDL-AMS language, and simulated in Matlab. So, this model provides a new approach for modeling Geiger–APD Microsystems, while enabling noise extraction through experimental measurements for modeling of luminous flux as a function of this noise. The last part elaborates on the study of a novel design, with the ambition in the long term, to develop multiple applications in astrophysics (in particular in the field of Cerenkov high energy astronomy), biology, optical sensing, and mostly, imaging systems.

I. INTRODUCTION

The technology and use of avalanche photodiodes (APD) have been known for around three decades now. Usual gain (electrons/photon) 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 PM”, or under other names; this technology is being used in few laboratories and firms worldwide, and unitary samples are commercially available [1].

CESR, a laboratory specialized in space physics, has been involved in early Very High Energy (VHE) astrophysics experiments in France, then in HESS I and II. Next door to CESR is LAAS, a CNRS laboratory working on micro-systems and micro-electronics. Four years ago, we started a collaboration to develop together solid state photo detectors, with the aim of developing sensors for future Cerenkov cameras. It is obvious today that progress in the field will come from progress in imaging capacities. At this time, our challenge was twofold: first catch up with current state of the art technology; and next offer better overall performances.

This could only be done by working from the start to manufacture an “on the chip” Cerenkov camera. Producing such a camera implies producing a sensor with a uniform sensitivity all over the chip, and a process maintaining this quality during the whole production phase.

Although equations of Geiger-APD physics are well known, there are some peculiarities when using the Geiger mode, especially regarding the thermally generated random noise. So, during our design phase, physical and electrical simulations were conducted to optimize the design of the process. We report here the models which have been used and some caracterisation results of the devices; keeping in mind, that past the application in VHE astrophysics, there are numerous fields that used a fast, high sensitivity imaging sensor, with around 100 X 100 pixels (about 20 µm each).

II. MODELIZATION IN GEGEIR MODE

The polarization circuit presented on Figure 1, allows to obtaining the Geiger mode, and so, the detection of very low luminous flux. In this circuit, we define Rq as the protective resistance strength the Geiger-APd. This resistance allows to shut down the avalanche when a photon is absorbed by the Zone of Space Charge ZSC, i.e. the region of multiplication.

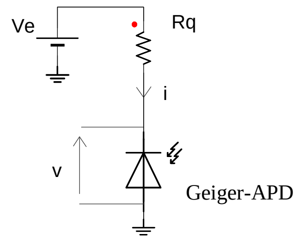

Fig. 1: the polarization circuit of a Geiger-APD

This kind of electric circuit is considered as a circuit of passif quenching, by using of only a resistance R_q. The Geiger-APD to be modeled is represented in the figure 2, the new model incorporates, essentially, the three following elements:

A. An open switch in the normal state, which closes down when a photon is absorbed.

B. A capacitor symbolizing the PN junction of the considered Geiger-APD, which loads and off-loads as the cycle of photon flows.

C. 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.

Conditionally, the considered Geiger-APD should be polarized above his breakdown voltage, setting a very intense electric field in the zone of space charge ZSC.

One considers that the incident photon creates an electron-hole pair that triggers the avalanche phenomenon generating a current [2]. The amplification in the current value is the result of the multiplication effect of the holders-electron-hole pair.

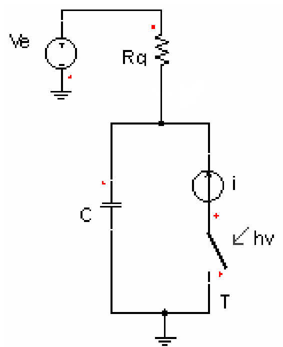

Fig. 2: the proposed model of the Geiger-APD

By using the different equations of the physic of semi-conductor [3], the equation of the current can be written:

$$\frac{di}{dt} = \frac{(M-1)}{\tau} * i \qquad (1)$$

Where:

M is the multiplication.

τ is the life time of the electrons and holders. $\tau = \frac{w}{v_l}$, w is the thickness of the ZSC and v_l: the limited velocity of the holders.

i: the current.

The second equation is obtained from the circuit of the figure 2.

$$v = Ve - R_q * (C * \frac{dv}{dt} + i) \qquad (2)$$

which represent the first equation include the current and the voltage.

Where v is the voltage across the Geiger-APD. V_e is the circuit polarization. R_q is the quenching resistance. C is the internal capacity of the Geiger-APD.

The final system of equations is thus:

$$\begin{cases} \frac{di}{dt} = \frac{(M-1)}{\tau} * i & (3) \\ v = Ve - R_q * (C * \frac{dv}{dt} + i) & (4) \end{cases}$$

These equations, with the initial condition and using the TIR method (a mathematical method of calculation that consists of replacing the limited conditions of a problem by the initial conditions), lead through the simulation software digital (Matlab) to the final equations:

$$i(j) = \frac{\frac{1}{1 - (\alpha * \frac{v(j-1)}{V_G})^m}}{\tau} * i(j-1) * dt + i(j-1) \qquad (5)$$

&

$$v(j) = \frac{(Ve - v(j-1) - R_q * i(j-1))}{R_q * C} * dt + v(j-1) \qquad (6)$$

Equations (5) & (6) are the two principal equations who produce v (t) & i (t) (figure 3).

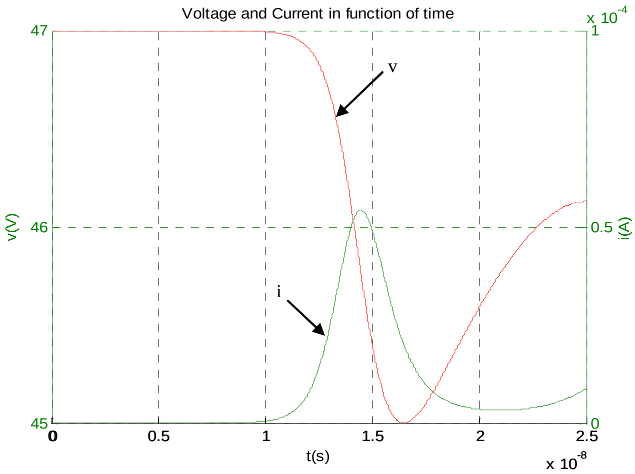

Fig. 3: the drop voltage and the current in function of time in the Geiger-APD

III.COMPLET ELECTRICAL MODEL

The complet model takes into account both phenomena existing in a Geiger-APD:

- the thermic generation due to defects in both crystal and temperature.
- the generation from a photonic source.

These two phenomena are the origin of the pulses generated from the detector.

The avalanche mechanism in Geiger-APDs takes effect when one photon is absorbed by its sensible and active area. It is originally produced by the creation of one electron-hole pair (effect of a hit photon on Si). The separation of this pair due to the presence of a very high electrical field reining the ZSC, resulting from a high polarization of the Geiger-APD, will release successively the electrons present in the structure. In this case, we speak about the generation photonic, which is the origin of this phenomenon.

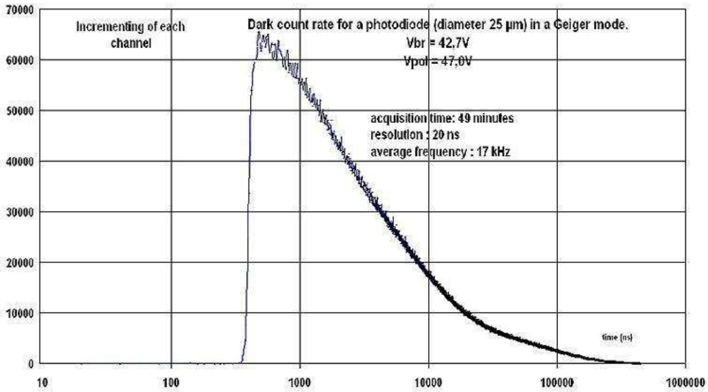

Fig. 4: the probability of thermal event as a function of passing time

Unfortunately, the avalanche phenomenon can be produced in the same structure, even if there are no photons. Typically, it gives rise to pulses, which have the same characteristics of those of photonic nature, called noisy pulses, and due to the thermic generation. This kind of noise is considered the most embarrassing factor in these devices. Several solutions have been proposed to eliminate or reduce its effect on the detection of real photons (use of cooling system, reduce of the thermic steps during manufacturing, use of coincidence system…).

For all these reasons, it was necessary to understand the nature of the noise. We used an electronic system, based on a FPGA card, which aimed to explore the noise by measuring its temporal dispersion [4]. The obtained curve in figure 4 (temporal histogram), represents the pulse numbers encountered in function of the gap between them, with a step of 20 ns. This distribution is defined as, the probability of occurrence of different periods between two impulses of noise.

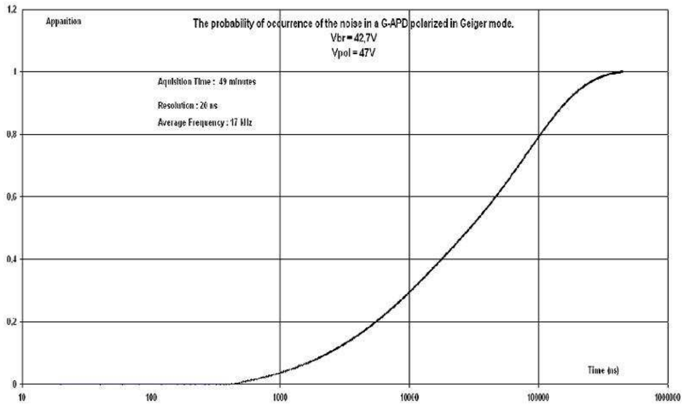

Fig. 5: the probability of occurrence of a thermal event

The modelization of the dispersion of noise is rendered possible through this curve. It's sufficient now to combine all the obtained events and to report them on a scale of zero to one. The figure assumes that the probability of occurrence of a thermal event reaches to its zenith (100%) when the time flows.

Whereas, in order to achieve this modelization, we should use a generator of random variables ranging between 0 & 1 in VHDL-AMS, then calculate every "simulation step" whether it will be a thermal event or not. The calculation is concluded through an equation interpolated from the curve in figure 5. This equation illustrates the relation between the fired number (random variable between 0 & 1) and the time between two thermal pulses.

By introducing this equation into the software hence, integrating the complete simulation of the two phenomena produced in the Geiger-APD, we can observe the pulses as system outputs, comprising the noisy pulses and the photons. The coincidence system between Geiger-APDs can be the most important application for this modelization. Calculations of the probability of a coincidence between noisy pulses showed a significant reduction of noise by coinciding of 2,3,4 or 5 Geiger-APDs [4].

IV. NOVEL CONCEPTS: SiPM AND IMAGER

A. To the Geiger-mode imaging

In paralel to the modelization, a work on technology advancement was ongoing, which aimed to produce Geiger-APD, SiPM and imager [5].

The concept of SiPM is to combine many Geiger-APDs in a matrix. The surface detection is optimized, but unfortunately, the detector suffers from more noise that is proportional to the number of Geiger-APD. To overcome this problem, it was necessary to introduce a cooling component, where the noise is divided by a factor of 2 every 8 ° C [6].

We represent in figure 6, a SiPM of 16x16 square Geiger-APDs.

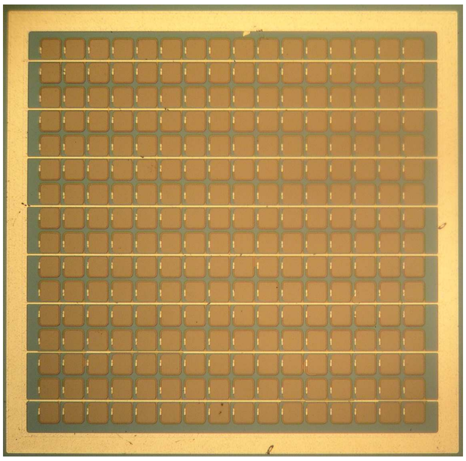

Fig. 6: SiPM

In our work, we considered two possibilities:

- Imaging based on SiPM: This system treats the pixels of the imager by collecting the photons detected and sending them to each output of a SIPM.
- Imaging based on Geiger-APD: Each pixel Basic (Geiger-APD alone) is treated separately. The addressing of pixels is done on the front of the chip, while detection of the flow is on the reverse side.

These two systems with their channels of command and addresses are the basis for the future imaging Geiger.

B. Results and interpretations

The measurements given the characteristics of Geiger-APD are made in the dark. Figure 7 shows the 'Dark Count Rate' in function of the bias voltage, where the curves highlight the importance of validating the unit as part of a high sensitivity imaging.

These caracteristics are shown for different Geiger-APDs at a temperature of 24°C, for diameters ranging from 15 µm to 30 µm with an external quenching resistance of 200 kΩ, and for a polarization between the breakdown voltage (Vbr = 43 V) at 49 V, which corresponds to over-bias of 6 V or 14% beyond the potential for avalanche.

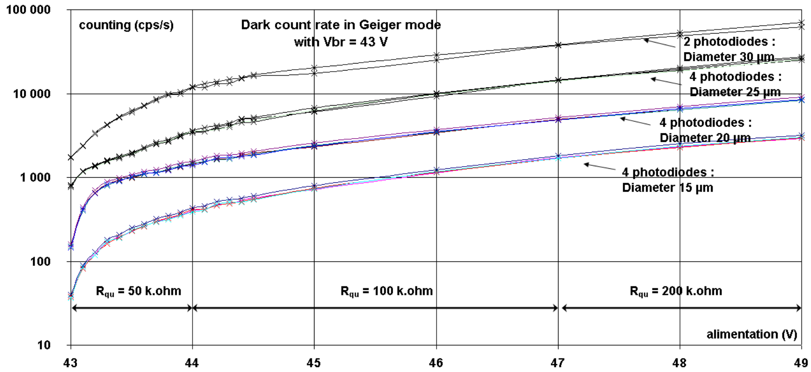

Fig. 7: Dark Count Rate in function of over-bias voltage for different detectors

A major drawback is that the active area is less than 70% and depends on the size of the photodiodes. An important future improvement will be to make microlenses (see Figure 8).

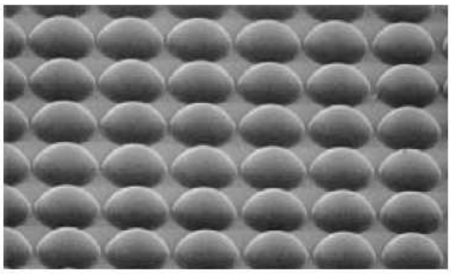

Fig. 8: Microlens for amelioration of the actif area

V. CONCLUSION

The results presented in this paper are enough evidence to pursue the manufacture of imaging types Geiger-APD or SiPM with a large number of pixels. This will produce a large surface-sensitive applications to single photon imaging. The possibility of coupling matrices based on Geiger-APD or SiPM with microlenses, made in trade or in a clean room, will increase the active surface of the matrix for the collection of light. This could be done while maintaining the low cost of the photodetector, the single photon sensitivity and high spatial and temporal resolution.

These latter characteristics are essential to the use of these matrices in many applications both commercial and scientific - telecommunications, optical computing, bioluminescence, the chemical analysis.

REFERENCES

[1]: http://sales.hamamatsu.com/en/products/solid-state-division/si-photodiode-series/mppc.php?src=hp.
http://www.sensl.com/Products/02Silicon_Photomultipliers_-_High_Gain_APDs.html.

[2]: D. Pellion, V. Borrel, D. Esteve, F. Therez, F. Bony, J.P.Gardou and A.R. Bazer-Bachi, "*APD photodetectors in the Geiger photon counter mode*", Nuclear Instruments and Methods in Physics Research A 567 (2006) 41–44.

[3]: S. L. Miller. *"Ionization rates for holes and electrons in silicon"*, Belle telephone laboratories, Murray hill, New Jersey. Physical Review, volume 105, number 4, 1957.

[4]: D. Pellion, A. Rennane, K. Jradi, V. Borrel, D. Esteve, C. Magenc, A.R. Bazer-Bachi. *"Geiger Avalanche Photodiodes as tentative light detectors for VHE gamma ray astronomy"*, Experimental Astronomy.

[5]: D. Pellion, K. Jradi, D. Estève, F. Moutier, T. Camps, F. Oms, JP. Gardou, C. Magenc and A.R. Bazer-Bachi. *"Fabrication process and performances of Geiger mode avalanche photodiodes"*, New developments in photodetection. Nuclear Instruments & Methods in physics research 2008.

[6]: J. C. Jackson, D. Phelan, A. P. Morrison, M. Redfern and A. Mathewson, "*Towards integrated single photon counting arrays*", Optical Engineering, vol. 42, no. 1, pp. 112-118, January 2003.