Study, Simulation and Manufacturing of new Geiger-APD for Applications in Astrophysics and Biology

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Abstract – Nowadays, there are two types of sensors to detect the low luminous flux, PMT (PhotoMultiplier Tube) and Geiger-APD (Geiger Avalanche PhotoDiode). The Geiger-APD is a component on Silicon that was developed in the early 90s to detect very low light flux, as is currently the PMT. The main advantages of these devices on the PMT are a very high sensitivity to light (single photon), a very high time resolution (<100ps), integration into imaging made possible by a great homogeneity. Unfortunately, these devices have some drawbacks compared to PMT; a very small sensitive area (30µm) and a leakage current (Dark Count Rate) higher per unit area.

I. Introduction

The domain of Geiger-APD has reached an advanced development in the last years. In our work, a first technological process has already been studied by collaboration between CESR and LAAS to develop a technology called "Geiger-APD" conducted through a project called SPAD for "Single Photon Avalanche Diode".

Future work to be done includes the integration into Microsystems, with ambition, in long term, to develop several applications in astrophysics, biology, optical detection, and most importantly, fast imaging systems. The manufacturing of imaging equipment in a new process should be defined by a detailed study on the imaging Geiger. Different applications in astrophysics are possible such as, detection of Cerenkov flash [1].

The considered technology is based on a structure of n/p junction making possible the light detection through a sensitive area. The principal idea of this structure consists in polarizing an APD in Geiger-mode by applying a voltage, so that the APD is biased beyond its breakdown voltage. This mode of polarization is called "Geiger Mode" and the APD is able to detect the single photon.

II. The First Technology

The work on a technological structure for detection of light in Geiger-mode was begun 7 years ago. During this last technology achievement [2], a characterization of the components was made and conclusion of measures gave principally that: the noise factor is the main drawback. This parameter is related directly to the life time of the carriers in the crystal lattice.

The structure of this technology is presented on the figure below (Fig. 1).

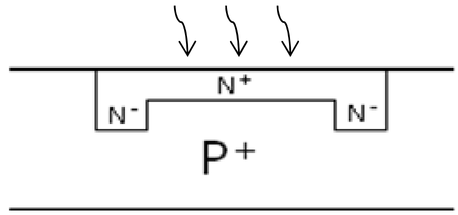

Fig. 1. The first technological structure of a Geiger-APD.

In this structure, we distinguish a substrate of P^+ type, who has a low resistivity (between $0.75\Omega.cm^{-1}$ & $0.85\Omega.cm^{-1}$) and a very low life time of carriers measured at (10µs).

When characterizing the fabricated APD, the results show a very high DCR. In order to understand the origin of this high DCR, one began by characterizing several APDs of different sizes and also as a function of temperature. The Fig. 2 gives the DCR of different APDs as a function of the over-bias.

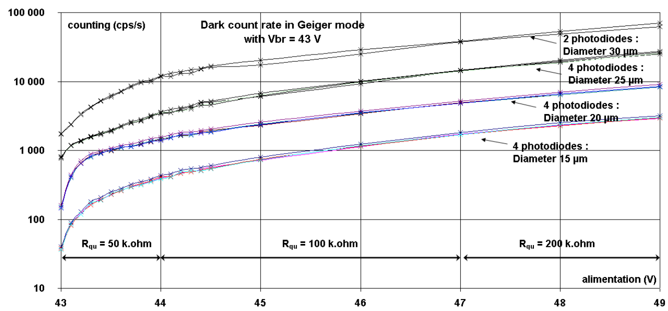

Fig. 2. DCR of different sizes of APD as a function of aver-bias voltage.

On the graphic of the Fig. 2, we can conclude a very high DCR of the components which increases with the increasing of sensitive area. This high DCR is due to the very low life time of the carriers.

It's obviously that, when the quality of the substrate at the beginning of the process technology is very low in terms of lifetime of the carriers, at the end of this process,

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lifetime is reduced mainly due to different thermal steps during the manufacturing process.

The characterization of the APDs as a function in temperature shows a significant reduction of noise when decreasing the temperature.

Fig. 3 gives the dark current of one APD (diameter of 30µm) when varying the temperature from 40°C to -50°C. The theory of semiconductor physics proves that the noise is halving every 8°C [3]. This law has been adequately demonstrated in this technology.

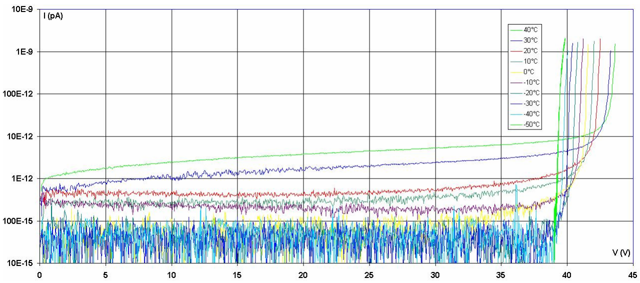

Fig. 3. Variation of the dark current as a function of temperature for one APD.

A very efficient solution to reduce the DCR is to use a cooling system coupling to the APD and controlled by an electronic card for adjusting the desired temperature and working with a good precision.

III. The New Proposed Technology

In the new technology, a different concept has been adapted to avoid the problem of noise. Based on wafers belonging to a high resistivity type (>2000Ω.cm), therefore a very high lifetime of carriers (>1500µs), studies and simulations on this new technology have been made and a new structure of the diode was adapted. The figure below (Fig. 4) shows the structure of this technology.

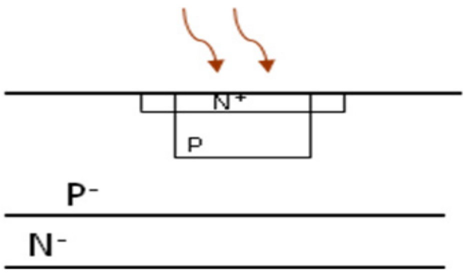

Fig. 4. The proposed structure of the new technology.

In this technology, studies and simulations have been made to establish the main characteristics of the structure and to obtain the principal results of simulations. The characterization of the structure showed that, the breakdown voltage is centered at the PN^+ junction of the diode. The Geiger mode can be treated only if the breakdown voltage is controlled in this operating area. The simulations argue that the PN^+ junction may be over-biased and the Geiger-mode can be established in this case.

The basic idea of this new structure lies in the quality of the wafers chosen for manufacturing the devices.

The cartography of the lifetime of carriers for a virgin wafer is given on the Fig. 5.

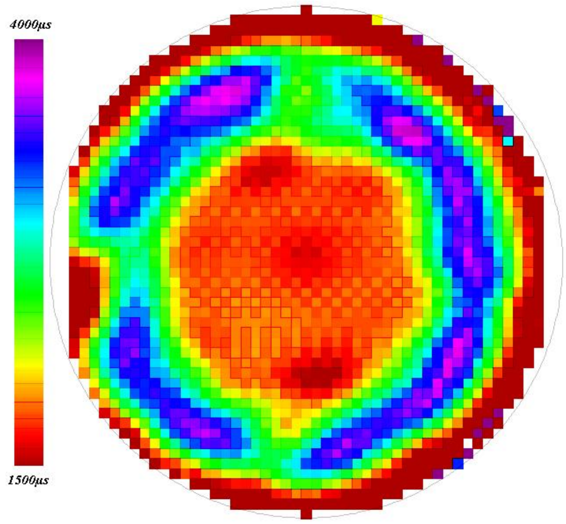

Fig. 5. Lifetime of carriers for one virgin wafer before any thermal steps.

This parameter is likely to undergo deterioration following to the different stages during the process. This deterioration may be limited or even improved by the annealing activation which is a reorganization of the crystal lattice. This cartography shows a lifetime values of the carriers between 1500µs and 4000µs.

IV. The Main Simulated Characteristics

Simulations made on the structure may give at first the characteristic I (V) of the junction.

The graphic giving the current as a function of the operating voltage is represented in the next figure (Fig. 6).

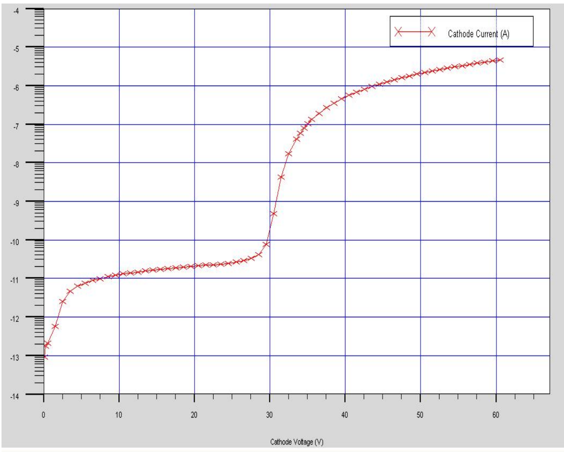

Fig. 6. Characteristic I(V) of the studied junction.

The breakdown voltage represented in this graphic has an important significant for the Geiger mode. The operating voltage of the system is basing on over biasing the diode in beyond of its V_{br}. The V_{ob} is defined by V_{br} + 20%*V_{br}, giving a V_{ob} of around 36V in this technology.

When over biasing the diode, its sensitive area receive photons which if they lead to be absorbed, they produce the avalanche mechanism which gives rise to an electrical signal.

Another important parameter has been simulated in this structure, which is the quantum efficiency (QE). This parameter explains the performance of the component in terms in efficiency of detection. Two kind of QE exists:

1. The optical QE, which gives the number of received photons in the sensitive area as a function of the emitted photons.
2. The electrical QE, which gives the number of detected photons as a function of the received photons by the sensitive area.

Next figure (Fig. 7), shows the global QE of the simulated structure which is the multiplication of two previous terms.

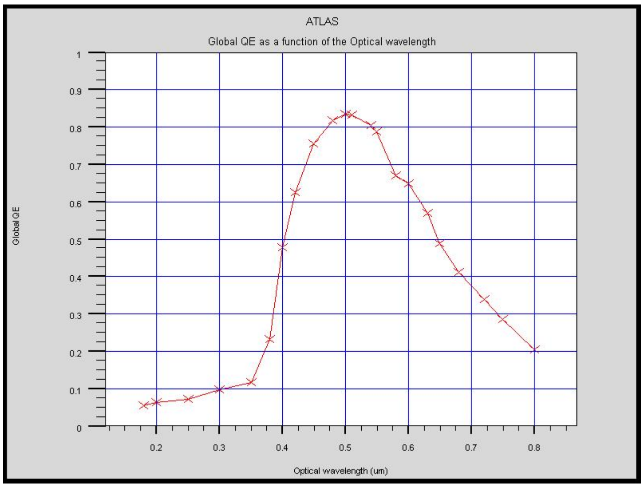

Fig. 7. Global QE as a function of optical wavelength.

This graphic proves an important efficiency of the detector in the visible spectrum. This is an essential result of this detector for its applications.

V. The Main Important Components

In this process, more than one component has been referred. Other the Geiger-APD which is principally the basic element in this domain, there are an additional components that where been designed. In fact, the beginning of the domain of Geiger mode has been initiated with the invention of a new concept of imaging different from the conventional imaging [4]. The idea was to create a matrix of elements without imperative of row/column addressing. This new concept is called SiPM for "Silicon PhotoMultiplier". The matrix is formed by NxN of Geiger-APDs and a quenching resistor is associated to each element.

To represent this concept, the Fig. 8 shows an illustration of a SiPM.

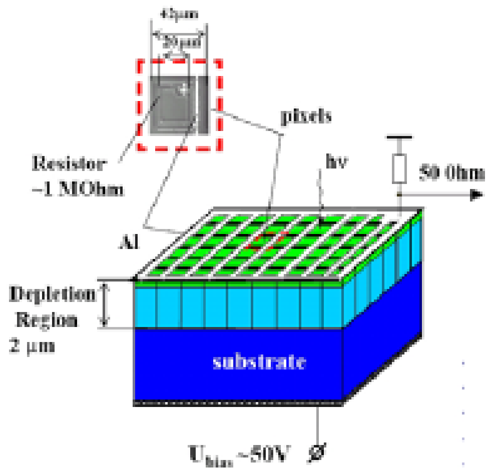

Fig. 8. Illustration of classical SiPM with the associated quenching resistors.

The important advanced of this concept that we have the equivalent of a large APD with an approximated size of $1mm^2$, albeit with less of sensitive area but also less of noise compared with an APD of the same size.

Noise in this kind of component is generally very embarrassed and it increases with the size of the APD [5]. That is why it's mostly preferred to design little APD, pitfalls of being less sensitive area. The SiPM can be designed by hundreds of APDs used in parallel and finally addressed to one output and one electrical signal is delivered. Another way to limit the noise effect is the choice of a very high quality of substrates expressed by a high lifetime and also the minimum of thermal operates during the technological process.

Other components of imaging system has been designed and implemented in this work. The multi-pixels of APDs consider a matrix of elements addressed in rows/columns. The electronic system needed for treatment of imagers is classical. In function of the size of one imager, electronic system is used. A card FPGA can be used if the numbers of I/O are not exceeded the 256 pixels. The reason is in the limited functions of the last FPGA card, they can't support more numbers of I/O. Beyond the number of pixels more than 512, a more completed system must be used, solutions in this case are not numerous, and the only one till now is the ASIC System.

More ideas of imagers are also designed in this process. Other designs will be characterized and detection of single photon will be proved in imaging system. All these results are actually in phase of preparation.

In the table below (TABLE I), a configuration of the designed components are represented with the size of each one.

TABLE I
CONFIGURATION OF EACH COMPONENT

Component	Size
Geiger-APD	100-2500 µm^2
SiPM	0.65-1.2 mm^2
Imager	16 mm^2

V. CONCLUSION

The domain of detection of low light flux has shown an important evolution in the last many years. Numerous studies, modeling and manufacturing have been developed till now. We have presented in this paper the main results of studies, simulations and first fallouts of manufacturing.

Work in this kind of detectors will continue and the principal aim in the future: its implementation in the imagery.

The important parameters of the presented structure have been well studied and calculated. Measurements on all components will be compared with those simulated.

An important advantage has been taken into account: the choice of high lifetime of carriers. The work is being processed in advanced way and drawbacks are improved in comparison with the previous technological process.

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