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SPAD Array Detectors for Astrophysical Applications

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Abstract. Astrophysical studies require more and more accurate, sensitive and fast detectors to detect faint sources with high variability. Since the ST-Microelectronics of Catania has been working on the development silicon devices and monolithic arrays called SPAD (Single Photon Avalanche Diode). These detectors are very innovative and have caracteristics that will offer interesting opportunities in astrophysics and in other science field. We describe the state of the art of the devices, the present limitations, the solutions and the potentialities of these arrays in adaptive optics and for the detection in the visible of astrophysical fast transient phenomena. We, moreover, describe the adopted solutions for the mechanical housing, the detection and control electronics, and report on the relevant electro-optical characteristics of these detectors.

Key words. Single Photon Avalanche Diode (SPAD), SPAD Array, Array Detector, Geiger Mode, Photon Counting, Adaptive Optics, Fast Transient Phenomena.

1. Introduction

In astrophysical observations, a very important problem is the discrimination of weak signal (few photons), that becomes crucial when images are obtained in short acquisition times (from micro to milliseconds). These fast events are typical in adaptive optics (AO) for real-time correction of atmospheric turbulence and in the detection of fast transient phenomena. Current high-sensitivity CCDs manufactured by industry are not able to detect fast and low-intensity sources. Since few years the R&D office of ST-Microelectronics of Catania has started to work on an array of monolithic silicon based devices called SPAD.This innovative device has characteristics and potentialities that can be exploited not only in astrophysical applications but also in the field of nuclear physics or medical imaging.

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2. SPAD Technology

Two epitaxial layers with different level of doping of boron are grown on the N- substrate. The P+ buried layer is introduced in order to reduce the series resistance of the device. The N+P

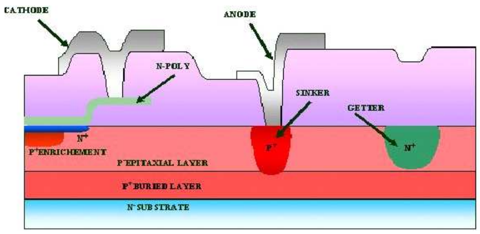

Fig. 1. SPAD Section

junction has a N+ shallow diffusion of arsenic impurities from the N-Poly layer and a controlled boron enrichment diffusion in the central zone of it. The P+ sinkers are created with a high-dose boron implantation step, in order to reduce the contact resistance of the anode and provide a low resistance path to the avalanche current. The regions N+, created with a process of POCl3 diffusion, are introduced to realize a local gettering process useful to reduce metallic contamination. In fig.1 is shown a SPAD section.

3. SPAD Operative Condition

The SPAD is realized with a process similar to that used for avalanche photodiodes that operate in Geiger Mode. These devices are P-N junctions, inversely biased, with voltage values applied so that the electric field is high enough to generate ionization from impact. In dark conditions, when the inverse voltage applied to the SPAD exceeds the breakdown voltage, in a finite interval of time, a couple of carriers can be generated, due to thermal effect, giving the avalanche. If a photon in the aforesaid interval of time and conditions strikes the SPAD, this generates a charge that in turn promotes an avalanche and therefore a macroscopic current flows in the diode.

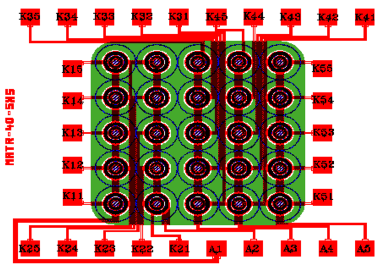

Fig. 2. Layout of 5X5 SPAD Array.

4. SPAD Array

ST-Microelectronics R&D of Catania has developed a monolithic arrays of SPAD. At present, study and characterization of a 55 array (with each SPAD having active area of 40 μm and pitch between adjacent pixels of 240 μm) are in progress. Figure 2 shows the layout of the SPAD array.

5. Detection and Control Electronics

The SPAD is biased and driven by an appropriate detection and control electronics (see fig.3), designed at the COLD laboratory of microelectronics and programmable logic systems of the INAF-Catania Astrophysical Observatory. This circuit, called Active Quenching (AQC), provides for extinguishing the avalanche and bringing the SPAD again in wait conditions, after a programmable hold-off time, making he SPAD ready to detect another photon. The circuit performances are summarised in Table 1.

V Break-Down :	20 V to 35 V
V OverVoltage :	+5 V to + 12 V
T Quenching :	≤ 30 ns
T Hold Off :	100 ns to 500 ns

Table 1

The design of a smart controller, based on a Xilinx Field Programmable Gate Array (FPGA), to drive the SPAD array and provide all necessary circuitry to acquire the image and send it to a host computer is in progress at COLD.

6. Geometric and Relevant Electro-Optical Characteristics

SPAD characterization is carried-out at two laboratories: the COLD laboratory of the INAF-Catania Astrophysical Observatory and the CNR-IMM laboratory. The geometric characteristics, the operating conditions and some results are listed on Table 2.

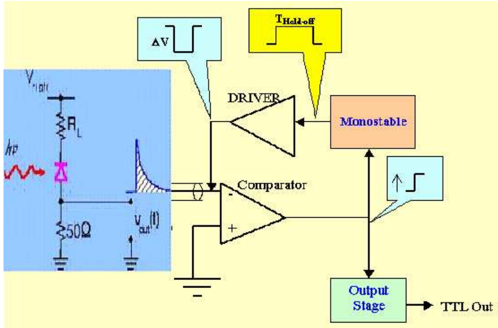

Fig. 3. AQC Block Schematic.

Pixel Diameter :	10 μm to 200 μm
Array pixels :	10 X 10 pixels
Pitch :	$\leq$ 250 μm
Dark @ 27 °C :	$\leq$ 500 c/s (20μm)
QE (V and R) :	50 - 60 %

Table 2

7. Advantages and disadvantages respect to CCD

SPADs are very different from CCDs. They are faster, are made with a simpler technology, are more robust and reliable (due to the silicon planar structure), show Quantum Efficiency (EQ) similar to that of Silicon detectors, and are intrinsically digital. The readout, thanks to appropriate electronic circuits, takes few tens of nanoseconds per photon, and in parallel for all pixels. The SPAD is not affected by readout noise. At the moment the disadvantages (still under study and improvement) are: the fill factor, the electrical and optical cross-talk, the dark count rate, the afterpulsing (spurious counts due to traps) and QE not optimized (no anti-reflection coating is used).

8. Criogenics and housing

To reduce the dark counts at few counts per second, is mandatory to operate the SPAD at temperatures below 0 °C. On the other hands temperatures lower than -30 °C have to be avoided because of the increase of the spurious counts due to afterpulsing. The cooling system works under vacuum conditions and is based on Peltier modules. Hydrophilic material (Zeolite) is used to adsorb contaminating molecule and preserving vacuum integrity.

9. Scientific Applications

SPAD array are particularly indicated for fast transient phenomena, for adaptive optics in the real time correction of the atmospheric turbulence and in the observations of stellar objects with low luminous flux and high temporal variation, like pulsar, polar and asteroseismological objects. Other possible applications include optical biopsy and nuclear physic. Through the phenomenon of the delay luminescence is possible to study the state of biological systems, to mark cancer cell from normal cell of the epidermis. To determine the particle trajectory, SPAD can be coupled to optical fibers scintillators to obtain detectors with resolution times of about 100 ps.

10. Conclusions

SPAD arrays manufactured by ST Microelectronics can be a valid alternative to CCDs and photomultipliers in detecting faint and fast sources. The planar standard technology used for the SPAD allows an high level of integration, and thus a perspective of large arrays can be viable. The preliminary results on dark counts, afterpulsing and quantum efficiency are very promising. To drive and control large SPAD arrays the integration of AQCs will be crucial, and relatively big efforts will be required. Integrated AQCs and SPADs performances optimization can surely lead to a useful device.

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