A CMOS Image Sensor Array Dedicated to Medical Gamma Camera Application

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Abstract

Generally, medical Gamma Camera are based on the Anger principle. These cameras use a scintillator block coupled to a bulky array of photomultiplier tube (PMT). To simplify this, we designed a new integrated CMOS image sensor in order to replace bulky PMT photodetetors. We studied several photodiodes sensors including current mirror amplifiers. These photodiodes have been fabricated using a CMOS 0.6 micrometers process from Austria Mikro Systeme (AMS). Each sensor pixel in the array occupies respectively, 1mm x 1mm area, 0.5mm x 0.5mm area and 0.2mm 0.2mm area with fill factor 98 % and total chip area is 2 square millimeters. The sensor pixels show a logarithmic response in illumination and are capable of detecting very low green light emitting diode (less than 0.5 lux) . These results allow to use our sensor in new Gamma Camera solid-state concept.

I. Introduction.

Gamma camera imaging devices are used in nuclear scanning. By far most widely used gamma camera was invented by H. Anger in the 1960s [1]and thus is also frequently called the Anger camera. Imaging equipment utilizing a radioactive isotope (RI) first appeared as scintillation scanner before undergoing successive improvements leading to the currently used gamma camera developed by Anger camera. As presented in [2], an external view of a gamma camera is shown in figure 1.

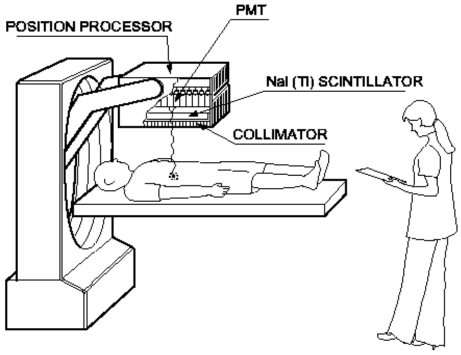


Figure 1. External view of a gamma camera.
(from Hamamatsu : PMT Handbook)

Figure 2 shows sectional views of a detector used in gamma cameras, in which dozens of photomultiplier tubes (PMT) are installed in a honeycomb arrangement. Each PMT is coupled, via a light-guide, to a large-diameter scintillator made from a thallium-activated sodium-iodide (NaI(TI) scintllator), serving as a gamma-ray detector. Three prime feature of gamma cameras are : high sensitivity, broad static field-of-view, high spatial resolution. These features lead to advantages such that rapid changes in the RI distribution can be measured and length of diagnostic time shortened.

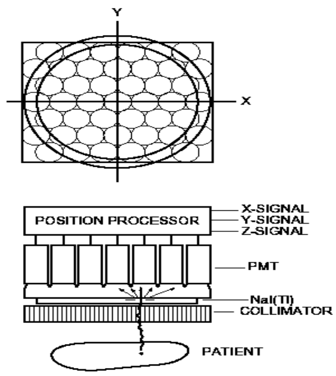


Figure 2. Sectional views of a detector used in gamma camera.
(from Hamamatsu : PMT Handbook)

To make more effective use of these advantages, a variety of gamma-ray nuclide drugs have been developed for used with the gamma cameras. In addition, improvements in the position processing circuit have achieved higher resolution, making gamma cameras more popular in medical diagnosis.

In recent years[3] there has been a growing interest in developing compact gamma cameras to improve nuclear medicine imaging. Conventional full-size gamma cameras using a NaI(TI) scintillator block coupled to a bulky array of PMT are, by nature of their large size,preclude from use in more clinic situation. There are three major design approaches to the development of compact gamma cameras : (1) discrete scintillator/photodiode cameras wherein the gamma-rays interact in an array of optically isolated scintillation crystals coupled 1-to-1 to an array of solid-state photodiode[4]-[7]; (2) solid-state cameras where the gamma-rays interact directly with a pixellated solid-state detector such as CdZnTe [8]-[10]; and (3) position-sensitive photomultiplier tube (PSPMT) cameras where the gamma-rays interact in one or more scintillation crystal which are subsequently read out by a single PSPMT [11]-[16]. The compact scintillation camera uses an array of discrete scintillator crystals and a matching array of photodiodes to detect the scintillation light that result when a gamma-ray is absorbed [5]. This scheme thus replaces the bulky PMT photodectectors used in conventional scintillation cameras with small photodiodes, greatly reducing the camera size as shown in figure 3 In addition, the scintillator CsI(TI) can be used with photodiodes (but not with PMTs) and replaces the NaI(TI) used in conventional cameras, allowing another decreases in camera size since NaI(TI) requires special, bulky packing but CsI(TI) does not.

The compact scintillation/photodiode cameras offer several advantages over conventional scintillation cameras : (1) array of small photodiodes provide improved intristic spatial resolution; (2) the small camera size allows shorter imaging distances, thus improving collimator resolution; (3) the compact design permits a

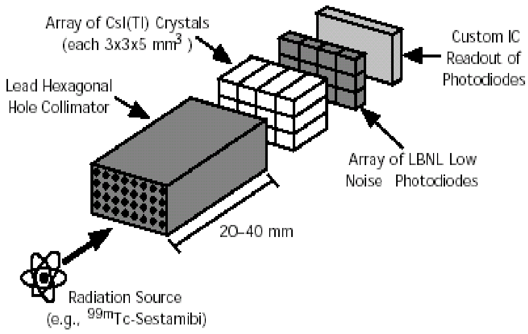


Figure 3. Module of discrete scintillation camera.

greater variety of viewing angles and allows multiple cameras to take different views simultaneously; and (4) the multiple scintillator photodiode channels yield a higher overall maximum event rate; (5) the smaller size lowers cost. The two advances that now make discrete scintillation camera technology a viable option for scintimammography applications are the low leakage current (~50 pA/pixel) photodiode array and the custom IC readout of the photodiode signals. This is important to achieving a compact, cost effective design, because with the many pixels that will be present in a complete camera, discrete electronics become prohibitively bulky and expensive.

In this context we designed a new CMOS image sensor array that we present in this article. We introduce in the second section scintillator photodiode detectors theory. In the third and fourth sections we describe our design of our CMOS Active Pixel Sensor dedicated to Gamma Camera Imaging. In the fifth section we present fabrication and test results about this new sensor.

II. Scintillator Photodiode Detectors.

II.1 Scintillator Detectors.

A scintillator is a material that converts energy lost by ionizing radiation into pulses of light[18]. Pulses of light emitted by the scintillating material can be detected by a sensitive light detector. The combination of a scintillator an a light detector is called a scintillation detector. Since the intensity of the light pulse emitted by a scintillator is proportional to the energy of the absorbed radiation, the latter can be determined by measuring the pulse height spectrum. To detect nuclear radiation with a certain efficiency, the dimension of the scintillator should be chosen such that the desired fraction of the radiation is absorbed. Furthermore, the light pulses produced somewhere in the scintillator must pass the material to reach the light detetor. This imposes constraints on the optical transparency of the scintillation material. The thickness of a scintillator can be used to create a selected sensitivity of the detector for a distinct type or energy of radiation. Thin (e.g 1 mm thick) scintillation crystals have a good sensitivity for low energy X-ray but are almost insensitive to higher energy background radiation. *Large volume scintillation crystals* with relatively thick entrance windows do not detect low energy X-rays but measure high energy *gamma rays* efficiently. Each scintillation material has a characteristic emission spectrum. The shape of this emission spectrum is sometimes dependent on the type of excitation (photon/particles). This emission spectrum is of importance when choosing the optimum readout device (PMT/*photodiode*) and the required window material. Figure 4 and 5 show the emission spectrum of some common scintillation material.

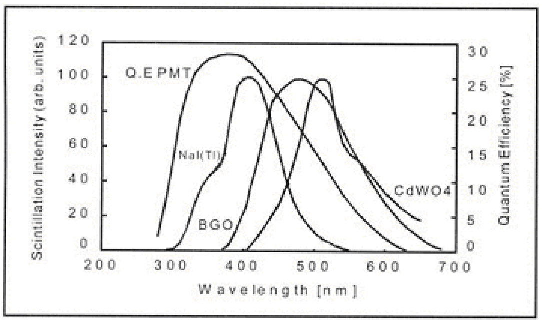


Figure 4. Emission spectra of NaI (TI), BGO and $CdWO_4$, scaled on maximum emission intensity.

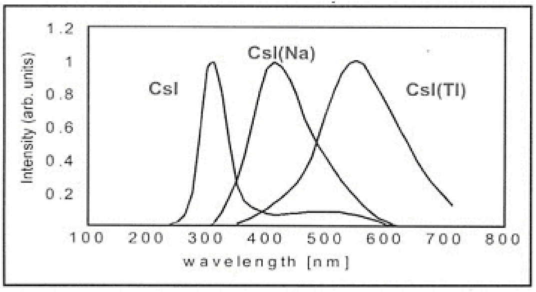


Figure 5. Emission spectra of CsI, CsI(Na) and ScI(TI) scaled on maximum emission intensity. Also a typical quatum efficiency curve of a bialkali photocathode is shown.

The light emitted by a scintillation material must be detected using some kind of sensitive light detection device. An alternative way to detect the scintillation light from a crystal is use of a silicon photodiode.

II.2. Photodiode.

Photodiode is a semiconductor device which consists of a thin layer of silicon in which the light is absorbed after which free charge carriers (electrons and holes) are created[19]. Electron and hole are collected at the anode and cathode of the diode. When a semiconductor is illuminated by light having an energy greater then its band-gap energy, the light is absorbed in the semiconductor and electron-holes pairs are generated. Those photoinduced electron and holes recombine radiatively (photoluminescence) and non radiatively. If an electrical field is applied to the semiconductor, some of the induced carriers take part in electric conduction and this leads to decrease in electrical resistance of the semiconductor. This is called photoconduction. If there is a *pn*-junction in the illuminated area, the electrons and the holes are separated by the electrical field at the pn-junction without any electric bias, and an electromotive force between the *p*- and *n*- side semiconductor is generated. This is called the *photovoltaic effect*, and with regard to the effect there is basically no difference between a *pn*-junction an a *pn*-heretojunction. Based on the phenomena described above, light power can be converted into electrical power in photodiode. A bias circuit for photodiodes and current-voltage characteristics under light illumination are shown schematically in figure 6.

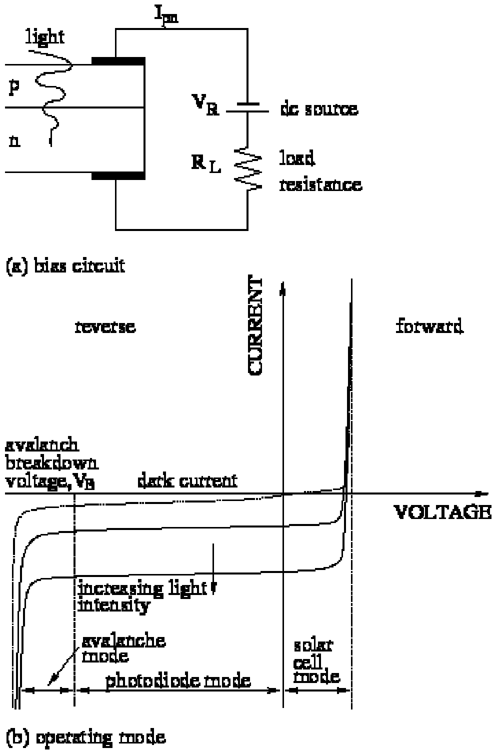


Figure 6. Photodiode (a) bias circuit and (b) operation mode

When these photodiodes are optically coupled to a scintillation crystal, each scintillation light pulse will generate a small charge pulse in the diode which can be measured with a charge sensitive preamplifier. Alternatively , the current produced in the diode can be measured. The quantum efficiency of silicon photodiode is typically 70% between 500 and 900 nm but decreases rapidly below 500 nm as shown in figure 7.

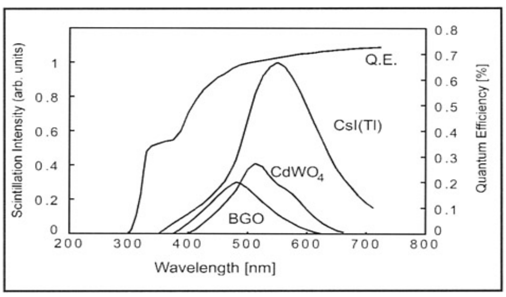


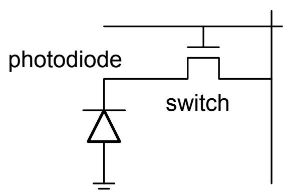
Figure 7. Quantum efficiency cure of a silicon photodiode together with the emission spectrum of CsI(TI), $CdWO_4$ and BGO.

It is clear that the highest signals can be expected from scintillation crystals that have an intense emission above 500 nm. CsI(TI) crystals, characterized by a large scintillation intensity with a maximum at 550 nm, are therefore well suited to couple photodiode. In contrary to photomultiplier, photodiode do not require a high voltage (HV) power supply but only a bias voltage of about 30 V. Photodiode are thin, rugged and insensitive to magnetic fields. Furthermore, the output signal from a crystal/photodiode detector is very stable due to the absence of drif of the diode gain since no charge amplification takes place in the device itself. Photodiode are thin (several mm) which can be advantageous. In oerder to implement solid state photdiodes, we used CMOS Active-Pixel Sensors (APS) Architecture. We present this architecture in the next section.

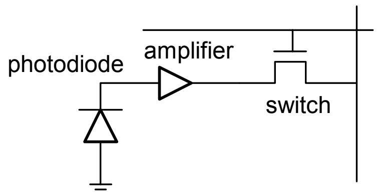
III. CMOS Active Pixel Sensor Design.

III.1 CMOS Imaging Sensor Architecture.

CMOS (Complementery Metal Oxidizes Semiconductor) Sensors intended for imagery cause much interest for industrial applications and research. These sensors based on this technology exceed the traditional sensors based on technology CCD (Charge Coupled Device) by offering many advantages: weak manufacturing cost compared to a CCD sensor, integration facility of multiple functionalities intended for imagery, high space resolution and pixels random access. Some disadvantages of CMOS sensors compared to CCD sensor are noise of reading which is more important and sensivity which is less important. CMOS imaging sensors use active or passive pixels as in figure 8. Active-pixel sensors (APSs) include amplification circuitry in each pixel.



(a)



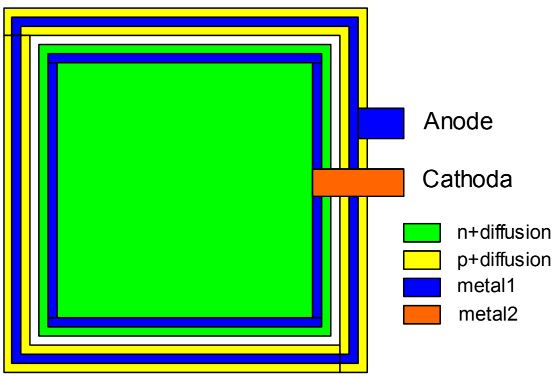
(b)

Figure 8. (a). passive pixels (b) acitive pixels

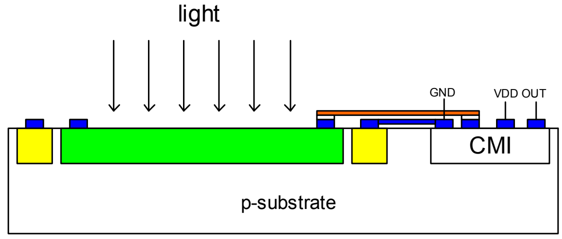
In order to test feasibility of using CMOS APS in solid state gamma cameras, we designed specific CMOS photodiodes that we describe hereafter.

III.2 Pixel Design Description.

Schematic and layout of a single pixel are shown figure 9. The pixel is realized using a photodiode formed by n+diffusion (n) and p+diffusion (p) in the p-substrate (photodiode type N). The cathode of the photodiode consist of a square of diffusion connected on all its periphery by a whole of contacts connected in crown. This provision makes it possible to reduce the resistance of the contacts. The anode is carried out by surrounding the photodiode of a ring of polarization of the substrate, this to limit the resistive effects of the substrate. The contacts of these two crowns are carried out with the minimum step authorized by technology[21]. The photodiode is forward biased, and when incoming photons are absorbed, a photocurrent proportional to the intensity of light flows through the photodiode. This current is converted to output voltage value using Current Mirroring Integration (CMI) readout circuits.



(a)



(b)

Figure 9. (a) Structure of Photodiode (b) Structure of CMOS Image Sensor using CMI readout Circuits.

Figure 10 shows the schematic of CMI readout circuits. The induced current on the forward biased detector photodiode is copied through a pMOS-nMOS combination of current mirror [20].

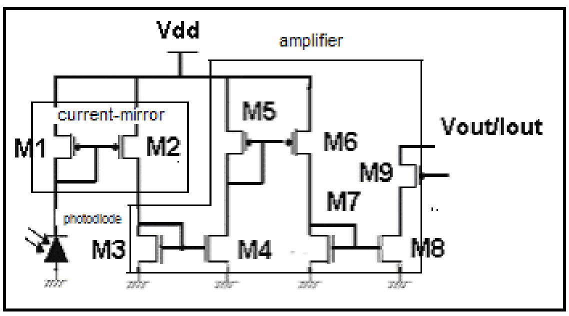
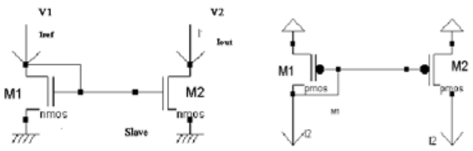


Figure 10 .Schematic of the Current Mirroring Ingration readout Circuits

CMI readout active pixel sensors are inherently advantageous in terms of readout speed because the fixed output line voltage at input of transresistance amplifier prevents charge-discharge phenomena . Another benefit of current readout is *current-mode* processing which is relatively compact in size and simple in its operations. Thus, in current-mode, the photo-current of detector can be mirrored and readout directly. We used current-mirror circuits in our pixel and we present the details of this hereafter.

III.3 The Operation of current mirror.

Current mirror circuits in its most simple configuration, consists in two MOS transistors as in figure 11.



(a) (b)

Figure 11. current mirror principles in (a) nMOS and (b) pMOS.

A current Iref flowing through the nMOS device M1 is copied to the nMOS device M2. If the size of M1 and M2 are identical, in most operating conditions, the current are the same. The remarkable point is that the current is almost independent of the drain voltage of the M2. if the ration W/L of the M2 is 10 times the ratio of the M1, the current on the right branch is 10 times the current on the left branch.

A current-gain analysis of current-mirror nMOS[22]. in figure 10(a) :

-M1 operates in saturation.

$$I_{ref}=I_1=\frac{k'}{2}\left(\frac{W}{L}\right)_1\left(V_{GS1}-V_{TH}\right)^2\left(1+\lambda V_{DS1}\right) \quad (5)$$

$$V_{DS1}=V_{GS1}=V_{GS2}$$

k'=current gain.

-if M2 operates in saturation.

$$I_{out}=I_2=\frac{k'}{2}\left(\frac{W}{L}\right)_2\left(V_{GS2}-V_{TH}\right)^2\left(1+\lambda V_{DS2}\right) \quad (6)$$

$$I_{out}=I_{ref}\frac{\left(\frac{W}{L}\right)_2\left(1+\lambda V_{DS2}\right)}{\left(\frac{W}{L}\right)_1\left(1+\lambda V_{DS1}\right)} \quad (7)$$

IV. Simulation and Layout of Current-Mirroring Integration CMOS circuit.

For simulation and layout of our current-mirror CMOS circuit, we used the Mentor Graphics CAD tools in combination with the 0,6 µm CMOS design kit from AMS (Austria Mikro System). In order to process the data provided by the photodiode, we tested circuits allowing the amplification and the selection of our signal.

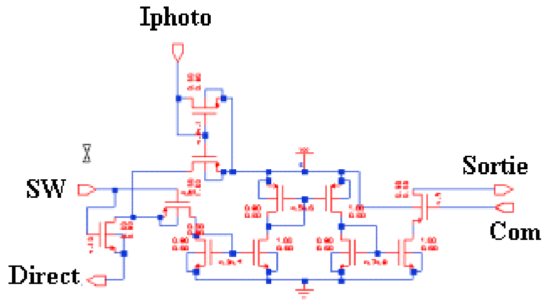


Figure 12. Current-mirror circuits with combination nMOS and pMOS .

In figure 12, we added two more CMOS transistors (nMOS (M10) and pMOS (M11)). This allows to read the outputs of this circuits, before or after amplification. The circuit has two switches (sw and com) and two outputs (direct and sortie). Figure 13 shows the layout of the current-mirror circuit with combination of nMOS and pMOS transistors.

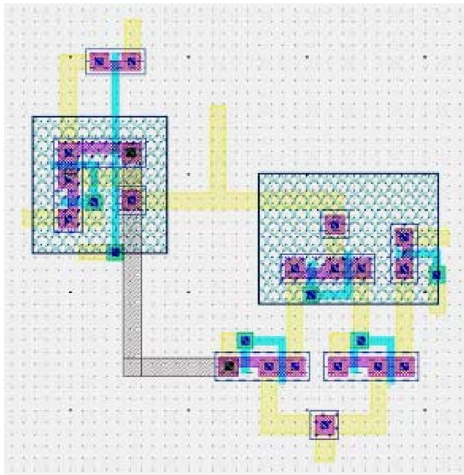
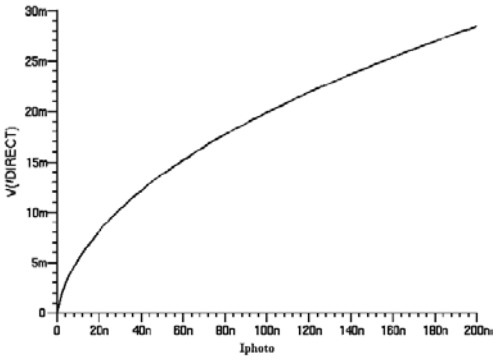


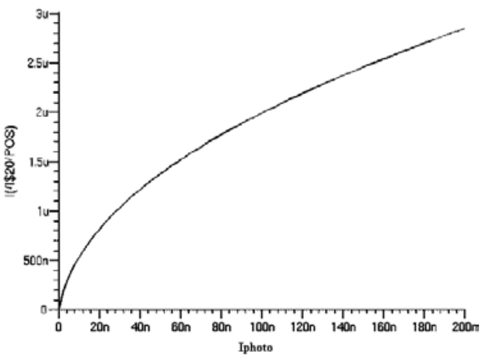
Figure 13. Diagram of Layout the current-miror combination nMOS and pMOS.

The circuit operations are very simple: the current I_{photo} passes through M1 and is mirrored to M2 using current mirror. If 5 volts is applied to switch SW and COM, the obtained results at the DIRECT output, are amplified by the current-mirror with combination of nMOS and pMOS transistors, as illustrated in figure 14. If 0 volts is applied to switches SW and COM, the results at SORTIE output, are amplified by the current-mirror with combination of nMOS and pMOS transistor, as illustrated in figure 15. For simulation, we used in place of the photodiode, a current generator with a variation from 0 to 200nA.

-Results of simulation: when 5 volts is applied to SW and COM.



(a)



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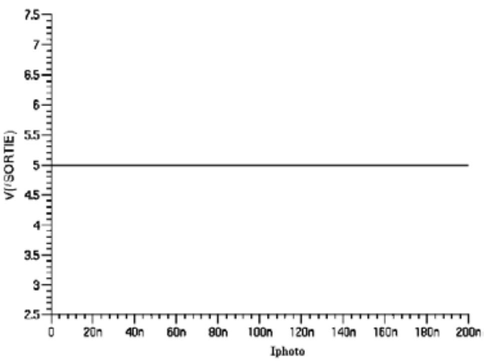

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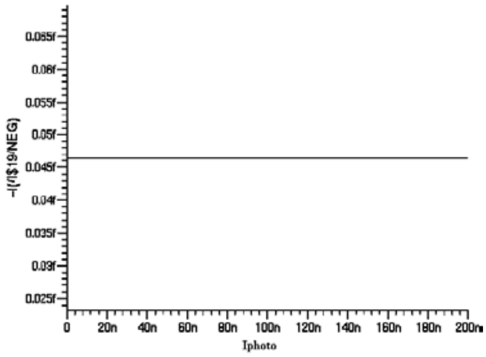
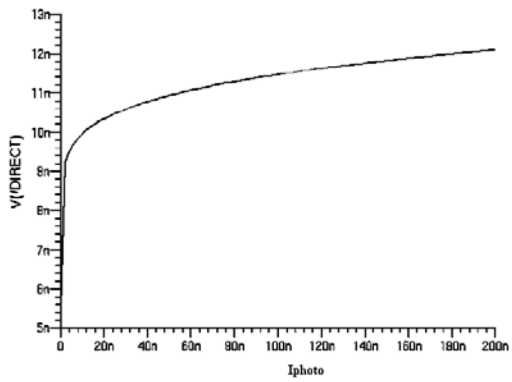


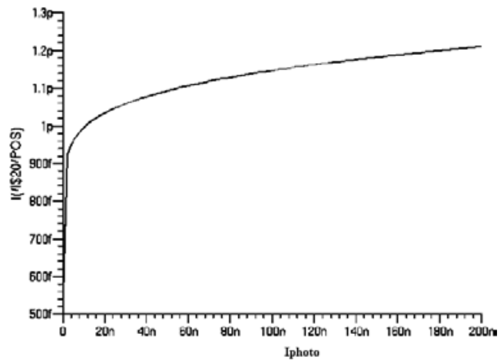
(d)

Figure 14. Output at Direct (a) in voltage (b) in current and at Sortie (c) in voltgae (d) in current.

-results of simulation : when 0 volts is applied to SW and COM.



(a)



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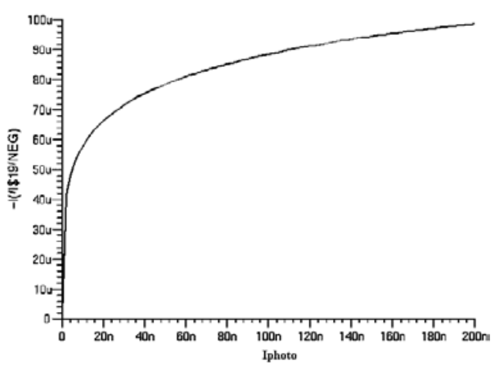

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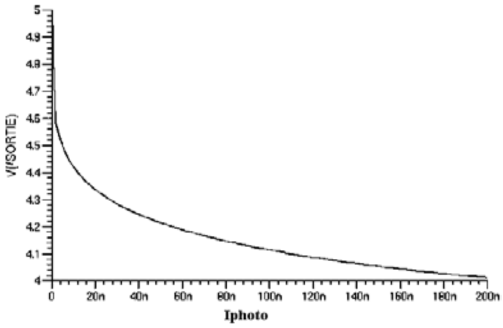


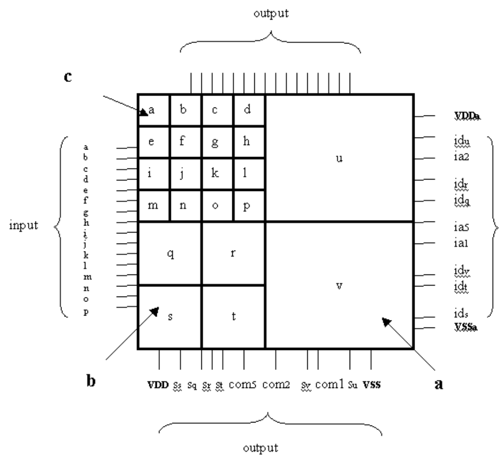
(d)

Figure 15. Output at Direct (a) in voltage (b) in current and at Sortie (c) in voltgae (d) in current.

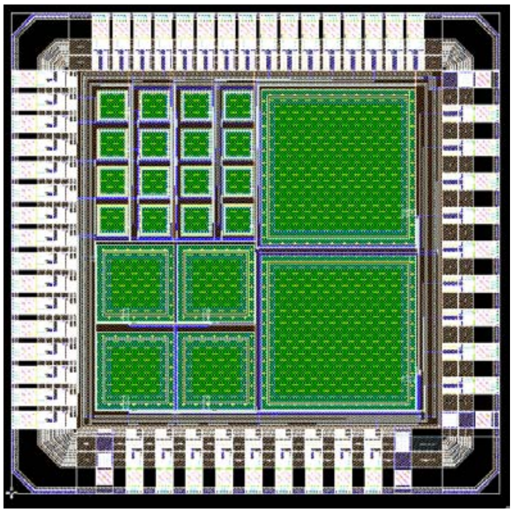
From the results of simulation, it is visible that the current mirroring integration circuit achieves a high current gain.

V. Fabrication and Test Results

Figure 16 shows a block diagram, layout and photograph of small test pixels implemented in a standard 0.6 µm CMOS process from AMS. The chip consists mainly of current-mirror active pixels with different sizes : (a) 1x1 mm^2 (the two pixels: u and v), (b) 500x500 µm^2 (the four pixels: q, r, s and t) and (c) 200x200 µm^2 (the sixteen pixels: a - p), each constituted of a photodiode with control switch and current output amplifier circuits.



(a)



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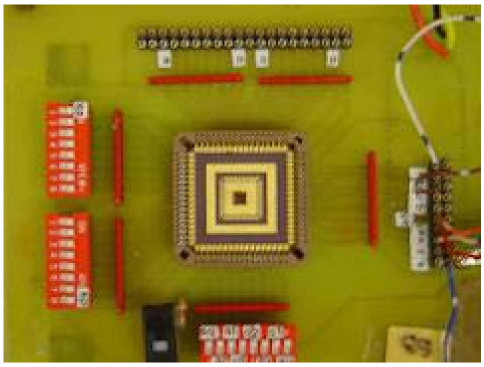


(c)

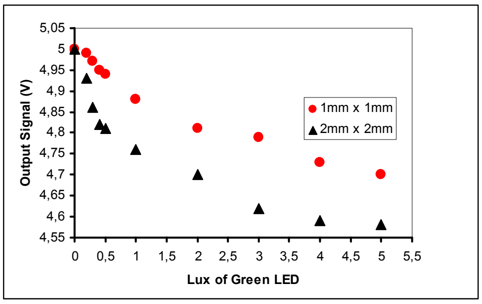
Figure 16. (a) Blok diagram , (b) Layout Of the Detector Pixel with a 2mm x 2mm area in a 0.6 µm CMOS process, (c) photograph of photodiode sensors .

The photo response of test photodiodes on the chip is obtained by measuring the photo current under illumination (Lux) from green and red light emitting diode. Table 1 summarizes the overall measurement characteristics.

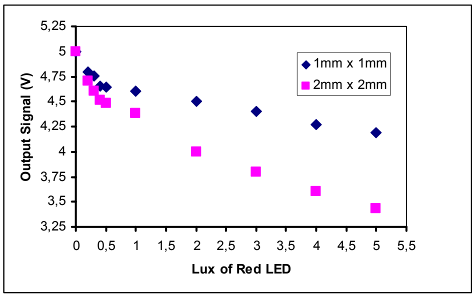
Table 1 .The measurement characteristics

Parameter	Result
Technology	0.6 µm CMOS, 2-layer Metal et 1-layer Poly
Photodetector	Diffusion N+/ P Substrat
Sensor Area	2 mm x 2 mm
Pixel Pitch	1 mm x 1mm, 0.5 mm x 0.5 mm and 0.2 mm x 0.2 mm.
Fill Factor	98 %
Spectral Respon	700 nm (RED) and 585 nm (GREEN) .
Power Supply	5 Volt
Response in Illumination	Logaritmic

Figure 17 shows variations output voltage with light intensity of green and red lights emitting diode. It shows a logaritmic relation of output signal in function of emitting light (Lux).



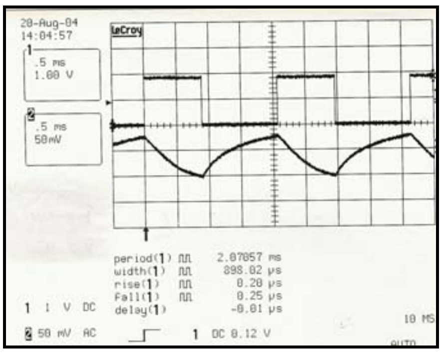
(a)



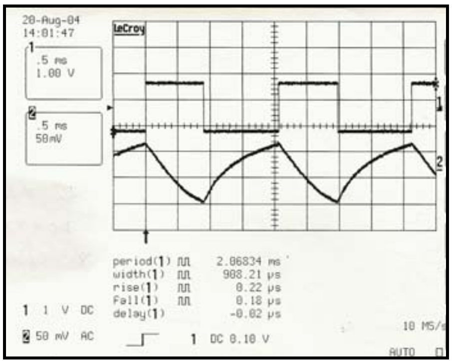
(b)

Figure 17. Output signal of pixels :1mm x 1mm and 2mm x 2mm with (a) lux of green led ,(b) lux of red led

Figure 18 shows variations of photo current in dynamic mode. In this mode, light emitting diode is driven with a pulse generator. Results presented in figures 18a and 18b are obtained with a green LED calibrated for a 0.4 lux illumination and in figures 18c and 18b are obtained with a red LED calibrated for a 0.3 lux illumination. In these figures the upper curves represent the LED voltage input and the lower curves represent the sensor output.



(a)



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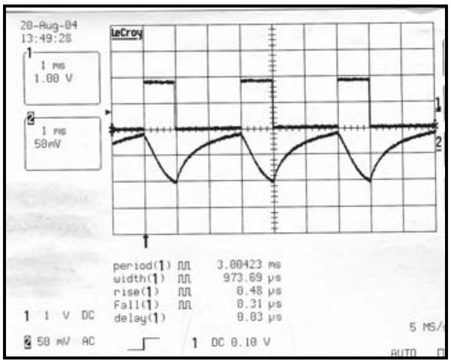

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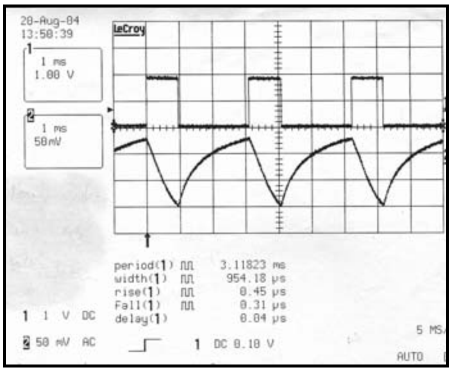

(d)

Figure 18. Photocurrent in dynamic mode :
(a)1mm x 1mm area and (b) 2mm x 2mm area with green LED,
(c)1mm x 1mm area and (d) 2mm x 2mm area with red LED

VI. Conclusions and Perspectives.

A 2 square millimeters area of CMOS active photodiode sensor with current mirror amplifier has been fabricated using a 0.6 µm CMOS process. The experimental results show that this sensor has logaritmic response in illumination and is capable of detecting very low green lights emitting diode. These results allow us to consider using of this tehnology in new solid state gamma cameras.

In order to improve sensitivity of our pixels, we are designing a new architecture of pixels with a better response in the blue wavelength

VII.References

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