

CMOS Monolithic Active Pixel Sensors (MAPS): developments and future outlook

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Happy New Year!

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Abstract

Re-invented in the early '90s on both sides of the Atlantic, Monolithic Active Pixel Sensors (MAPS) in a CMOS technology are today the most sold solid-state imaging device, overtaking the traditional technology of Charge-Coupled Devices (CCD). The slow uptake of CMOS MAPS started to low-end applications, like for example web-cams and is slowly pervading the high-end applications, like for example in prosumer digital cameras. Higher specifications are required for scientific applications: very low noise, high speed, high dynamic range, large format and radiation hardness are some of these requirements.

This paper will present a brief overview of the CMOS Image Sensor technology and of the requirements for scientific applications. As an example, a sensor for X-ray imaging will be presented. This sensor was developed within a European FP6 Consortium, I-ImaS

Keywords: pixel, sensors, imaging, CMOS

1. Introduction

In the early '90s, CMOS Monolithic Active Pixel Sensors (MAPS) were invented for the detection of visible light. It was immediately recognised they promise several advantages [1, 2] over existing imaging devices, in terms of functionality, power, radiation hardness, speed and ease of use. They were first used in low-end imaging products, like web cams, toy cameras, etc... Continuous improvement in the technology, reducing the dark current and improving the electronic noise, have made CMOS sensors gain more and more ground and today, CMOS sensors are the dominant image sensing device, and gaining ground in high-end prosumer applications too.

Because of the even higher requirements, applications of this technology to scientific applications are somehow lagging behind, although some examples can already be found in the literature [3, 4, 5, 6]. This paper will briefly review the state-of-art of the CMOS Image Sensor technology and then explore the requirements for sensors for scientific applications. It will also illustrate an example of a CMOS sensor developed for X-ray imaging, for medical and security applications.

2. CMOS Image Sensor Technology

In general, the basic devices in a CMOS process are the PMOS and NMOS transistors corresponding to that specific feature size. This allows the design of complicated logic functions. Other devices need to be generated in order to make the process usable for different functions. For example, transistors with different threshold voltage V_{th} make possible to trade-off between different parameters, like speed, leakage current or voltage swing. Different types of resistors and capacitors can also be added, including precision components, needed for the design of analogue circuits. The end result is that for a specific feature size, a CMOS process normally consists of several flavours: the logic/digital one is the basic one; the analogue process includes the precision passive components; the high-voltage flavour would include higher threshold voltage, as needed for example in automotive applications. Some processes also

propose flash-memory modules as well as image sensors.

In the image sensor flavour, special processing steps are often added to optimize key imaging parameters like leakage current and optical response. The process is normally implemented on an epitaxial layer as this gives better imaging performance, including better control of lateral cross-talk. The absorption length of visible light requires only a few micron thick epitaxial layer, but for application aiming at near infrared detection, thicker substrates are used, generally up to 20 μm . Special BEOL (Back-End-Of-The-Line) processes are also used to improve the optical transmission of the passivation layers [7, 8], which would otherwise tend to be quite opaque in deep sub-micron processes with multiple routing metal layers. As consumer and prosumer colour cameras applications are the driving force for the development of the image sensor flavour, many foundries give also the possibility of designing and processing microlenses and colour filters. Many foundries also have pixel IPs that can be used to readily generate arrays with proven performance. The availability of pixel IPs is particularly important when a 4T (4 transistors) pixel is needed as this structure requires special optimization [9] of the implants to insure proper functioning of the pinned diode/transfer gate combination to give full charge transfer. The push towards the development of 35mm sensor for the replacement of films is also making more and more foundries develop stitching modules so that sensors larger than one reticle, which is usually about 20-25 mm in side, can be fabricated. This is of course very convenient for scientific imaging as it is often required to design sensors with very large physical size.

3. CMOS Sensor for scientific applications

In this section, we want to first briefly describe the requirements for CMOS sensors for scientific applications, and then we will give one example of a CMOS Monolithic Active Pixel Sensor designed for X-ray detection for medical and security applications.

3.1. General requirements

A schematic cross-section of a CMOS sensor is given in the figure below. Electron-hole pairs are generated by the impinging radiation. The electrons, the minority carriers in the P-doped epitaxial layer, diffuse and drift and are eventually collected by the N-well to P-epi diode [10]. The silicon band-gap sets the cut-off wavelength at $1.1 \mu\text{m}$, in the near infrared. The epitaxial layer can be considered as the detecting volume, although part of the charge generated in the first few microns at the transition between substrate and epitaxial layer will diffuse into the epitaxial layer where it can then diffuse and drift towards the collecting diode. The thickness of the epitaxial layer, generally up to $20 \mu\text{m}$, determines the maximum energy of photons for direct detection. At 4 keV , about 90% of the impinging X-rays are absorbed in a $20 \mu\text{m}$ silicon substrate, but then the efficiency drops rapidly and it is of only 2% at 20 keV . So for efficient detection of X-rays a converter, typically a scintillator, needs to be used. It should also be noticed that in the ultraviolet region, the absorption length is so short that the passivation layers would make the sensor very inefficient for front-illumination. It is then necessary to remove the thick P-doped substrate and back-illuminate the device in order to achieve high-efficiency [3].

The signal generated by radiation is relatively small: one visible light photon will generate only one electron-hole pair, while for photon energies sufficiently high or for charged particles, the number of electron-hole pairs will be given by the energy loss ΔE divided by 3.6 eV/pair . Low noise is then of paramount importance. In imaging applications, dynamic range is also important, and the two requirements of low noise and large dynamic range can be somehow conflicting [11].

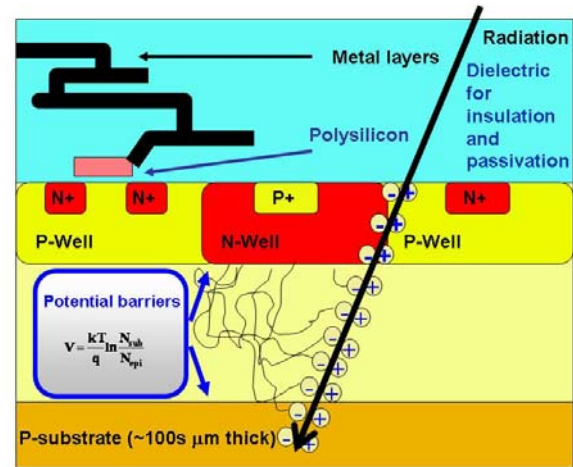


Figure 1. Schematic cross-section of a CMOS Image Sensor

Scientific applications require a large range of integration time, in the range of nanoseconds or below in some applications like measurement of lifetime of fluorescence decay, up to seconds or more in applications like astronomy. In long integration time applications, leakage current can be the limiting factor and devices might need to be cooled.

The readout rate can also be very challenging. For fast imaging applications, where every pixel needs to be readout, and with typical sensor formats ranging in millions of pixels, data rate of the order of 100 Mbytes/second are encountered, but more could be required for applications at bright light sources like synchrotrons or X-ray free electron lasers. These high data rate sets also severe constraints on the data acquisition systems as typically only lossless compression can be applied so that the data acquisition must be able to sustain the data flow coming from the sensor and transfer the data to a storage volume at the same speed.

In applications like particles physics, where the image is essentially formed by a few spots on a black background, on-chip or even in-pixel data sparsification can become a must. This normally requires the use of complex electronics inside the pixel. With the architecture presented above only NMOS transistors can be integrated while retaining high detection efficiency. Different ways to overcome this limitation are currently being explored. One way would be to design the sensor and the electronics on two or more different substrates ad

then connect them together through vias in the silicon [12]. A second route to full electronics in a high efficiency pixel is to use silicon-on-insulator (SOI) CMOS, where the handle wafer is made of high resistivity silicon and then vias between the electronics and the handle wafer are produced in the buried oxide. Good preliminary results have now been obtained and a depletion depth of up to almost 50 μm achieved [13].

Radiation hardness is also important in many scientific applications. Typical radiation hardness requirements are in the order of Mrads or tens of Mrads and of 10^{14} - 10^{15} hadrons/cm².

Last, one should not forget that the size is also important. While in prosumer/consumer applications the emphasis is on very small pixels as light can be focused and sensor cost is important, in most scientific applications neither of these two aspects is present. Very seldom pixel size of the order of 10 μm is required and it is more common to see pixel requirements in the order of 50 μm or even more. As the pixel counts is still normally high, in excess of a million, this means that the physical size of a sensor tends to be quite large. A 25- μm 1kx1k sensor, would have a focal plane of 25mmx25mm in size. As some space is required on the periphery for the readout electronics and for the connectivity, such a sensor would probably exceed the size of a reticle. Stitching would then be needed. This makes possible to design full wafer sensors, where normally the sensor is 200 mm in diameter. The maximum usable square is then about 13cmx13cm.

3.2. An example. CMOS Sensor for X-ray imaging

Examples of CMOS sensors in several scientific applications can be found elsewhere. Here we just want to present some results obtained with a sensor designed for an X-ray application. The sensor was designed within a FP6-funded European consortium, called I-ImaS, and is part of a novel concept of an X-ray camera. In this novel concept [14, 15], the camera is made of two lines of sensors and a full image is obtained by scanning the two lines across the image. Collimators ensure that only the area above the sensors is exposed, thus ensuring a low dose is delivered to the patient. The presence of two lines is the key to the new concept. The first line in the

direction of scanning produces a ‘scout’ image. This image is processed in real time in order to find interesting features. By a special system of collimators, only parts of the image containing interesting features would be analysed by the second line, thus ensuring that the best image quality is obtained in those areas that most need it. A step-and-shoot scanning movement is used as continuous scanning would not deliver the required signal-over-noise ratio [16], contrary to what happens in charged-coupled devices, where time delay integration (TDI) is possible.

A full description of the sensor is given in [6]. Here we just want to remind the basic features. The sensitive area of the sensor consists of an array of 512x32 32- μm pixels, each of them consisting of a standard three-transistor (3T) architecture. On each side, 4 rows and 4 columns are added to reduce the edge effects so that the array is overall made of 520x40 pixels. The pixel addressing is controlled by shift-registers and the sensor is read out in a rolling-shutter mode. A programmable 4-bit fixed pattern noise (FPN) mitigation circuit is present in each column. 32 columns are multiplexed into a single programmable gain amplifier (PGA), where a gain of 1 or 2 can be selected. The PGA is connected to a 14-bit successive approximation ADC. A conversion is performed in 16 clock cycles of a 20 MHz clock, corresponding to a conversion rate of 1.25 MHz or 800 ns per conversion. The ADC architecture is based on a hybrid resistor-capacitor charge redistribution topology [17], with 4 MSBs resolved by means of a resistor string and the 10 LSBs using a capacitor array. The choice of this topology come from considerations on area, power consumption and conversion speed. To reduce the total capacitance and the matching requirements, the array has been split in two sub-arrays connected by a series capacitor, at the expense of including a calibration block, which compensates for the mismatch due to the total parasitic capacitance associated to the floating internal node of the array. The ADC can be tested separately from the array and no missing or repeated code was found.

The sensor noise is dominated by the reset noise and, given the input capacitance, the reset noise is 48 electron rms, while the full well capacity is of about 200k electrons, giving a dynamic range of 72 dB.

The output multiplexer scans through all ADCs' outputs and splits them to be sent out on a 7-bit bus at 40MHz rate. Since there are 16 ADCs and it takes 16 clock cycles for a conversion, there's no dead time and all data are read out before a new sample (next pixel value) is converted.

The sensor was extensively tested both optically and with X-ray before mounting the scintillators and then with the scintillators with X-ray. The measured performance is in good agreement with the simulation results.

The whole camera consists of two lines of 10 sensors and is currently assembled. Results from the full camera will be presented elsewhere. Here we just want to show the good imaging performance of a

single sensor module. Images of different objects were obtained by scanning the sensor across the imaging area. All images were then stitched together by using the correct pixel overlap. Gain corrections were then applied to take into account both variations in gain within the sensor and variation in beam intensity during the scan. Below is an image of a sensor mount ceramic card. The image shown below was taken at 75 kVp and 4 mA. The card is 30x10mm and the distance between each scanning step was taken equal to 832 μm , corresponding to 26 pixels. The integration time for each single step was 10 ms. For this image, the sensor was coupled to an unstructured CsI scintillator.

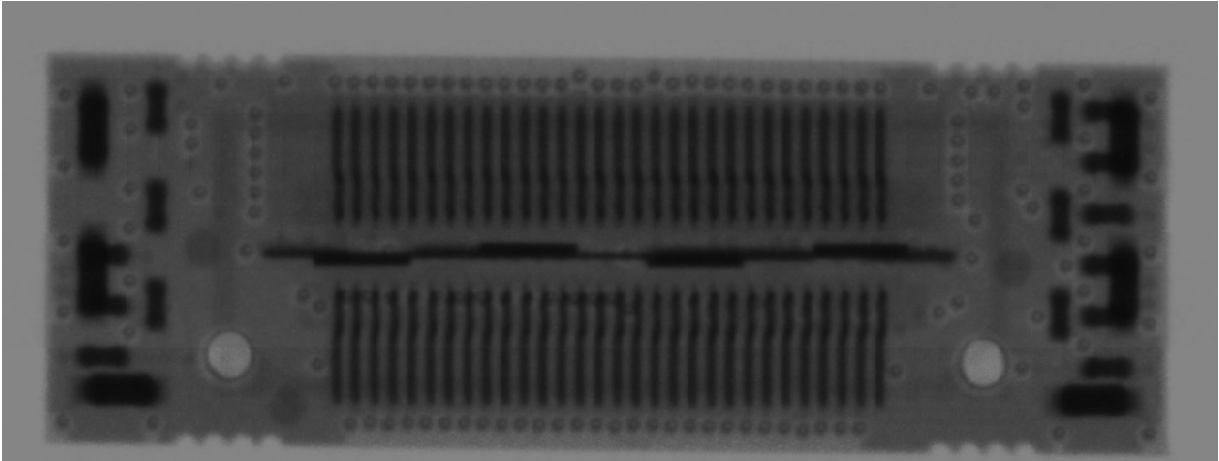


Figure 2. X-ray image of an I-ImaS sensor mount card taken with the I-ImaS CMOS Image Sensor coupled to a scintillator.

4. Conclusions

Driven by consumer and prosumer applications, CMOS technology has evolved in order to provide good performance to CMOS image sensors. Nowadays, among the other flavours, many foundries propose a CMOS Image Sensor (CIS) flavour as well. Apart from improvement on imaging performance, stitching is also often proposed so that large sensors, up to the full wafer size, can be designed.

All these improvements made CMOS Monolithic Active Pixel Sensors (MAPS) more and more appealing for a variety of scientific applications, with very stringent requirements. CMOS MAPS can then

be used for the detection of photons from infrared up to low energy X-rays in direct detection, higher energy X- and γ -rays when coupled to a scintillator and for direct detection of charged particles. In this paper we presented some recent results from a CMOS Image Sensor designed to be coupled to a scintillator for the detection of X-rays in the energy range of interest for medical, mammography and dental, applications as well as for security. The sensor, which includes sixteen 14-bit successive-approximation ADCs, was designed and manufactured in a 0.35 μm CMOS Image Sensor technology and extensive tests show it works according to specifications. First images were obtained with a single-sensor module and the full X-

ray camera, with two lines of 10 sensors for adaptive imaging is currently being assembled.

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