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A SHORT PROSPECTIVE REVIEW ON ACTIVE PIXEL SENSORS

Nicolas T. Fourches
DAPNIA/SEI , CEA Saclay , Bat 141
91191 GIF/YVETTE CEDEX France

FOREWORD :

This short review was made to summarize the present knowledge in the field of Active Pixel Sensors , F. Darnieaud ask me to do this work . I apologize for the use of english instead of french but I must meet the potential need of a large diffusion of useful information , if necessary.

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I – Are APS (Active Pixel Sensor) the future for imaging ?

1- Reasons for the development of a new kind of imaging sensors

Imaging requires now a high integration density , a reduction in power consumption and an increase in sensitivity because the applications of imaging sensors widens. High definition television (HDTV) is the most important of all requiring a important number of pixels and a reasonable frame rate. The development of a camera on the chip (see [FOSS97] , [HAUS96] , [SOLI96] , [YADI97]) is clearly the aim of such research efforts. Other applications for the detection of other particles than visible light can be met by imaging sensors (particle detectors spectrometers , detectors for (high energy[KUCE99] , nuclear , astro) physics or medical sciences. The choice of a technology for these applications depends on many requirements (frame and readout rate , pixel density ,total number of pixels etc..). Semiconductor based sensors are basically CCDs or of the APS type.

2- Advantages of Active pixel sensors compared with CCD

For the past twenty years a lot of research has been done on CCD based imaging sensors . CCDs (Charge Couple Devices) were more simple to develop than other type of sensors to reach high integration densities. Because of their sequential access the total number of devices per pixel is reduced to zero . In spite of that a number of drawbacks appears [FOSS93] . The most important is the charge transfer ratio which reduces as the number of pixels increases. The second is the access time to the pixel which , because of the sequential nature of addressing is more important than if a random addressing scheme was used instead [DIER96] [SCHE97] [FOSS97 and references therein]. These considerations have lead to an increased effort to the development of pixel sensors based on random addressing . Similar sensors were in fact developed in an early stage (the nineteen sixties) but the absence of CMOS devices and their low sensitivity made the CCDs succeed. These pixel sensors are described as active , to say they contain one or more a active device per pixel [FOSS97] and the charge transfer can be directly made from the pixel to the output by addressing randomly. One drawback of the Active Pixel Sensors (APS) is the high integration density they require , thus making them feasible only when the feature size is sufficiently reduced [WONG96] , [PARD97] . By using the Moore’s law it was then possible to predict that the APSs could be worthwhile nowadays [WONG98], [YAMA96] . Careful design make also possible an increase of the filling factor (ratio of the detection active region to the total (active + dead) region). APSs have the tremendous advantage of being implemented in standard microelectronic technologies.

3- Why is CMOS well adapted

The active pixel sensors can be made on a standard CMOS technology [FUNA97] [YAMA96][ZHOU97][ZHOUPAIN97][PARD97][NAKA97][MCIL97][SCHE97][YADI97][SCHA97] [MA99] which has the advantage of simplicity compared with bipolar schemes [SHIN97] . CMOS transistors can be used in buffer functions , switch functions and have a feature size that decreases rapidly with the progresses of micro or nanolithography . This enhances filling factor and access speed with costs reduced compared with BiCMOS technologies. The issue is now the existence or not of a limitation in feature size based on noise or other performance considerations such as the optical reasons for visible light sensing [FOSS97]. The reduction in feature size made possible the increase in sensitivity needed for such devices.

4- Different detector/sensor schemes

Two type of sensors can be used within active pixel sensors. The pn or pin photodiode (described as early as 1968) is one the most popular as it can be implemented with a standard CMOS technology [LEE97][TSAN99] using the drain or source contact for one electrode and the bulk contact for the other (ref) for example. This is the most popular detection scheme. The other is the phototransistor [MEND97][SCHA97] which can be used. One common feature is the simplicity of design that makes it compatible with commercial technologies. Lateral APS differs from vertical APS in the way that for vertical APS the charge is stored under the vertical transistor. In addition a CCD derived detector scheme has been proposed [FOSS97] where the charge is trapped by an electrically driven potential well (Double gate floating surface transistor developed by TOSHIBA)[FOSS93]; these devices have in common with the CCD the need for a charge transfer .

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4- Different readout schemes : origin

Many front end schemes have been proposed for an addressable readout [FOSS97]. They have often in common the fact that each pixel must be selected by a selection command. To reduce power consumption the buffer/amplifier part (designed with CMOS transistors) is functional only when it is selected . Many schemes are based on a CMOS readout using a source follower transistor stage and a capacitor to store the charge information with a sample and hold scheme implemented. A selection switch is necessary usually made of a N/PMOS transistor . In some case the storing capacitor is only at the bottom of the column [MEND94] the order of magnitude of the capacitance is of a few picofarads. The area should be higher than 30*30 um*um. For the different readout that have been published since several years most interesting are CMOS based although bipolar readout have a potential (BASIS (Base stored image sensing) developed by CANON[SHIN97]) . SOI technologies are also potentially interesting .

5- Noise reduction

The noise which adds to the signal depends on the applications viewed. First for imaging the noise is a noise in the pattern . Subsequently the so called FPN (Fixed Pattern Noise) exists due to the geometrical mismatch of readout transistors . This noise can be suppressed by various canceling methods [FOSS97 and reference therein][OSHA97] . Other sources of noise are not an issue for a visible light imager . For spectroscopy one should be careful to the noise induced by the dark current of the detector and the noise induced by the front end transistors. These source of noise cannot be easily eliminated contrary to FPN; they will depend on the integration time of the readout circuitry. A adequate filtering will be necessary at the output to increase signal to noise ratio.

II - From visible light imaging to radiation detection : is it feasible ?

1- What kind of sensor scheme to choose ?

For long , detectors based on pin structures have been used for radiation (particle) detection and spectrometry [KENN99 and reference therein]. The constraint for radiation detection is the number of electron-hole pairs created per impinging particle . This obviously leads to thick detectors made up of a semiconductor of high Z (and electronic density) for high energy photons and other particles . A few hundredth of microns is the standard thickness for such detectors. For a:Si:H detectors [FOUR97] attempts to reduce the thickness of the layer below 100um has not been very convincing up to now Why such a matter of fact ? , it is simply because a minimum energy must be deposited in the layer to produce enough e-hole pairs that will overtake the total noise (in charge (electrons)). With minimum ionizing particles often encountered in physics (high energy) this is can be difficult , although there has been successful results recently [BERS00] . Another possibility not explored to our knowledge is the use of a scintillating layer on the top of detector/sensor. A minimum ionizing particle would induce a light pulse that could be detected in the bulk of the photodiode/phototransistor . The feasibility of such a technique should be studied.

2- The case of low energy particles (lower energy than a MIP)

For low energy particles the minimum energy deposited should be evaluated to ascertain if it will be sufficient to be detected with a standard APS scheme , vertical sensors would be preferable because of their greater thickness. It would be possible to develop APS based detector for spectrometers with a very good spatial resolution. Attempts to develop such spectrometers for charged particles have already been carried out with success [SOLI96].

3- APS for high energy particles

As stated earlier high energy particles are more difficult to detect than their lower energy counterparts , because they are mostly at their minimum ionizing energy . For direct ionization one needs thick detectors. The use of high resistivity silicon could be necessary. Present day technology offers the possibility of less than 100 squared micrometers area detectors (Fig 1) but for some high energy physic experiments the present needs are for larger detectors (10000 squared micrometers) . Low dimension detectors have many advantages: reduction of the leakage current value leads to lower “parallel noise” , reduction in capacitance diminishes the “series noise” from the front end transistors.

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The ideal detector would be thick and small in area with low leakage current. For the while is under study by some authors [KUCE99][KENN99] the feasibility of thick APS detectors (Pixel) on high resistivity silicon for energy physics but the readout electronic has to be defined.

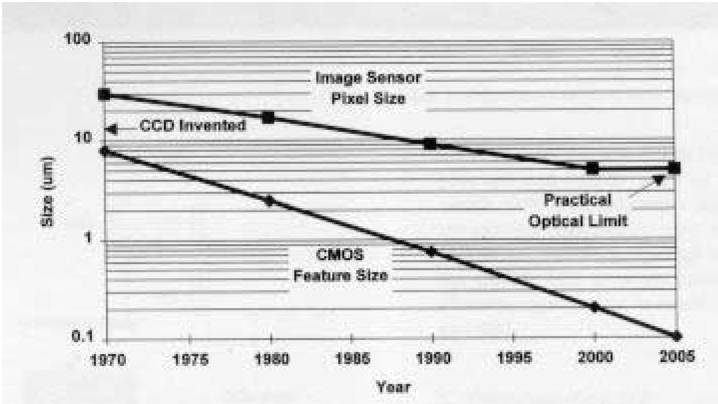

Figure 1 : Sensor pixel size versus year , CMOS design rule versus year (after [FOSS97])

4- Energy resolution and the role of noise

The resolution in energy deposited and the robustness to noise is of primary importance for spectrometry. As seen previously for visible light a great source of noise is fixed pattern noise due to technological mismatch. It may be a spatial noise. It can be cancelled by calibration or self compensation . For spectrometry noise due to the leakage current of the pixel and to the front end transistors are the main source of noise. These can be reduced by filtering , this means a shaper could be necessary at the output of the APS chip. In this case the question that remains is if a charge amplifier would be necessary at the front end of the readout. This would make the readout more complex.

6- Pixels , spatial resolution and readout

The number of pixels should be increased to improve spatial resolution . But because of the tremendous number of channels that would result it would be necessary to have a random addressing of the pixels to reduce the amount of data . With larger pixels it could be necessary to use a charge amplifier to reduce the noise, so the readout would be more transistor consuming and take a larger area. Larger pixels have a greater capacitance and so increase the series noise. On the other hand small pixels imply a large number of them for the same total area. This means that it could reduce the frequency of operation of the whole system. For high energy physics the operating frequency must be high in order to cope with the collision repetition rate. Surely the readout is a point that should be studied further. This problem will not exist in other applications such as astrophysics or astroparticle where the counting rate is low enough or some e+e- collider experiments (TESLA : bunch spacing 283 ns to 708 ns [ALTM97]) . The highest spatial resolution will be the best.

III – Radiation tolerance and operation under realistic conditions

1- Operating conditions in Space and near accelerators

The problem often encountered in Space measurements and high energy/nuclear experiments is the exposure to radiation , both ionizing and not. The main difference between the two environments is the dose rate , total dose and fluence received during the lifetime of the equipment . In Space dose rate is low together with total dose and fluence allowing standard technologies to be used ; for future high energy/nuclear physics experiments the doses reached are very high together with the total fluence , this may preclude the use of standard (radiation soft) technologies .

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2- Is hardening necessary ?

The problem of exposure to radiation was recently addressed for space applications[HANC97]. The total doses remained very low (a few tens of kilorads) and still irradiation effects were observed despite specific design. Thus for low and high doses hardening by any means (technological or by design) should be used. Closed MOS transistors should be designed in standard technologies , or radiation hard technologies (SOI) should be chosen. This may concern the readout , that may be easily hardened with the use of hardened technologies but the problem of the detector feasibility in hardened technologies remains open.

3- Can CMOS sensors be developed with hardened technologies ?

The use of hardened technologies (SOI) implies the possibility of making the detector with them. This is difficult because as stated earlier thick (> 10 micrometers detectors could be needed) for direct detection of MIPs (Minimum ionizing particles). Even with relatively thick film SOI technology (DMILL) there remains a technological gap : the active epitaxial layer is of the order of 1 micrometer . It should inevitably be increased for Signal/ Noise reasons , but dislocation propagation through the layer is a difficult problem for SOI technologies [TRUC95] Another possibility would be to use the back substrate for detection purposes but this seems a technological challenge as this would require to make contacts through the insulator (thickness 4000 angtroems) . Research in this field should be pursued as it would mean a great step forward for the detector community . In the meantime the use of scintillating layers should be regarded as an alternative.

4- Consequences for the geometric size and the future performances

The effects of irradiation is usually always a degradation of performances : increase in leakage currents , decrease of the maximum operating frequency , etc … Total loss of functionality is often the case for unhardened technologies and designs. Hardening and radiation hard technologies are usually space consuming since a squared transistor is larger than its linear counterpart , dielectric insulation together with less than state of the art minimum feature size increases the size of individual transistors. This means a reduction of the performances of Active Pixel Sensor based detectors and an increase in their overall dimensions.

IV – Concluding remarks

The first item that should be considered is the relatively limited work carried out for Physics experiments compared with the huge activity for imaging in the visible light spectrum . A lot of efforts should be now made to assess the value of APS for the applications in higher energy particle imaging and tracking together with spectrometry . Most of the published work and patents deal with visible light imaging demonstrating the fact that APS technology is mature enough to be altered further to meet the physics and astrophysics community requirements. Steps should be considered to reduce risks. First an effort for visible light imaging should still be made. Second scintillating material should be used to characterize the APSs for high energy physics particle tracking. Third direct detection should be a research direction for future APSs based trackers , this means a very important technological effort on hardened (Silicon On Insulator) technologies since the feasibility has been recently demonstrated for standard CMOS epitaxial technologies [BERS00].

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