CMOS Sensors for High Energy Physics

P.P. Allport[b], G. Casse[b], A. Evans[b], L. Jones[a], R.Turchetta[a*], M.Tyndel[a], J.J. Velthuis[b], G. Villani[a], F. Zakopoulos[a]

[a] *Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom*

[b]*University of Liverpool, Oliver Lodge Laboratory, Oxford street, Liverpool, L69 7ZE, United Kingdom*

*Corresponding author: r.turchetta@rl.ac.uk

Tel: +44.1235.446633 Fax: +44.1235.445008

1 Introduction

In High Energy, or Particle, Physics experiments, silicon detectors have long been used to detect the secondary particles generated by high-energy collisions, where the energy depends on the accelerating machine and generally ranges from GeV to TeV, i.e. 10^9 to 10^{12} eV. The secondary particles have still very high energy and travel at relativistic speed, generating about 80 electron-hole pairs per µm of silicon. So far, silicon detectors have been built with a thick (hundreds of µm), high resistivity substrate connected via wire or bump bonding to a separate readout microelectronic chip. A natural evolution of this concept would be to integrate the sensor and the readout electronics on the same piece of silicon. The first attempts were in the direction of developing customised technologies, trying to optimise the sensor part on high resistivity silicon and the readout block on low resistivity silicon. Although positive results were obtained, none of these technologies have been so far able to scale from small scale, a few mm^2 in size, demonstrators up to useful devices of a few cm in size [1, 2, 3].

Recently we proposed [4] to use standard CMOS technology to detect charged particles (fig. 1). CMOS sensors were already proposed for visible light imaging [5, 6] and their advantages in terms of radiation hardness, functionality, pixel size, speed and ease of use immediately recognised. In order to bring this technology into particle physics experiments, some more tight requirements need to be fulfilled.

- Low noise: the charge generated by the particle is mainly determined by the thickness of the epitaxial layer. Given the standard value of thickness for epitaxial layers, the signal generated by a particle is generally just a few hundreds.
- Radiation hardness: depending on the application, it can be required to be in excess of to 10^{14} neutron/cm^2 or several Mrads.
- Speed: the frame rate is normally in excess of 1MHz.
- Large area: in most cases, sensors larger than several cm^2 are required.

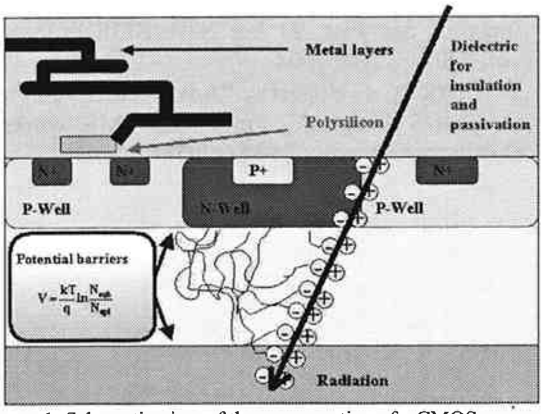

Figure 1. Schematic view of the cross-section of a CMOS process, and the principle of 100% efficiency detection of charged particles.

In order to explore the best architectures able to satisfy the requirements of a particle physics experiment, we designed and characterised a family, RAL_HEPAPS, of parametric test sensors. The pixel structures were also simulated with an advanced device simulation software (ISE-TCAD). The RAL_HEPAPS2 was designed in a 0.25 µm CIS process with 8 µm thick epitaxial layer and RAL_HEPAPS3 in a 0.25 µm mixed-mode process with no epitaxial layer.

In both sensors, pixels with 3 and 4 transistors were designed. In RAL_HEPAPS2, we also integrated pixels with a charge preamplifier (CPA) and with a 10-cell analogue memory, called Flexible APS (FAPS) [7]. In RAL_HEPAPS3, we also integrated pixels with a deep n-well structure. The RAL_HEPAPS2 has 384*198 pixels at 15 µm pitch (3, 4MOS and CPA) and 40*200 pixels at 20 µm pitch (FAPS). The RAL_HEPAPS3 has 192*128 pixels at 15 μm pitch and 96*32 at 30 μm pitch.

2 Physical device simulation

The device simulation allows studying how the charge is collected by a pixel before fabrication. Different pixel architectures were benchmarked against charge collection efficiency and speed at different radiation dose. The effects of radiation on the sensors are complex, but the main one is the reduction of minority carrier lifetime. At high radiation dose, the lifetime becomes shorter than the charge collection time. This effect generates a reduction in the collected charge and then a reduction in signal over noise ratio.

Out of the various pixel configurations we studied, the two most promising were found to be: a standard pixel with 4 small diodes in parallel instead of one and a pixel with a deep N-well diode.

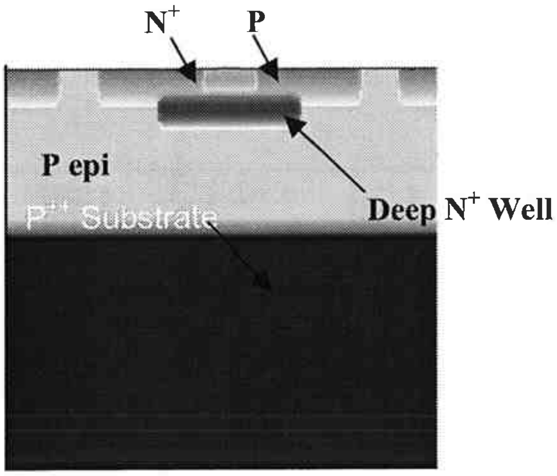

Figure 2. Cross section of the deep N-Well pixel. NMOS transistors sit in the P-well inside the N-well, while the deep N-well is the diode, but can also be used as the substrate for PMOS transistors.

In the first case, the charge collection is mainly by diffusion. By connecting a few diodes in parallel, the average charge collection distance is reduced and hence the collection time. In the second case (fig. 2 and 3), the deep n-well structure generates a more uniform field in the pixel volume, so that the charge collection is speeded up. The higher noise due to the larger capacitance of the diode is compensated by the fact that the charge is spread over few pixels so that the average signal per pixel is higher.

After irradiation and in a standard pixel, very little charge is seen when a particle crosses the sensor in the 'corner' of a pixel (fig. 4). On the contrary, in a deep N-well diode, the effect of the radiation is reduced on the entire surface of a pixel (fig. 5). If the average collected charge is plotted as a function of the dose for the two pixels (fig. 6), it is seen that at 10^{14} neutron/cm^2, the loss in charge is about 80% in a standard pixel but it is only a few percents in a deep N-well pixel. Pixels with deep N-well were integrated in the RAL_HEPAPS3 and successfully tested.

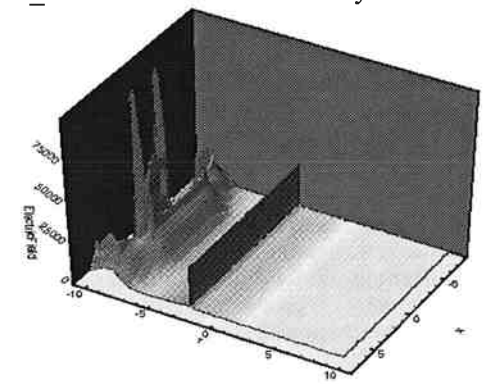

Figure 3. Simulation of the deep N Well internal electric field configuration. $V_{bias} = 2V$ applied to N$^+$ Well. The electric field extends a few μm inside the silicon, down to the boundary of the epitaxial layer.

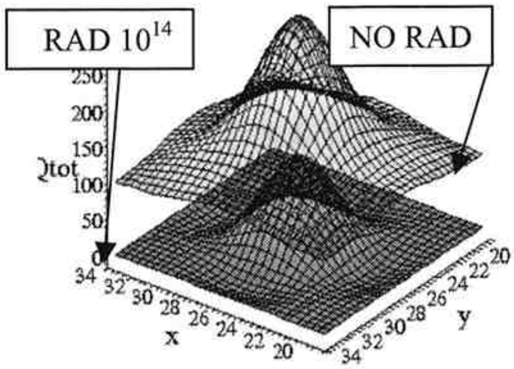

Figure 4. Standard APS, N-well/p-epi diode: simulation of the charge collected by a single pixel as a function of the impact point of a charged particle inside the pixel, before and after irradiation at 10^{14} n/cm^2.

3 Sensor characterisation.

Noise measurement. In a particle physics experiment, the sensors operate in the dark and the collected charge is small. This suggests that the reset noise can be reduced by using soft reset. This was confirmed by our measurements. In fig. 7, on the left is the histogram of the measured noise in hard reset on an array of 64x64 pixels. The most probable value is around 40 e- rms as expected from the simulation. On the right, the measurement was repeated in soft reset. The distribution is shifted towards zero and it is now peaking at about 20 e- rms. The reduction is higher than the expected $\sqrt{2}$ since the sensor is operated in the dark [8].

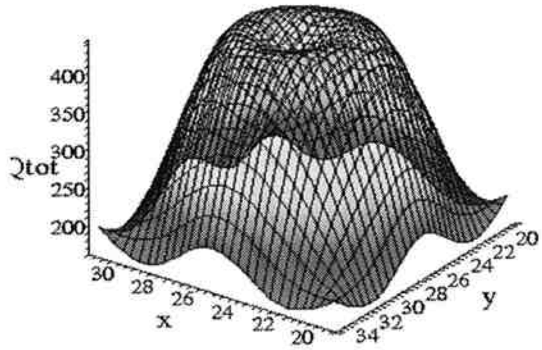

Figure 5. Deep N Well: simulation of the charge collected by a single pixel as a function of the impact point of a charged particle inside the pixel, before and after irradiation at 10^{14} n/cm^2. Note that in this figure, it is not possible to observe any degradation due to the irradiation and that the charge collection is much more uniform over the entire pixel.

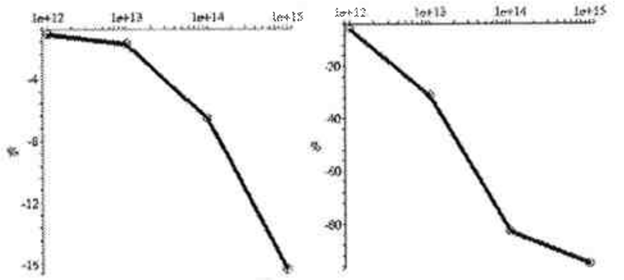

Figure 6. Simulated degradation of the average collected charge by a single pixel vs. the dose. The degradation is expressed as a percentage change with respect to the unirradiated structure. On the left is the Deep N Well, while on the right is an n-well/p-epi diode.

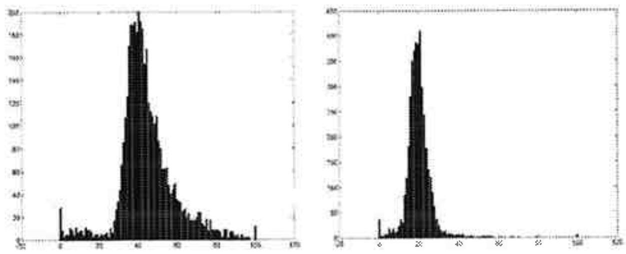

Figure 7. Measured distribution of noise for an array of 64x64 pixels. The noise in e$^-$ rms is in abscissa is and the number of entries in ordinate. Measurements in hard (left) and soft reset (right)

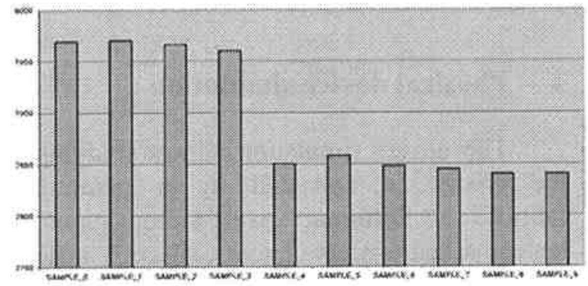

Figure 8. FAPS. In-pixel sampling of a light pulse. In abscissa, the sample number, and on the ordinate the read voltage. A light pulse was shown in correspondence with the 5th sample.

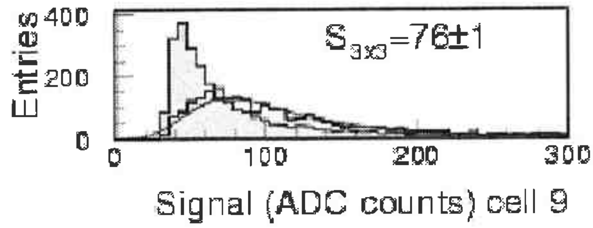

Figure 9. Cluster signal distributions for the seed, 3×3 and 5×5 clusters for all 10 memory cells in the FAPS. The S/N is between 14.7 and 17.0.

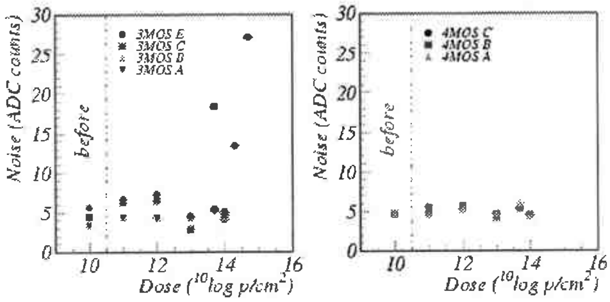

Figure 10. Noise as a function of radiation dose. The substructures operate well up to 10^{14} proton/cm^2.

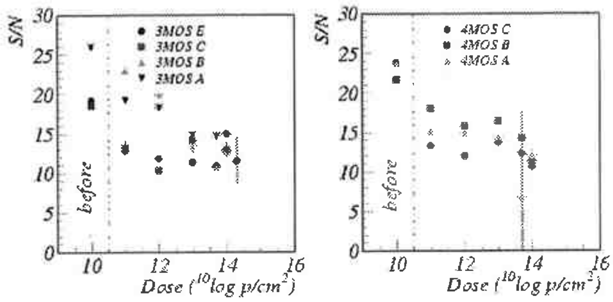

Figure 11. Signal/noise ratio of the RALHEPAPS 2 as a function of the irradiation dose. The substructures operate well up to 10^{14} proton/cm^2.

Detection of high-energy, charged particles. Several pixel types were tested with high energy charged particles. We tested pixels with 3 and 4

MOS, with 1 or 4 diodes, with normal or enclosed geometry transistors and with different shapes of the P-well. The distribution of the signal generated by a single particle is shown in fig. 8. As expected, this has the characteristic shape of a Landau distribution. The S/N is as high as 25 depending on the pixel. This value, together with the measured noise, agrees well with the expected signal of about 600 electron-hole pair for an 8 μm epitaxial layer thickness.

Flexible Active Pixel Sensors (FAPS). We also tested several types of the FAPS, all with 10 in-pixel storage MOS capacitors of 75 fF each. Fig. 9 shows the response of one pixel to a pulsed LED. The light pulse was generated in between SAMPLE_3 and 4 as measured by the device. The sensor was also tested with high-energy particles and the response recorded for each cell in the sensors. Again, the typical Landau distribution is measured (fig. 10). From this curve we could estimate a noise of about 40 e- rms, which is higher than expected. The reason for this discrepancy is under investigation. It might be due to a fault in the logic of the sensor, which prevents the correct operation of the sensor. This fault would be easily corrected in the next sensor.

Radiation hardness. Different pixels were tested up to 10^{15} proton / cm^2. The noise and S/N (fig. 11 and 12 respectively) stay within reasonable values up to about 10^{14} proton / cm^2.

More experimental results can also be found in [9, 10, 11]

4 Conclusions

We designed, manufactured and characterised several types of CMOS active pixel sensors for high-energy physics. We also successfully tested a Flexible APS, which contains in-pixel memory cells and could also be used for high-speed imaging. Our results show CMOS APS could be used in particle physics experiments. We have now designed the next sensor in the family, RAL_HEPAPS4, which consists of 384*1024 pixels at 15 μm pitch, with low noise performance (< 40 e- rms), radiation hardness and with a line rate in excess of 5 MHz. We will fabricate three types of this sensor, one with 2 diodes in a pixel, one with 4 diodes, and one with only one diode but enclosed geometry transistors

5 References

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