CMOS Pixel Sensor for a Space Radiation Monitor with very low cost, power and mass

Y. Zhou,[*] J. Baudot, C. Duverger, Ch. Hu-Guo, Y. Hu and M. Winter

IPHC-DRS, University of Strasbourg, CNRS-IN2P3
23 rue du loess, BP 28 67037 Strasbourg, France
E-mail: Yang.zhou@iphc.cnrs.fr

ABSTRACT: With the purpose of measuring simultaneously the proton and electron environment using a single sensitive device, we propose a CMOS pixel sensor featuring a 10 mm^2 sensitive area, and counting capability up to $10^7/cm^2/s$ within a second and with a marginal error due to pileup of two close particle impacts on the matrix. The proposed architecture includes a 64×64 square pixel matrix with 50 µm pitch size, 64 column level 3-bit ADCs to provide an appropriate energy resolution, and an embedded digital processing logic for directly giving the impinging particle information. To validate experimentally the expected performances within the year 2012, a first prototype has been designed and fabricated in a 0.35 µm process without the integrated digital processing part. The device simulation and design architecture are presented.

KEYWORDS: Pixelated detectors and associated VLSI electronics; Particle identification methods; Front-end electronics for detector readout.

[*] Corresponding author.

Contents

1. Introduction

The need for highly miniaturized and versatile real-time radiation monitor has become a general trend for spacecraft applications [1]. CMOS Pixel Sensors (CPS), being monolithic full detection systems, match well these requirements and offer additional advantages including low power, low weight, low fabrication cost and advanced radiation tolerance.

Previous works [2] by the PICSEL[†] group of IPHC demonstrated that CPS reach excellent performances for charged particle tracking in high energy physics. In this context, the pixelated sensor granularity provides spatial resolution while the ionizing signal extends typically over one or two order of magnitude. For space radiation monitoring, we propose to exploit the granularity in order to separate and count many particle impacts in a single frame as well as to estimate the energy deposited over a wide dynamical range.

In this work, we describe such a CPS architecture dedicated to monitor high fluxes of differentiated charged particles. On top of detecting particles, the proposed sensor is intended to include a full signal treatment, providing directly the overall dose and differentiated particle fluxes as outputs.

The second section of this article is devoted to simulation studies, which were conducted to optimize the main features of the device and estimate its performances. In the third section, the main components of the fabricated prototype are detailed. We conclude with perspectives on the test of this prototype.

2. Design study and performance simulation

According to current NASA models [3-4], the Earth's radiation belt consists mostly of protons from about 100 keV up to 400 MeV and electrons from about 10 keV up to 10 MeV. Also the omnidirectional flux of these particles is expected to reach up to several $10^7/cm^2/s$.

[†] Physics with Integrated CMOS Sensors and Electron colliders

Assuming a 10 mm^2 sensitive area read out every 20 µs (corresponding to a frame rate of 50 kfps), the lowest particle flux measurable by counting all impinging particles during one second and with a 10 % statistical uncertainty is $10^3/cm^2/s$.

Higher fluxes are estimated either with a better accuracy or within a shortest time. The highest flux measureable depends on the particle pileup probability, mainly driven by the pixel pitch, for the fixed frame rate.

2.1 Four steps simulation

The complete response of the proposed CPS has been simulated with the four following steps.

1) The energy deposited in the thin (14 µm) sensitive area was generated using the GEANT4 package. Results indicate the possibility to distinguish protons from electrons below an energy of 50 MeV through the measurement of their energy loss.

2) The signals generated over each pixel were calculated with a dedicated Monte-Carlo algorithm, which was developed from many test results of the MIMOSA CPS series [5].

3) In order to allow for a further treatment inside the sensor, the signals collected on pixels are digitized over 3 bits. In the simulation, the digitization step is reproduced with a simple algorithm taking into account the different thresholds corresponding to each bit.

4) A clustering and hit counting algorithm was programmed to emulate the data processing flow inside the sensor (see section 2). This algorithm groups adjacent pixels in a cluster and sums their digital values to estimate the deposited energy associated.

2.2 Estimated performances

Using this simulation, the best performances with respect to the dose and particle flux measurements, were obtained with a pixel pitch of 50 µm. These performances are illustrated in figure 1 for the following conditions. Each frame contains a number of particles uniformly distributed between 1 and 20. The particle type is a 50-50% mix of electrons and protons and their incident energy fits a uniform distribution between 1 and 100 MeV, while the incidence is always normal to the sensor surface.

The left plot shows a linear matching between the reconstructed energy and the deposited one. The measured standard deviation of the distribution of the difference between the reconstructed and deposited energy amounts to a relative value of 10%. One observes a deviation of the linear behavior only for very high ionizing doses, generated by particles of ≥ 5 MeV.

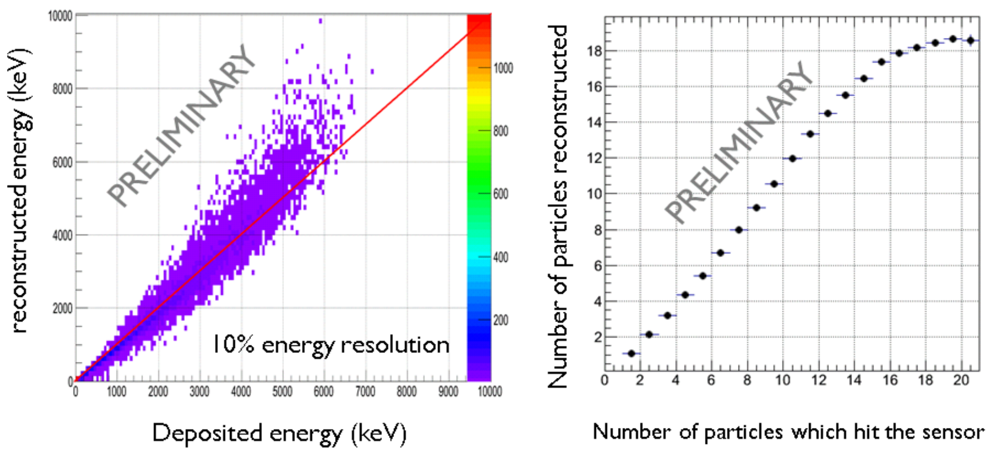


Figure 1. Reconstructed energy versus deposited energy (left); number of clusters reconstructed per frame versus number of particles effectively impinging the sensor (right).

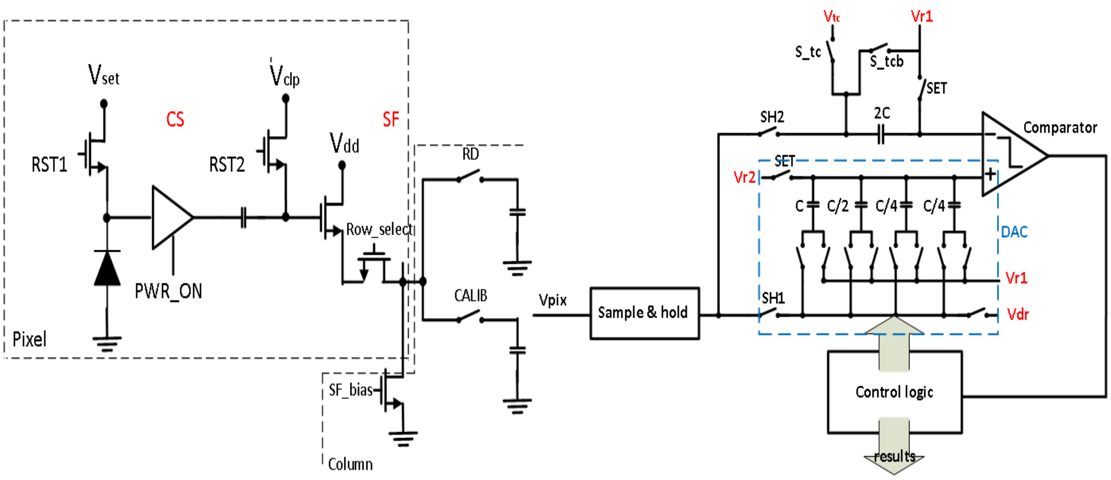
The sensor's capability to count particles is displayed in the right panel of figure 1. Good performances are obtained up to about 16 particles per frame, which corresponds to a flux of $0.8\times10^7/\mathrm{cm}^2/\mathrm{s}$. This limitation stems mostly from the presence of low energy particles, generating large clusters which merge and confuse the simple clustering algorithm. Thus, the current results shall not be taken as an absolute limit of the architecture.

3. Overview of the proposed prototype

Based on the previous study, a prototype CPS was designed and submitted for fabrication in a 0.35 µm CMOS technology, in spring 2012. It features a sensitive area of 3.2×3.2 mm^2, comprising 64×64 square pixels of 50 µm pitch size. Each pixel includes pre-amplification and correlated double sampling (CDS) micro-circuits. The matrix is read out within less than 20 µs, in a column parallel rolling-shutter mode, as described in [2]. Columns are individually ended by a 3-bit ADC, which feeds the digital algorithm reconstructing online the dose deposited by each particle. Each ADC converts a single value in 240 ns, matching the pixel row read-out time. The current prototype does not yet include any clustering and hit counting logic.

3.1 Pixel architecture

The pixel architecture is illustrated in figure 2 (a). A simple n-well/p-epi diode is used as charge sensing element, a Common Source (CS) preamplifier is placed very close to the sensing diode. The pixel level double sampling is achieved by this CS preamplifier, a serially connected capacitor and two reset switches. The first switch (RST1) is used to reset the diode and the second one (RST2) is used to memorize on the capacitor the offset of the preamplifier and the reset level of the diode. A Source Follower (SF) is used to output the signal on the column data bus. "RD" and "CALIB" are column level commands to memorize the output signal level and the column reference level respectively. Only NMOS transistors are used in this architecture, since any PMOS transistors would compete for charge collection with the sensing N-well diode. Relatively linear pixel-level pre-amplification and pixel-level CDS are necessary to increase the signal-to-noise ratio (S/N) and to prepare for the column level digitisation, since the smallest signal amounts to only about 300 e$^-$. Full simulation of the pixel micro-circuits estimated the expected equivalent noise charge (ENC) to 15 e$^-$, which should be small enough to detect the smallest signal.



(a) (b)

Figure 2. The architecture of pixel (a) and column level 3-bit ADC (b)

3.2 Column level 3-bit ADC

Considering the size, speed and power dissipation, an ADC architecture based on a successive approximation register (SAR) is chosen. Only one comparator is needed for this architecture and three comparisons are already enough for the complete conversion of a 3-bit ADC.

The global ADC structure is shown in figure 2 (b). A sample-and-hold block (S/H) is used to perform the column level CDS. A capacitor DAC based on the "charge redistribution" principle is implemented. Control logic is integrated inside each column, transferring the serial switch select signal according to the response of the column level comparator. The thresholds corresponding to each bit are fully adjustable through four external reference voltages (Vr1, Vr2, Vtc and Vdr in figure 2b).

4. Conclusion and perspectives

We proposed a CMOS Pixel Sensor architecture which aims at monitoring proton and electron fluxes up to $10^7/cm^2/s$ in real time. Expected performances were obtained through a simulation of all the sensor functionalities. They show that the ionizing dose can be estimated within a 10% accuracy, while the maximum flux the architecture can correctly measure depends critically on the energy spectra of the incoming particles. Electron/proton separation can be achieved genuinely through the energy deposition measurement per particle up to 50 MeV incident energy. Differentiation beyond this energy would require a strategy exploiting several sensors equipped with various shields.

A prototype sensor without the clustering and hit counting logic was fabricated during summer 2012. The estimated total power consumption amounts to 50 mW. Its tests will establish the dose measurement and particle count performances, from which, a full-functional demonstrator will be designed.

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