

A Fast Monolithic Active Pixel Sensor with Pixel Level Reset Noise Suppression and Binary Outputs for Charged Particle Detection

Yavuz Değerli, *Member, IEEE*, Grzegorz Deptuch, *Member, IEEE*, Nicolas Fourches, *Member, IEEE*, Abdelkader Himmi, Yan Li, Pierre Lutz, and Fabienne Orsini

Circuitry is integrated in a monolithic structure of a $0.18\ \mu\text{m}$ CMOS technology. These sensors are designed with standard CMOS technology and have significant advantages over Charge Coupled Devices (CCDs). Two exemplary strong points of the proposed sensor are the high radiation hardness and the flexibility of the

I

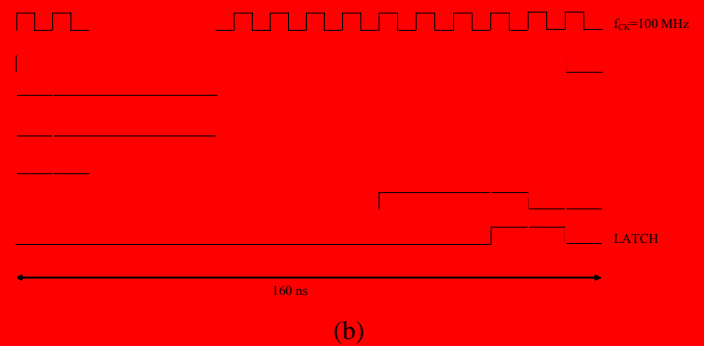
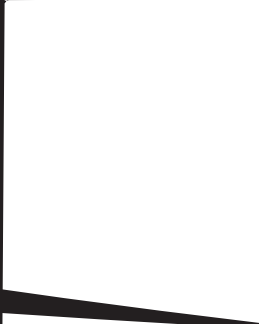
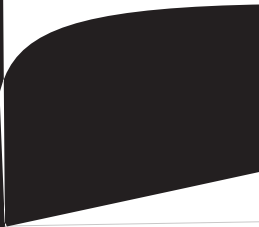


Fig. 1. (a) Schematic of the proposed DC-coupled pixel and, (b) related timing (clocking stimuli) with $f_{CK}=100\text{ MHz}$. RD, CALIB and LATCH signals are used by the column readout circuitry.



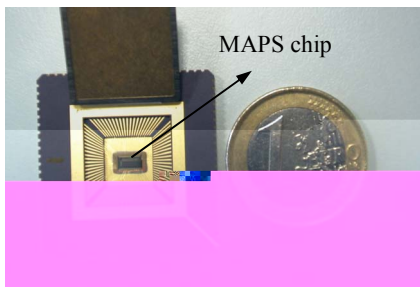
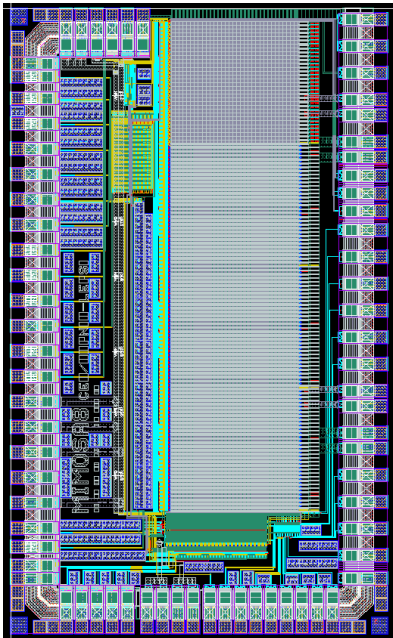
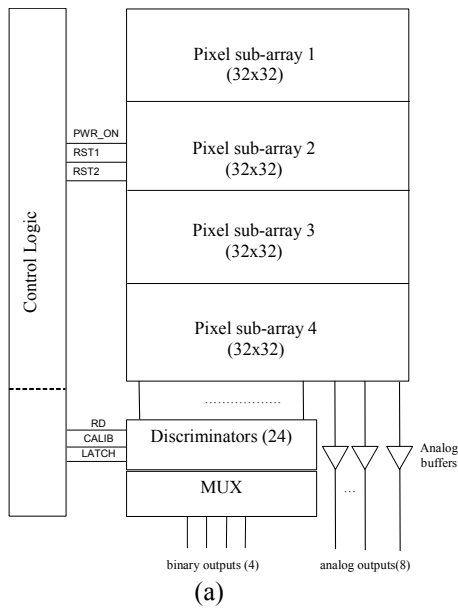


Fig. 3. a) Block diagram, b) layout and c) photography of the realized prototype chip.

The signal of the charge sensitive element is delivered to the amplifier via the series capacitance obtained by placing the polysilicon plate over the n-well area, as it is shown in Fig. 2b. The gate oxide is used providing a high value of the coupling capacitance. The signal is then amplified with a voltage gain about 15-20, aiming at total CVF about $150 \mu\text{V}/e^-$.

The principle of the direct AC coupling of the auto-reverse polarized charge sensitive element and the amplifier is shown in Fig. 2b. The choice of AC-coupling instead of DC-coupling allows independent bias of the input transistor in the amplifier from the potential settled on the n-well region during the detector operation. At the same time, the n-well diode is polarized with the maximum voltage available in the technology process bearing the optimization of the charge collection process. Since the second pixel does not use reset transistor for the diode, the CDS is used to extract the signal in subtraction from the reference level. The reference level for each new measurement is the state from the previous readout cycle.

III. ARCHITECTURE OF THE CHIP

A test chip was designed using a $0.25 \mu\text{m}$ CMOS digital process available through MOSIS. The chip consists of four sub-arrays of 32×32 pixels each, 24 column-level discriminators for signal sparsification, a fully programmable digital sequencer and output multiplexers for binary outputs, as it is shown in Fig. 3. The pixel pitch is $25 \mu\text{m}$. The bottom three arrays contain the DC-coupling pixel type. The three arrays were designed aiming at different values of CVFs with different diode sizes. The first array from the top of the chip is built with the AC-coupling pixel type.

The chip readout is organized in columns processed in parallel. The first 24 columns are connected to discriminators, multiplexed onto 4 outputs. The last 8 columns of 32 are not connected to discriminators. Their analog outputs can be observed directly on the output pads. These direct outputs were used for testing of pixels with the results presented in the latter part of the paper. An additional output of the eighth column of the group of columns with analog outputs allows to examine internal point of the amplifier before the clamping capacitance used for CDS processing.

The digital part includes two circuits. One is the digital control circuit, which is fully programmable and generates the patterns necessary for addressing, resetting and double sampling of the signals in pixels in a column parallel way. The rows are selected sequentially using a multiplexer every 16 clock cycles. The pattern is loaded to the chip serially during a programming phase at low frequency. The second circuit realizes a temporal multiplexing of the binary outputs signals (column discriminators) at a frequency value half that of the main clock frequency.

The design of comparators is based on an auto-zeroed amplifying stage and a dynamic latch, as it is shown in Fig. 4. They are an improved version of the previous design MIMOSA6 presented in [6][2]. The architecture was modified to use MOS capacitors instead poly-poly linear capacitors, because the fabrication process used does not feature this type of capacitors. To obtain a good linearity, a care had to be taken

to bias the capacitors in the accumulation regime. Level shifters before capacitors were used for this purpose. Thanks to the MOS capacitors, which have small dimensions, the size of the comparators is the same as the ones used in the previous design (220 μm x 25 μm).

The discriminators subtract V_{RD} from V_{CALIB} for each pixel, and compare it with the reference differential voltage $\Delta V_{ref} = V_{ref1} - V_{ref2}$.

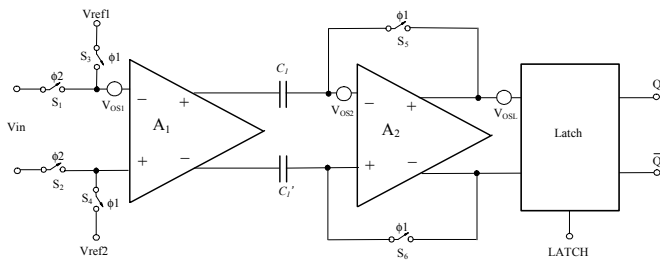


Fig. 4. Bloc diagram of the offset compensated comparator.

IV. TEST RESULTS

Two kinds of measurements were performed on the chip. At the first step, the analog outputs were tested with a digital oscilloscope. The digital part generates a signal synchronized with the access to the first row of the pixel array. The analog signal from a single, selected column was examined using this synchronizing signal. It was possible to observe the signal of one single pixel in this way. During the tests with the oscilloscope, the clock operating frequency was of the order of 10 MHz, allowing clearly observing different phases (the first readout, reset of the charge collecting diode, reset of the clamping capacitance, second readout – calibration in the pixel access). At the latter step, measurements with main clock frequency of up to 100 MHz were also successfully performed. A thorough study of the analog outputs was made. The arrays of pixels with the DC-coupling were tested at the beginning as the basic option. The tests of the matrix containing pixels with AC coupling were also started. Experiencing some problems during the tests of AC-coupling pixels, the results of the DC-coupling option are presented in this paper only. The tests of the AC-coupling will be continued.

Fig. 5 shows the direct analog output signal observed. Note that the 2 levels for each pixel (V_{RD} and V_{CALIB}). The black part is the pedestal and the grey lines correspond to the signal. The useful signal is the difference between these two levels. Tests without the source showed that the double sampling could eliminate offset dispersions of the in-pixel amplifying stage. The offset dispersions of the source follower output stage are to be corrected later by the column readout circuitry (discriminators). The two samples were recorded for each pixel and then subtracted offline, resulting in dispersions level less than 1 mV. The typical consumption of each pixel is reduced to 60 μA (the pixel dissipates only when it is powered-up).

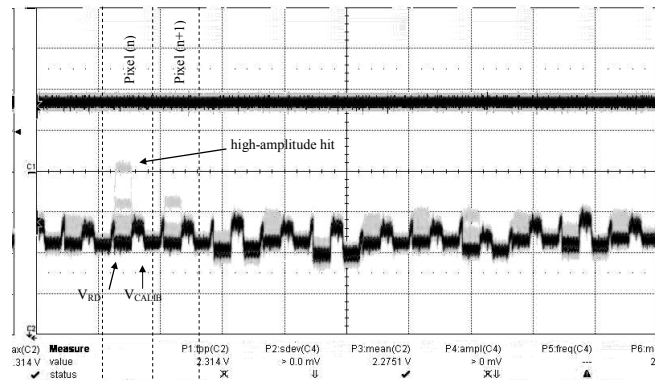


Fig. 5. Output analog signal from 12 pixels of a column recorded on a scope (50 mV/div.). The useful signal for each pixel is the difference between these two levels, normally extracted by the column readout circuitry. A high-amplitude hit is clearly detected on pixel (n) during the read phase, corresponding to full energy deposition of the X photon. Other hits appear distinctly.

The ability to detect ionising radiation was tested with soft X ray photons from a ^{55}Fe source in a second step. A 9.8 mCi ^{55}Fe source was placed in the dark box at approximately 1 cm of the chip with no material in between. After 15 minutes of the acquisition time, the hits could be seen on the oscilloscope as jumps on the output signal during the RD phase, as it is shown in Fig. 5 and 6. The conversion factors for different pixel architectures were grossly estimated from the maximum signal observed¹. A good agreement comparing to ones simulated was obtained. The conversion between the measured voltage and the charge collected by the diode was estimated knowing the energy of the photons from the source to be 5.9 keV for the dominating emission mode, corresponding roughly to 1600 e^- . The knowledge of the CVF allows estimating of noise, which does not exceed 20 e^- ENC for the worst case, i.e. the pixel with lowest CVF (@ $f_{CK}=100$ MHz and with a measurement bandwidth of 200 MHz). The results obtained in this way can be only be considered as preliminary, allowing however demonstration of good ionising radiation detection capabilities, with low noise and low pixel-to-pixel DC level dispersion, of the new pixel architecture. The results obtained in tests are summarized in Table I.

The signal for an ^{55}Fe source is higher than the one which would be expected for a MIP (an average of 80 $e^-/\mu\text{m}$ x 6 μm = 480 e^-), so the tests of the MIPs detection will be the next step forward. The good signal to noise ratio shows MIP detection should be possible. Beam tests are expected to clarify this issue.

The binary outputs were all proved functional.

¹ The calibration is done, assuming that maximum signal observed for the exposition time correspond to the events of the photon impacts with conversion taking place in the n-well volume or in the depletion zone of the charge collecting diode, where the full quantity of the generated charge is collected within one pixel.

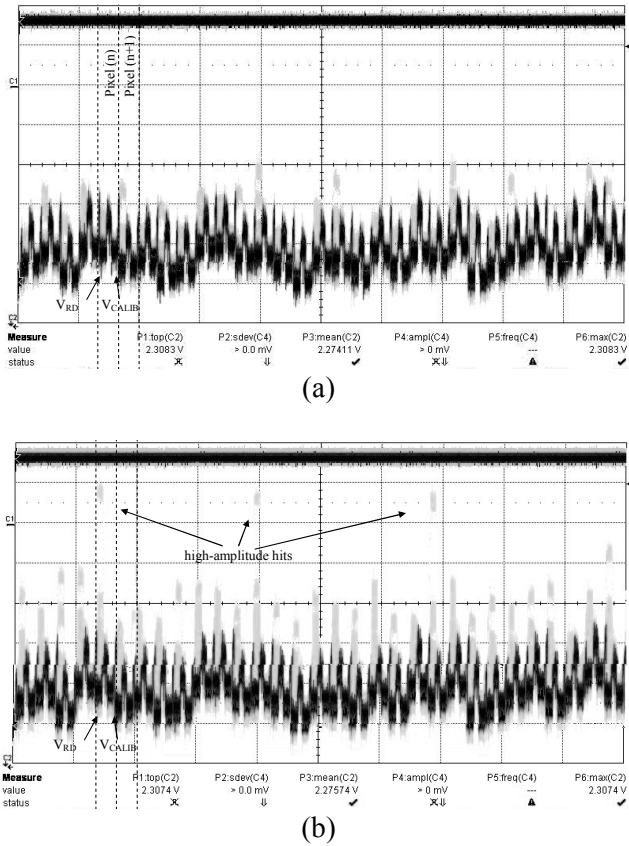


Fig. 6. Output analog signal from 32 pixels of a column recorded on a scope (20 mV/div.) a) with few small-amplitude hits, and b) with multiple high-amplitude hits.

V. CONCLUSIONS

The new method with series connection of the clamped capacitance used in the pixel design for double sampling enables the offset of each pixel to be literally eliminated. The prototype detector, consisting of 128 rows, can be read out and discriminated within 20 μ s with this design. Taking into account the temporal noise level and the residual FPN, the detection of MIPs should be possible using this technique. The small value of the residual pixel-to-pixel DC-level variation paves the way to the efficient on fly discrimination of signal during the readout of the detector, leading to the on-line data sparsification. The on-line sparsification is an issue for the layers L1 and L2 of the vertex detector in a future linear collider, where the high hit occupancy is expected. The feasibility of in-pixel double sampling with pre-amplification was successfully established. Implementation of the on chip analog to digital conversion and full data processing with digital hit reconstruction is still another future challenge.

The next step for the characterization of the chip will be to make statistical measurements on analog and binary outputs using a fast data acquisition system currently under development.

TABLE I
CHARACTERISTICS OF THE PIXEL AND THE READOUT ESTIMATED FROM MEASUREMENTS

Pixel array n°	Sensing element	CVF (μ V/e ⁻)	Output RMS Noise @f _{CX} =100 MHz	Input Referred Noise (ENC)	S/N*	Pixel-to-Pixel FPN
1	self-biased n-well/p-epi diode (4.1 μ m x 2.5 μ m)	150**	-	-	-	-
2	n-well/p-epi diode (1.2 μ m x 1.2 μ m)	70	~ 1 mV	14 e ⁻	120	<1 mV
3	n-well/p-epi diode (1.7 μ m x 1.7 μ m)	60		17 e ⁻	100	
4	n-well/p-epi diode (2.4 μ m x 2.4 μ m)	50		20 e ⁻	80	

* The signal to noise ratio S/N was calculated using the maximum amplitude measured, divided by the rms noise voltage of the pixel.

** Simulation value, not yet tested.

VI. ACKNOWLEDGMENT

The authors are thankful to E. Delagnes, F. Lugiez, M. Rouger, all from DAPNIA/SEDI, and C. Colledani from LEPSI, for their help and advice.

VII. REFERENCES

- [1] G. Deptuch, J.-D. Berst, G. Claus, C. Colledani, W. Dulinski, Y. Gornushkin, D. Husson, J.-L. Riester, and M. Winter, "Design and testing of monolithic active pixel sensors for charged particle tracking," *IEEE Trans. Nucl. Sci.*, vol. 49, no. 2, April 2002, pp. 601-610.
- [2] G. Deptuch, G. Claus, C. Colledani, Y. Degerli, W. Dulinski, N. Fourches, G. Gaycken, D. Grandjean, A. Himmi, C. Hu-Guo, P. Lutz, M. Rouger, I. Valin, and M. Winter, "Monolithic active pixel sensors with in-pixel double sampling operation and column-level discrimination," *IEEE Trans. Nucl. Sci.*, vol. 51, no. 5, October 2004, pp. 2313-2321.
- [3] R. Merrill, "Intra-pixel reset noise cancellation," in *Proc. 2001 IEEE Workshop on Charge Coupled Devices and Advanced Image Sensors*, Lake Tahoe, Nevada, USA, June 2001, pp. 153-156.
- [4] Y. Degerli, "Monolithic active pixels with in-pixel amplification and reset noise suppression for charged particle tracking in a 0.25 μ m digital CMOS process", preprint n° DAPNIA-04-184, CEA-Saclay/DAPNIA.
- [5] G. Deptuch, "Charge sensitive elements optimised for particle tracking," in *Proc. 2003 IEEE Workshop on Charge Coupled Devices and Advanced Image Sensors*, Schloss Elmau, Elmau, Germany, 2003.
- [6] Y. Degerli, N. Fourches, M. Rouger, and P. Lutz, "Low-power auto-zeroed high-speed comparator for the readout chain of a CMOS monolithic active pixel sensor based vertex detector," *IEEE Trans. Nucl. Sci.*, vol. 50, no. 5, October 2003, pp. 1709-1717.