A new digital pixel for particle detection

Nicola Massari
IRIS group
Fondazione Bruno Kessler
Via Sommarive 18,
Povo (TN), Italy
massari@fbk.eu

Luca Parmesan
IRIS group
Fondazione Bruno Kessler
Via Sommarive 18,
Povo (TN), Italy
luparmesan@fbk.eu

Gianluigi Casse
Department of Physics
University of Liverpool
Oxford Street, L69 7ZE,
Liverpool - UK
gcasse@liv.ac.uk

***Abstract*—In this work a new concept of binary pixel for particle detection has been introduced. The binary pixel, consisting of multiple junctions and coupled with an only-nmos circuit, tries to exploit the latchup effect to enhance the detection of particles and convert them directly into digital bit. A test array of 128x128 pixels has been realized in a 65nm standard CMOS technology showing a final pitch of 6.5 µm. Preliminary results demonstrate the capability of the sensor to detect both visible light (pulsed laser) and alpha particles (^{90}Sr).**

Keywords—particle detectors, binary pixel, latchup effect

I. INTRODUCTION

Researchers want to study, in particle physics experiments, the nature of particles that constitute the matter and radiation in the universe. In these experiments, it is essential to use high performance custom detectors to enhance the detection capabilities of such systems. Nowadays the trend to build even more advanced experiments will result in the need for even more stringent requirements for the detector design in term of event rate and tracking capabilities [1]. It is desirable to design novel sensor architectures able to fast collect charges with a high number of pixels with reduced pitch to improve the position estimation of a particle hitting the active area. Moreover, power consumption has to be always minimized to ease the integration of multiple detectors in the system to cover the required area.

Most particle detectors found in the literature are based on a mixed-signal approach, having an analog front-end circuit, directly connected to the sensing node, followed by an analog to digital circuit, providing a multibit output to the readout electronics. The analog circuit has to amplify the useful signal, filter out possible noise contribution allowing the discrimination of the event. Due to the need to minimize mismatches and noise, the analog part of the design takes most of the area into the pixel. Typical pixel sizes for state-of-the art particle detectors range between 50×50 µm^2, in the case of hybrid pixel detector module pixels [2-3], and 28×28 µm^2 in Monolithic Active Pixel Sensors (MAPS) [4]. Moreover, the size of analog transistors, whose dimensions are driven by mismatch and noise requirements, do not scale with the same pace of digital transistor when more advanced technology nodes are used. For similar reasons, also power consumption of the analog front-end can be considered as an additional issue especially when the number of pixels of the array substantially increases. All these points prevent the realization of high-resolution detectors, representing a physical barrier for shrinking the pixel size towards µm or even sub-µm size. It is clear from this analysis that a new approach must be introduced to solve these issues.

In the proposed paper a novel concept of particle detector is presented. The main novelty of this approach consists of converting the acquired charge in digital signal as soon the event is detected. The binary pixel toggles when the particle has been detected, providing spatial information about the particle hit. This approach not only radically simplifies the pixel and the overall architecture, but also reduces the pixel size and the array power consumption. This fully digital concept was proposed already in [5] where a prototype based on 2 µm pitch with a bistable circuit was presented as a possible implementation. The pixel, thanks to the positive feedback, was able to toggle in a presence of less than 1000 e$^-$. Nevertheless, the collection efficiency was poor due to the use of standard substrate resistivity and of shallow junctions as sensing nodes. In this paper an exploratory pixel is shown. This new pixel exploits a positive feedback mechanism based on a controlled latch-up phenomenon that is triggered as soon a certain amount of charge is detected. Moreover, it uses a deeper junction as sensing node differently from [5]. The paper is organized as follows: the new pixel concept is presented in section II, while the array architecture in section III. Experimental results are eventually shown in section IV.

II. THE LATCH-UP PIXEL

The interaction of ionizing particles with digital circuits implemented in silicon gives rise to the observation of some unwanted behavior, called Single Event Upset (SEU), causing the change of state of some elements in the logic. Depending on the type of interaction, these events can be temporary or permanent, sometimes causing relevant current discharge and circuit damage.

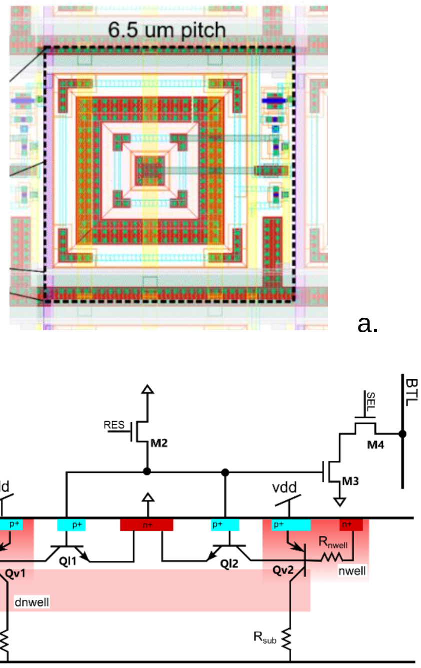


Figure 1: Cross-section (a.) and schematic (b.) of the pixel based on latch-up phenomenon.

A fully digital particle detector can be thought as an array of memory elements whose state, initialized at a specific value, may toggle when a particle hits the pixel. With this idea in mind, the new pixel is designed to be sensitive to the acquired charges favoring the change of status as soon as the sensitive node is stimulated by the particle transition.

The layout and cross-section of the pixel is shown in Figure 1a-b. As observed, the main collecting junction consists of a squared deep-n well connected through a n-well to the reference voltage V_{high}. Due to layout constraints, the pixel pitch is limited at 6.5μm, consisting of a minimum size deep-n well surrounded by similar deep-n wells placed at the minimum allowed distance. In the inner part of the pixel a central n+ junction is enclosed by a p+ ring, composing respectively the emitter and base of a lateral NPN BJT transistor. An only n-MOS circuit has been designed outside the sensing node to avoid the implementation of additional n-well, that may compete on the charge collection with the main junction. Next to the lateral BJT, other parasitic transistors can be identified. In particular, a vertical PNP BJT is formed by a p+ junction (emitter) embedded in the n well and forced to Vdd, by the n well (base) and the p- substrate (collector). In the cross-section, parasitic resistances R_{nwell} and R_{sub}, respectively referred to the n well and substrate, are also visible.

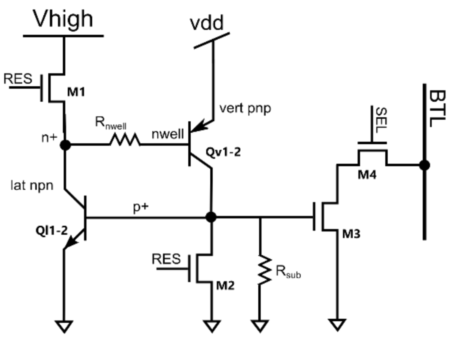


Figure 2: Schematic of the proposed pixel.

Figure 2 reports the schematic of the pixel including implemented MOS transistors and presence of active and passive parasitic devices for a better understanding of the pixel behavior. In this schematic transistors M_1 and M_2 are only used to pre-charge nodes n+ and p+ respectively to a reference value V_{high} and ground. The initial value of V_{high} is properly set to maximize the sensitivity of the pixel to the variation of node n+. After this first reset phase, both junctions are left floating, then free to move as soon as a particle is detected. The main junction (deep-n well) is connected through the n+ node and M_1 to V_{high} and when charges are generated and collected due to a particle hit, the voltage of node n+ suddenly decreases activating the vertical bjt Q_{v1-2}. The current flowing through Q_{v1-2} charges node p+ that activates the lateral npn transistor Q_{l1-2} thus implementing a positive feedback that toggles the status of the pixel. The pixel status will be readout by switching on transistor M4 (SEL=H) and using the common source amplifier M3 directly providing a binary value on the bit-line (BTL).

III. Sensor Architecture

The sensor array, designed in a 65nm technology, consists of 128x128 pixels. As shown in Figure 3, the array contains three different pixel topologies in order to compare their behavior when exposed to ionizing particles.

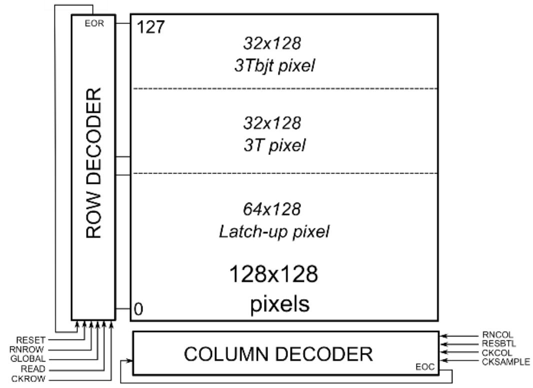


Figure 3: Architecture of the 128x128 pixels.

The detector is designed to work in rolling shutter mode using a row decoder for scanning all rows of the array sequentially and a column decoder for sampling data from the bit-lines and delivering the pixel content out of the chip. The readout consists of a register that, once sampled input values, serially scans data organized in byte (in this way reading an entire row needs 16 periods of clocks CKROW). Figure 4 shows the typical timing diagram needed for sensor initialization and data readout.

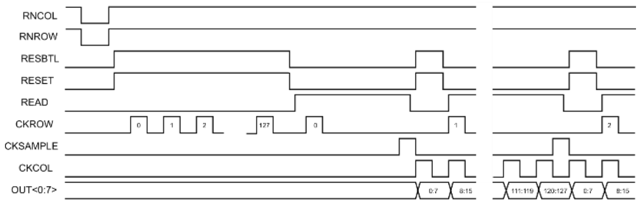


Figure 4: Timing diagram for pixel reset and readout phase of the array working in rolling shutter mode.

As observed in Figure 3, half of the array (64x128 pixels) is based on latch-up pixels. The remaining half array is divided in two other sub-arrays. The first sub-array of 32x128 pixels is made of a single deep-nwell junction readout using three transistors' pixels (3T pixel of Figure 3) while the last sub-array consists of 32x128 pixels based on vertical BJT (phototransistor, 3Tbjt of Figure 3).

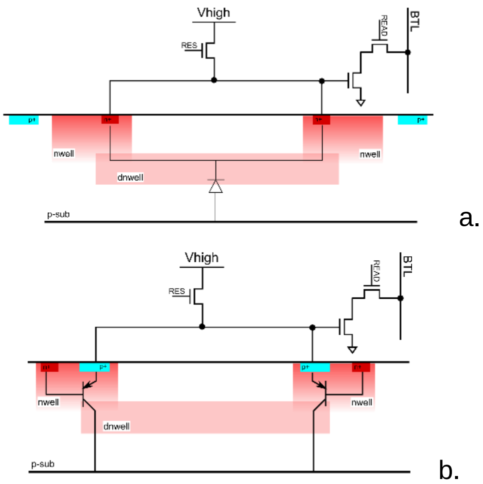


Figure 5: Cross section of 3T and bjt3T pixel of the proposed sensor array.

Figure 5 shows the cross section of the 3T and bjt3T pixel, having same size of the latch-up pixel. As observed, the 3T pixel mainly differs from the bjt3T pixel using an extra junction for the implementation of a vertical bipolar transistor. The goal in this case is to introduce an intrinsic gain in the charge collection operation.

IV. Experimental Results

The characterization of the latch-up pixel was first done using a test structure external to the array. This structure allows us to have access to the analog value of the pixel output, being not possible to read it from the digital array. The test structure schematic in Figure 6, which shows the presence of electrical stimulator consisting of a MOS transistor working as a capacitance placed at the input of the pixel. After the pixel reset, a negative edge of amplitude V_{IN} is applied to the capacitance to emulate a certain amount of charge injected by the particle. Due to a problem in the design, only a maximum voltage can be applied (Vin = 1.2V), corresponding to an estimated value of 7000 e-. With this stimulus, the pixel is always able to toggle.

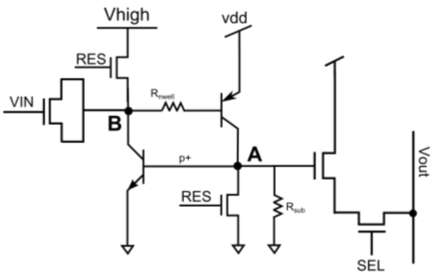


Figure 6: Schematic of the test structure: the input of the test pixel is connected through a MOS capacitance to an input voltage V_{IN} able to inject a certain amount of charge into the sensitive node.

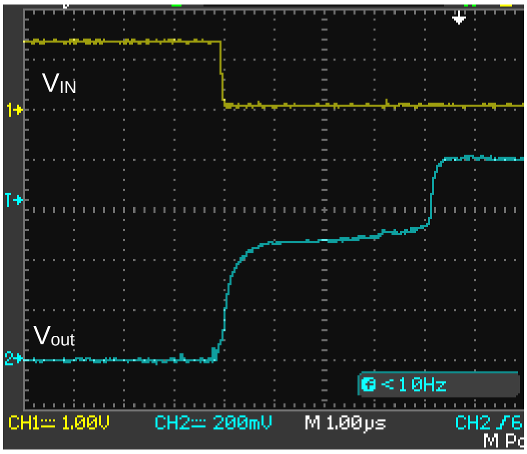
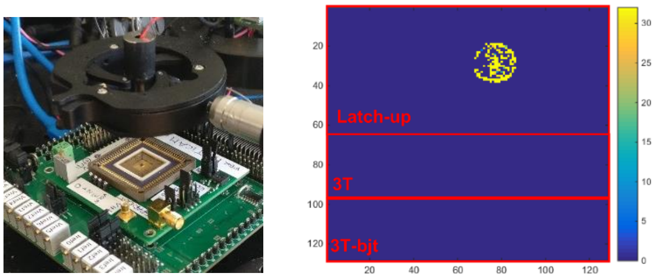


Figure 7: Analog value of the output of the test pixel acquired with an oscilloscope when an electrical stimulus is injected at the input.

Figure 7 shows the typical evolution of the output in correspondence of the stimulus. As observed, the injection of charge increases the value of node V_A until the positive feedback of the latch-up is activated (second rising edge), thus forcing the output voltage to Vdd (1.2V). The activation of the latch-up happens when the lateral BJT is enabled (V_A~0.7V).



a) b)

Figure 8: a) Measurement setup: a pulsed blue laser is focused on the active area of the array to check the response of the pixel to an optical stimulus; b) output of the array after the accumulation of 32 consecutive frames.

The array of pixels was also optically tested using visible light. In the setup of Figure 8a an external pulsed laser peaked at 490 nm was focused on the detector in order to stimulate the pixel with a certain amount of charge. The detector, synchronized with the source of light, acquired a sequence of subsequent 32 binary images that were accumulated to obtain a final image with 5b resolution (see Figure 8b). A burst of four subsequent laser pulses, impinging in the array, were synchronized at every image. As result, the projection of the laser spot is clearly visible while no activity is also observed in all other pixels.

The detector was also exposed to radiation to prove its capability to detect high energy particles. In this first experiment a ^{90}Sr was placed on top of the detector at minimum distance in order to maximize the flux of events. The image of Figure 9 is the results of the accumulation of 10000 frames of 35ms each. As observed, the image is clearly divided in two sub-array showing a different response to the exposure. The sub-array placed at the left of the image refers to the 3T and bjt3T pixels while the right part refers to the latch-up pixel. The distribution of events accumulated in every pixel after multiple exposures is clearly more uniform in the sub-array of 3T and bjt3T pixels than the sub-array of latch-up pixels. Nevertheless, the latch-up array seems to have, as average, pixels with more sensitivity than the other sub-array.

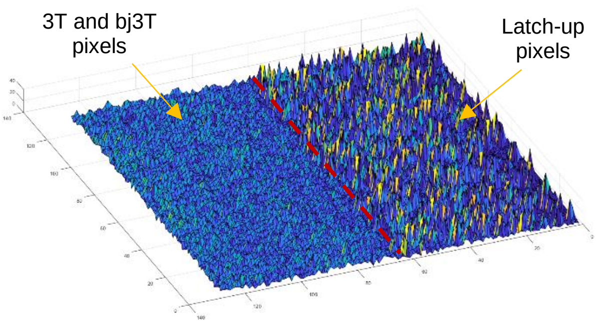


Figure 9: Image obtained after exposure to a ^{90}Sr source. The radioactive source was placed as close as possible to the active area to maximize the detection activity. Two main regions can be distinguished.

Figure 10 shows the histogram of number of events has been detected in al 10000 frame of the experiment for the two different sub-arrays. As result of this analysis, the rate of detection in the latch-up array is higher than the 3T and bjt3T approach. The average number of detected particles in the latch-up array is equal to about 15, corresponding to an equivalent flux of about 480 events/s, while the other sub-array the rate is of about 280 events/s.

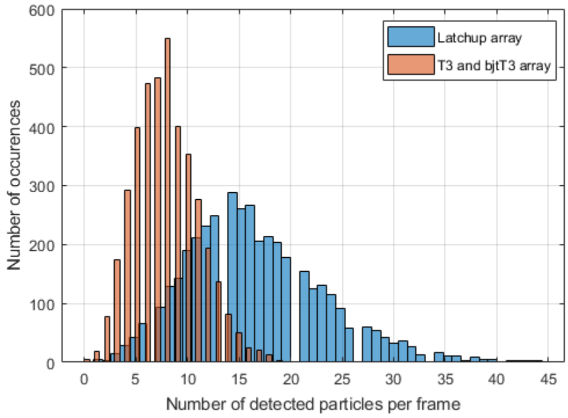


Figure 10: Number of detected events at different frames for the two sub-arrays.

Figure 11a shows the pixel value distribution of both 3T and bjt3T implementation. Such distribution can be approximated by a Poisson distribution with average value equal to 9.8 events per pixel. Figure 11b instead shows the distribution of latch-up pixel values. This histogram shows the overlap of multiple distributions with different coefficients due to pixel sensitivity variations across the array. We suppose the non-uniformity of the latch-up pixel is likely due to the variation of parameters of parasitic elements across the array that change the sensitivity of each pixel with respect to similar stimulus.

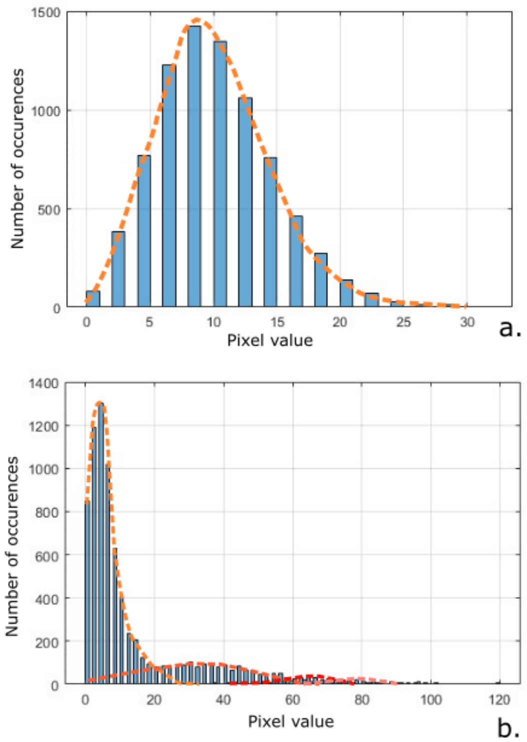


Figure 11: Distribution of pixel values in the two sub-arrays. a) distribution in the 3T and bjt3T pixel: a single distribution is clearly visible. b) distribution of values in the latch-up pixel: multiple overlapped distributions are identified.

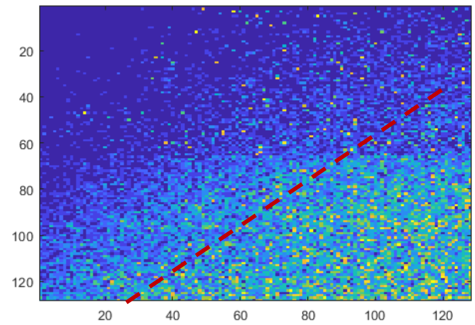


Figure 12: Events detected when the detector, exposed to ^{90}Sr source, is partially shielded by a sheet interposed between the source and the sensor.

The second experiment shows the response of the sensor with the same alpha source placed on the top of the detector and a sheet which partially cover the active area. As a result of this, only a portion of the array shows activity. In this experiment the different response of the two pixels topology is even more enhanced than the previous experiment.

V. Conclusions

The present paper shows the implementation of new fully digital pixel for particle detection. Preliminary results show that the detector responds to an optical stimulus as well as to a radioactive source. Images obtained after exposure to an alpha source (^{90}Sr) clearly show a spread of the pixel sensitivity in the array resulting in a relevant non-uniformity especially if compared with the image of another pixel topology (3T and bjt3T) implemented in the same array.

References

[1] F. Hartmann, Evolution of Silicon Sensor Technology in Particle Physics 2nd edn (Springer, 2017).

[2] M. Garcia-Sciveres, N. Wermes, A review of advances in pixel detectors for experiments with high rate and radiation, Rep. Prog. Phys. 81, 066101 (2018)

[3] The RD53 collaboration, www.cern.ch/RD53.

[4] M. Mager, ALPIDE, the Monolithic Active Pixel Sensor for the ALICE ITS upgrade, Nucl. Instrum. Meth. A824 (2016) 434–438.

[5] G. Casse et al 2022 JINST 17 P04010.