CMOS pixel sensors optimized for large ionizing dynamic

W. Ren, J. Baudot, L. Federici, C. Finck, C. Hu-Guo, M. Kachel, C.-A. Reidel, C. Schui, R. Sefri, E. Spiriti, U. Weber and Y. Zhao

Institut Pluridisciplinaire Hubert CURIEN (IPHC), 23 rue du Loess, 67307 Strasbourg, France
PLAC, Key Laboratory of Quark & Lepton Physics (MOE), Central China Normal University, 152 Luoyu Road, 430079 Wuhan, China
Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Frascati, I-00040, Frascati, Italy
GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstrasse 1, 64291 Darmstadt, Germany

E-mail: jerome.baudot@iphc.cnrs.fr

ABSTRACT: Monolithic active pixel sensors (MAPS) are now well established as a technology for tracking charged particles, especially when low material budget is desirable. For such applications, sensors focus on spatial resolution and pixels with digital output or modest charge measurement ability are well suited. Within the European Union STRONG-2020 project, which focuses on experiments using hadrons, the TIIMM (Tracking and Ions Identifications with Minimal Material budget) joint research activity intends to expand granular MAPS capacity to energy-loss (ΔE) measurement for ion species identification. The TIIMM prototypes are developed in the Tower Jazz 180 nm CMOS image sensor (CIS) process. The Time-Over-Threshold (ToT) method is applied to the sensor for the energy-loss measurement. The main design details and the preliminary test results from laboratory measurements of the initial TIIMM prototype are presented in this work.

KEYWORDS: dE/dx detectors; Front-end electronics for detector readout; Particle identification methods; Solid state detectors

© 2022 IOP Publishing Ltd and Sissa Medialab https://doi.org/10.1088/1748-0221/17/09/C09015
1 Introduction

The TIIMM (Tracking and Ions Identifications with Minimal Material budget) joint research activity of the European Union STRONG-2020 project aims to create a new class of instrument combining precision tracking and energy loss measurement with minimal material budget. This development is in particular motivated by the need to distinguish different ion species when measuring the heavy ions fragmentation cross-sections \cite{1}. In high-energy physics, Monolithic Active Pixel Sensors (MAPS) are used for charged particle tracking \cite{2, 3}. More recently they have also been used in ions fragmentation cross-section measurements for hadron therapy treatment improvement \cite{4}. The TIIMM goal is to complement the excellent tracking capabilities in current MAPS with the measurement of the energy lost in the sensor (usually referred to as $\Delta E$ measurement) to identify the crossing ion species in combination with another measurement, typically velocity through time of flight or full kinetic energy through calorimetry as implemented in \cite{1}. Measurements with binary output sensors already reported \cite{5} that the cluster size generated by impinging ions depend on their atomic number $Z$, however with limited precision.

TIIMM sensors target multi-bits signal digitization within small pixels from minimum ionization particles up to heavily ionization ions, such as carbon at few 100 s MeV/u. The challenge lies in the implementation of a dynamic range of the order of $1:10^3$ within a pixel pitch of about 40 $\mu$m. TIIMM exploits recent advances in CMOS pixel sensors, where the sensitive layer is fully depleted for more efficient charge collection. Two prototypes have been developed to investigate the feasibility of the time-over-threshold (ToT) method for large dynamic energy-loss measurement.

This contribution details the analog pixel design and initial test results.

2 The TIIMM prototypes

The Tower Jazz 180 nm CMOS image sensor (CIS) process has been chosen for the TIIMM project. A first sensor prototype, TIIMM0, has been fabricated in 2020, while a second sensor, TIIMM1, is being submitted to the foundry at the end of 2021. Both prototypes have common features: $2.2 \times 1.5$ mm$^2$ total area, $32 \times 16$ pixel matrix, and a similar pixel architecture described in the next subsection. Both prototypes use a sensitive layer grown by epitaxy to 25 $\mu$m thickness as
baseline. TIIMM1 will also be fabricated over a 50 μm epitaxial layer to investigate the potential benefits of larger signal, especially for species close to the minimum ionizing level.

A standard I2C interface is applied for the slow control of the chips, including the matrix configuration. Thus, it is possible to inject test pulses to the pixel analogue part or the in-pixel digital logic. A simple serial readout is implemented in the sensors.

10 DACs are implemented for biasing the pixel front-end circuits. The analogue outputs of the last column are connected to an output pad through an analogue buffer, allowing the analogue output investigation.

2.1 Pixel design and simulation

Each pixel is composed of a charge collection diode, a Charge Sensitive Amplifier (CSA), a comparator, and a digital logic providing the 6-bit ToT measurement. The comprehensive schematics for the pixel cells are shown for TIIMM0 and TIIMM1 in figure 1. The collection diode is an octagonal-shaped n-well with 1.3 μm diameter, in contact with the highly resistive p-type epitaxial layer. The diode is surrounded by p-wells with a spacing of 3.5 μm. The CSA is composed of an amplifier and the Krummenacher feedback circuit [6]. When the pixel is fired, the charges collected by the diode generate a signal amplified by the CSA. If the output signal of the CSA exceeds the threshold set to the comparator, the output of the comparator will flip. Then the pulse width of the comparator is digitized over 6 bits by the Time-Over-Threshold (ToT) [7] in-pixel digital logic.

![Figure 1.](image)

Figure 1. (a) Pixel structure of TIIMM0. (b) Pixel structure of TIIMM1.
The early TIMM0 prototype was designed to validate the pixel architecture. The pixel area is exactly $40 \times 40 \, \mu m^2$. It includes in each pixel a 4-bit local DAC for tuning the threshold.

For the TIIMM1 sensor, the feedback capacitor $C_f$ was increased from 1 fF to 5 fF to enlarge the dynamic range. The trimming DAC presented in the TIIMM0 pixel was replaced by AC-coupling the CSA output to the comparator to mitigate offset problems. This solution also decreases the power consumption as well as gains extra area to optimize the transistor size improving pulse width fluctuation. The pixel size increases only slightly to $41.2 \times 40 \, \mu m^2$.

Post layout simulation results of both pixel cells are discussed below. From figure 2, we observe that the dynamic for the pulse duration is much larger than the pulse amplitude and the linear range in TIIMM1 can reach 250 ke$^{-}$ against 110 ke$^{-}$ for TIIMM0. The AC-coupling also drastically decreases the baseline spread from 9.27 mV to 1.11 $\mu$V. These improvements are obtained with a modest ENC increase from 42 e$^{-}$ (TIIMM0) to 78 e$^{-}$ (TIIMM1). Finally, the predicted relative fluctuation of the pulse width does not exceed 10% over the whole dynamic range for TIIMM1 while it reaches up to 30% for TIIMM0.

![Figure 2](image.png)

**Figure 2.** Results from post-layout simulations: (a) CSA output (b) pulse width of the comparator vs the input charge.

### 2.2 Preliminary test results of first prototype

TIIMM0 sensor was fabricated in 2020 and samples were wire-bonded on a custom-designed PCB and characterized in the laboratory to study the chip functionalities.

As shown in figure 1(a), an injection capacitor $C_{inj}$ is implemented in each pixel. The pulse width of the CSA analog output signals increases with large injections as depicted in figure 3(a). Due to the small $C_{inj}$, the maximum injection is around 4 ke$^{-}$. Considering that the smallest measurable signals will be around 100 e$^{-}$, this maximal injection corresponds currently only to a small fraction (1:40) of the targeted final dynamic range (1:10$^3$). For performance under larger injections, tests under the radiation source and ion beams will be carried out.

Figure 3(b) shows the image with the digital readout test. A digital pulse signal with different pulse width is injected into each pixel directly as the input of the ToT module. This image shows the difference of the pulse width for each pixel which means that the ToT module works properly.
Figure 3. (a) The analog output of the CSA under different injections. (b) Image with digital readout test. This image is created with digital test signals injected into the pixels.

3 Conclusion

The TIIMM prototype family explores CMOS pixel sensors combining relatively small pitch for tracking and energy loss measurement useful for ion species identification. The ToT concept to measure energy loss has been validated with the TIIMM0 prototype, though with a limited dynamic range (1:40) compared to the $1:10^3$ target. The next sensor benefits from an optimized design for larger dynamic and smaller pulse width relative fluctuation. TIIMM1 with two depleted sensitive layer thickness, 25 and 50 μm, will be available in 2022 for performance tests with various ion beams.

Acknowledgments

This project has received funding from the European Union’s Horizon 2020 research and innovation program under Grant Agreement No. 824093. The support provided by China Scholarship Council (CSC) No. 201906770018 is acknowledged.

References

[1] G. Battistoni et al., Measuring the impact of nuclear interaction in particle therapy and in radio protection in space: the FOOT experiment, Front. Phys. 8 (2021) 568242.
[2] G. Contin et al., The STAR MAPS-based PiXeL detector, Nucl. Instrum. Meth. A 907 (2018) 60.
[3] M. Mager on behalf of the ALICE collaboration, ALPIDE, the monolithic active pixel sensor for the ALICE ITS upgrade, Nucl. Instrum. Meth. A 824 (2016) 434.
[4] E. Spiriti, M. De Napoli and F. Romano, The FIRST experiment: interaction region and MAPS vertex detector, Nucl. Phys. B 215 (2011) 157.
[5] E. Spiriti et al., CMOS active pixel sensors response to low energy light ions, Nucl. Instrum. Meth. A 875 (2017) 35.
[6] R. Szczygiel, Proceedings of the 17th International Conference Mixed Design of Integrated Circuits and Systems — MIXDES 2010 (2010), pp. 412–415.
[7] I. Kremastiotis et al., PoS(TWEPP2019), Vol. 370 (2020), p. 039.