FASTPIX: sub-nanosecond radiation tolerant CMOS pixel sensors

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ABSTRACT

Monolithic CMOS sensors potentially provide an ideal sensor for high energy physics covering large areas at reasonable cost combining tens of ps timing resolution and extreme radiation tolerance if a sensor structure eliminating the tradeoff between minimum pixel size and signal timing variation is found. We aim to provide such a structure and lay the basis for a "dream" sensor, revolutionizing high energy physics experiments, and also other scientific instruments and sensors used in daily life. We are now evaluating prototypes designed and manufactured in this first phase to prepare production of a dream sensor at a later stage.

Keywords: silicon sensor; CMOS imaging sensors; particle detection; fast timing.

1. INTRODUCTION

Silicon sensors and radiation tolerant readout circuits in commercial CMOS technologies have become the standard for all experiments at the Large Hadron Collider (LHC) at CERN. Monolithic CMOS sensors combining both sensor and CMOS readout circuit in a single silicon wafer, are ideally placed to provide a "dream" sensor with an almost noise-free, large amplitude signal, tens of ps timing resolution, extreme radiation tolerance, covering large areas at reasonable cost, and significant in-pixel functionality.

Complex monolithic CMOS sensors are already produced to cover a few square meters in some experiments, and techniques like stitching and advanced packaging are expected to further facilitate covering very large areas at reasonable cost. Sub-femtofarad, tiny submicron collection electrodes can be manufactured in very deep submicron CMOS technologies and provide a large amplitude signal, low noise, low detection threshold and enable fast operation for precise timing.

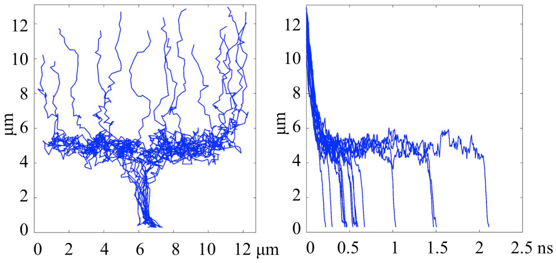
Missing at present is the combination of precise timing and extreme radiation tolerance. The key to this combination is a sensor structure virtually eliminating the tradeoff between minimum pixel size and signal timing variation when collecting charge on a very small collection electrode. This structure will accelerate the signal charge to the collection electrode, reduce charge trapping and timing spread and increase radiation tolerance. We aim to provide such a structure and lay the basis for a "dream" sensor, ultimately revolutionizing not only high energy physics experiments, but also other scientific measurement tools as imaging Time-of-Flight Mass Spectroscopy and Fluorescence Life-Time Imaging Microscopy, medical applications like proton therapy and sensors used in daily life like LIDAR in cars.

We studied how improvements indicated by simulation can be best applied to further define the optimal sensor structure as a **first objective**. Performance limits of an optimal sensor structure were benchmarked as a function of pixel pitch and minimum feature size as a **second objective**. This is essential to properly motivate technology choice and to determine ultimate performance if new technologies like 3D-stacking are applied in the future allowing a further reduction of the pixel pitch. Prototypes were fabricated as a **third objective** to ensure manufacturability of the proposed sensor structures. Within one year this could only be done in less advanced technologies we already work with. We are now working on the characterization of these first prototypes. The **overall objective** is to prepare technology choice and prototype production of a "dream" sensor at a later stage.

2. STATE OF THE ART

Small feature size CMOS technologies offer submicron signal collection electrodes with sub-femtofarad sensor capacitances. This leads to excellent signal-to-noise ratios essential for precision timing, and practically digital signals at the sensor input for ionizing particles, eg 220 μV/e- in 110 nm and 350 μV/e- in 45 nm, or several 100's of mV for a minimum ionizing particle generating a 1000 e- charge, at least a factor 3 to 10 better than present CMOS sensors in particle physics.

There is a trade-off in a pixel with a very small collection electrode between minimum pixel size to fit circuitry and the variation in travel time of the signal charge to the collection electrode. Fig. 1 shows a Monte Carlo simulation for visible light illustrating significant arrival time variation with varying horizontal travel distance, and hence significant degradation of the time resolution.



(a) (b)

Fig. 1. Monte Carlo simulation of (a) trajectories of signal electrons generated by visible light incident on the backside of a pixel (top in the figure), and (b) their vertical travel distance towards the collection electrode (bottom of the figure) versus time. The large arrival time variation, several ns, clearly correlates with the horizontal travel distance. The pixel pitch is 12.73 μm[1].

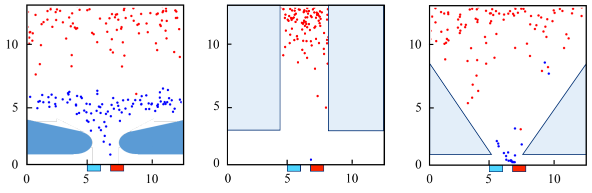
Another promising approach to increase the signal-to-noise ratio is to use charge multiplication achieved by applying large electric fields near or over breakdown, like in Single Photon Avalanche Diodes (SPADs) and Low Gain Avalanche Diodes (LGADs). However, these devices are usually not sensitive or not uniformly sensitive over the full sensor matrix, more prone to radiation damage, and often require tight operation control (e.g. temperature stability). When uniformly sensitive over the full area, they usually do not permit integration with readout circuit in the same substrate. The random nature of charge multiplication or avalanche processes also adds to the timing uncertainty.

3. BREAKTHROUGH CHARACTER OF THE PROJECT

Tab. 1. Performance overview for the structures in Fig. 2. The pixel size is 12.73 μm, the thickness 13.1 μm, and the width of the light-electron guide pipe (square) 4 μm.

Structure	p-well	Light/electron guide pipe	Convex silicon pyramid
Cross section			
Temporal resolution 2σ	990.0 ps	49.0 ps	87.5 ps
Fill factor	100%	10%	100%
Vertical field	5 kV/cm*	25 kV/cm**	25 kV/cm**
Dark current	less	middle	large
X-ray	Applicable	Low efficiency	Ideal
Technical feasibility	Already applied	Existing technology	Process improvement

This project aims to eliminate the trade-off in sensors with very small collection electrodes between minimum pixel size to fit circuitry and the variation in travel time of the signal charge to the collection electrode depending on where it was generated. The key is to shape the electric field to focus the signal charge to the collection electrode and drastically reduce timing variation.



(a) (b) (c)

Fig. 2. Multiple approaches improve pixel timing performance for back side illuminated image sensors, visible light is incident at the top in the figure, photo-electrons are shown by dots in red when they are just created, and in blue after 200 ps: (a) a special pwell implant to shape the electric field and accelerate signal carriers towards the collection electrode, (b) a light and charge guide pipe, using only the pixel center, best for timing as almost all photo-electrons are collected after 200 ps, but with low efficiency, and (c) 3D shaping of the electric field for instance by placing the collection electrode on top of a convex silicon pyramid, not yet realized but providing significant improvement (see also Tab. 1). The blue and the red rectangle illustrate the possibility to use multiple readout electrodes, scales are in μm[1].

Fig. 2 shows multiple sensor structures improving the collection time of photo-electrons for visible light, and Tab. 1 compares performance. 3D shaping is not yet available but provides significant improvement creating a funnel to push signal charge to the collection electrode.

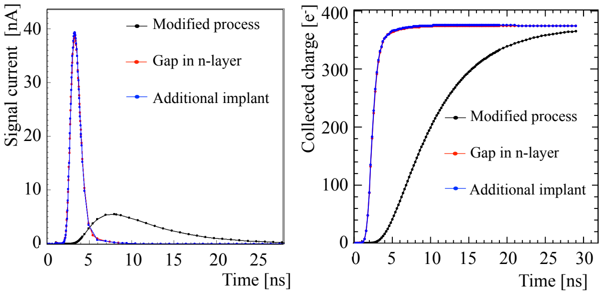


Fig. 3. Introducing a gap in the n-layer or an additional implant in the modified 180 nm process improves the time response of pixels by an order of magnitude. The signal current is shown on the left, the collected signal charge on the right [3].

The ALICE experiment at CERN constructed a new Inner Tracking System (ITS) covering 10 m^2 with the ALPIDE sensor, fabricated in a 180 nm CMOS imager technology. The installation of this detector is foreseen during the next long LHC shut down. A first process modification [2] adding a blanket low-dose n-type implant in the pixel matrix was developed in collaboration with the foundry, allowing full depletion of the sensitive layer and an electric field to accelerate signal charge towards the collection electrode. A specific development effort towards more aggressive timing requirements for the CLIC [3] and ATLAS experiments at CERN [4] was then started. Fig. 3 shows the simulated signal generated by the incidence of a minimum ionizing particle in the pixel corner for a 36.4 x 36.4 µm^2 pixel in the modified process, and the significant signal acceleration achieved with either of two additional modifications, creating a gap in the blanket n-implant or an additional pwell implant near the pixel edge.

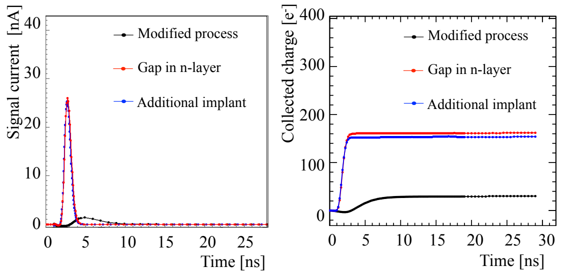
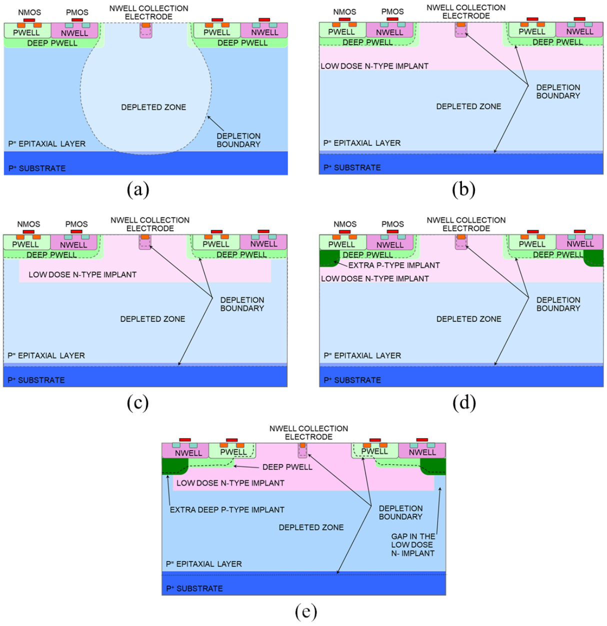


Fig. 4. The same modifications as in fig. 3 improve the time response also after irradiation, and significantly reduce the radiation-induced signal loss. The signal current is shown on the left, the collected signal charge on the right [3].

Significant radiation damage will cause a fraction of the signal to be caught by radiation-induced traps and lost for readout. Fig. 4 illustrates the significance of this effect for a sensor irradiated to 10^{15} n_{eq}/cm^2. The faster signal collection due to the additional modifications yields a ~ 6x signal improvement.



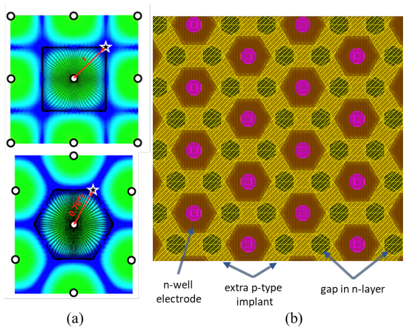
(a) (b) (c) (d) (e)

Fig. 5. Cross section of a 180 nm CMOS imaging sensor process. (a) Standard process (b) Modified process with low dose n-implant (c) with extra p-type implant (d) with gap in the low dose n-implant (e) with extra p-type implant, gap in the low dose n-implant and retracted deep pwell[5].

These first 3D TCAD simulation results illustrate an order of magnitude timing improvement down to ~2ns, sufficient for ATLAS and CLIC. More complex full 3D shaping of the electric field using micro-machined structures as in Fig. 2 or more complex implant structures as in Fig. 5 will bring additional orders of magnitude and eliminate the trade-off between pixel size and timing variation for practical in-pixel readout circuits. This also reduces charge sharing and makes more charge available in a single pixel with better efficiency and timing performance.

4. PROJECT RESULTS

We used TCAD simulations to study how earlier process modifications (Fig. 5b-d) of a 180nm CMOS imaging technology could be further combined and optimally applied (Fig. 5e) as a **first objective**. The electric field pulls the signal charge away from the pixel border towards the collection electrode as fast as possible. This reduces charge sharing and maximizes the seed pixel signal hence reducing time-walk effects.



(a) (b)

Fig. 6. (a) Comparison of square versus hexagonal grid. (b) Layout of the FASTPIX collection electrode hexagonal grid with extra p-type implant and gap in the low dose n-implant[6].

Collection electrodes on a hexagonal grid and a reduced pixel pitch minimize the maximum distance from the pixel border to the collection electrode. The hexagonal geometry limits charge sharing at the pixel corners to only three pixels instead of four. Fig. 6. compares square and hexagonal pixels, and gives an example of the layer geometry to accelerate the charge collection.

For the **second objective** the optimization was benchmarked for various pixel pitches, and reduced the timing spread to less than 500 ps for the smaller pixel pitches in the same process. First simulations for more advanced processes indicate a timing spread of the charge collection **down to a few tens of ps, about three orders of magnitude better than the original starting point**. Fig. 7. shows an example in a 65 nm technology where a modification reduces the worst case peak of the signal current from 400ps to 100ps. Simulations for modifications in Fig. 5b-d for ATLAS [4] and CLIC [5] have now also been experimentally confirmed and improved radiation tolerance.

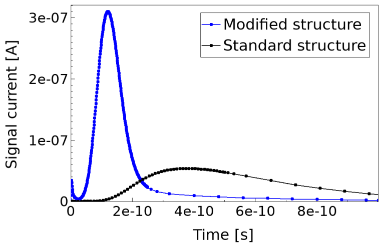


Fig. 7. A modification in a 65 nm process reduces the peak of the signal current from 400ps to 100 ps, hexagonal pixel with 10 µm pitch, pixel hit in the corner (worst case).

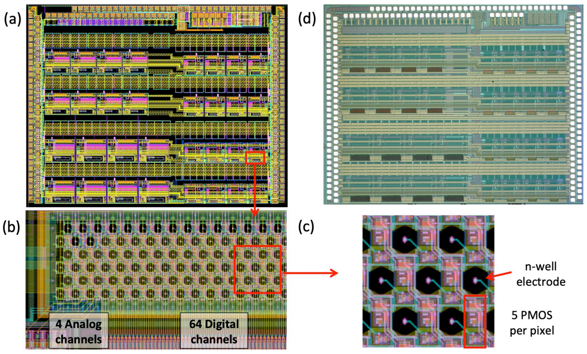
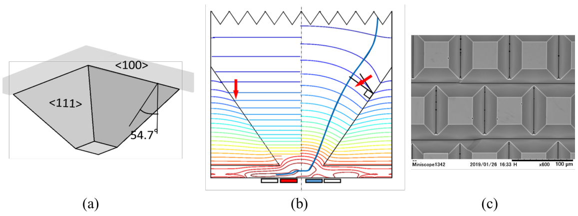


Fig. 8. Layout (a-c) and die picture (d) of the FASTPIX test chip fabricated in a 180 nm CMOS technology.

Verifying manufacturability of the proposed structures was the **third objective**: a test chip was designed and fabricated in a 180 nm CMOS technology including 32 pixel matrices with different pixel flavours and pitches of 8.66, 10, 15 and 20 µm (Fig. 8) and is now under test. A variation of this test chip is now being submitted for a second fabrication. Micromachining process steps (Fig. 8) were explored as a feasibility test for the inverted pyramid structure referred to in Fig. 1 and Tab. 1.



(a) (b) (c)

Fig. 8. (a) Truncated pyramid with square section. (b) Potential simulation, the right side shows the equipotential lines when adding 100 nm B implant on the wall + a deep P implant from the surface. (c) Process example using micromachining.

5. FUTURE PROJECT VISION

Reaching tens of ps timing in small pitch pixel sensors for particle detection and bringing this technology into the field will require significant effort and investment. It would come timely with increased interest and research and development both on precise timing and CMOS sensors in various applications, its potential impact on science and society, and the increasing availability of high-resistivity starting material and mature simulation as enablers to implement such sensors in very advanced CMOS technologies.

5.1. Technology Scaling

The same techniques to accelerate charge collection in very advanced, small feature size CMOS technologies will bring an essential extra performance step. Masks and design in these technologies are very expensive, reaching 1 million Euro or beyond for a mask set of a single run alone for the most advanced ones, and an even larger design cost for large sensors. To bring devices to a level of maturity where they can be applied in the field typically takes several runs over three to five years. Sensors need to be designed using extensive simulations within the constraints specific to the technology, and then verified in a first fabrication run. After that significant circuit and system design effort is required to finalize and fine-tune sensor chips and systems in a few iterations to field a prototype system for specific applications.

5.2. Project Synergies and Outreach

Synergies with other projects were essential to realize the prototype in this first phase of ATTRACT. We plan to continue this way to allow fast progress and efficient use of funds. We did not charge any manpower to the project for the first phase, neither on the design nor on the testing, and devoted most of the funds to the manufacturing of prototypes. Manufacturing cost was optimized sharing runs with other projects. Close contact with several foundries, built up over several years, is essential to make fast progress establishing practical manufacturing steps for specific sensor designs, and introduce them into the line.

Collaboration with several groups is already established to study CMOS pixel sensors for particle detection in the framework of a 5 year research and development program initiated by the experimental physics department at CERN[7]. This would form the natural basis for growing the consortium for the second phase. Cost and effort could be shared with other projects as during phase 1. Discussion has started with other ATTRACT projects working on timing, and with groups working on some of the applications mentioned below. We would first focus on high energy physics, where the performance improvements reached already now are of interest for various projects, and would continue to exploit our privileged relationship with foundries. After that we would like to establish partnerships with companies/institutes specialized in one or more applications mentioned below, and implement prototype systems to be tested in the field. We also have good contacts with a project [8] building a prototype of a detector for proton therapy using the ALPIDE chip, and could use this application as a test case.

Our community has a culture of publishing. The first phase work was presented at a conference, submitted as a journal paper, and we have been invited to another conference. Research institutes partner with universities, supervise Ph.D. students and post docs, and also participate in or organize short courses for students.

5.3. Technology application and demonstration cases

Particle detection of ionizing particles in fine pitch pixels with timing in the 100 ps range or below will make the "dream" detector for high energy physics a reality, a break-through to help future experiments in their quest for answers to fundamental questions: precision timing enabling tracking with time of flight ("4D" tracking) to disentangle more complex events, combined with radiation tolerance is essential to cope with higher collision and particle rates.

Such detector will revolutionize many other scientific instruments for instance in Time-of-Flight Mass Spectroscopy (ToF-MS), used in environmental biology, and medical diagnosis, Fluorescence Life-Time Imaging Microscopy (FLIM), visualizing molecular effects in real time, like the evolution of the metabolic state of cells and tissue, protein interaction, cancer, etc, and electron microscopy and cryo-electron microscopy visualizing macromolecules like viruses. Such detector would also reduce the time and the dose received by the patient in proton-therapy centers to adjust the machine to locate the tumor within the patient before applying the treatment, making more time available for the actual treatment.

Achieving precision timing for single visible photons would be a game-changing technology for many industrial applications, and in daily life, in LIDAR mounted in cars for instance, where state-of-the-art technologies typically use avalanche multiplication or indirect detection imposing significant practical constraints.

The project would also push the development of several software tools in the community combining information from TCAD simulators with Monte Carlo analysis and significantly accelerate simulations. European Community funded irradiation facilities would be used to qualify the prototypes for several types of radiation.

5.4. Technology commercialization

Close contact with foundries enables fast progress introducing new process steps into the line but also accelerates making the newly developed technologies available. Ritsumeikan University has many industry contacts also in Europe for visible light sensors. INFN and CERN collaborate with institutes all over the world and participate in many experiments. Several are involved in developments for other applications. All this places us in an ideal position not only to develop a break-through sensor, but also to disseminate the work and its results and bring it in the field quickly.

5.5. Envisioned risks

Risks associated with a single foundry should be avoided, working with at least two will multiply fabrication costs but some economy can be made on the design cost and different processes might have also specific advantages. Process modifications and optimization always contain a risk of delays or iteration before full qualification as a standard process.

5.6. Liaison with Student Teams and Socio-Economic Study

Several of us already participated in sessions with MSc. student teams on other developments, and contributed to phase 1 with video presentations, etc. We are ready to do both and help the consortium in its actions for phase 2.

6. ACKNOWLEDGEMENT

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