MonPicoAD - a Monolithic Picosecond Avalanche Detector

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ABSTRACT

This project introduces a novel silicon sensor structure devised to provide unprecedented time resolution in a monolithic pixel silicon sensor, for precise time measurement of ionizing particles. This goal is achieved by the introduction of a fully depleted multi-junction structure buried in the silicon substrate, coupled with fast electronics capable of picosecond-level time resolution, in a monolithic sensor of thickness down to 25µm. This development represents an extraordinary enabling technology for the large spectrum of high-tech applications that will benefit of picosecond-level Time-Of-Flight measurements of ionizing radiation, like for example Positron Emission Tomography and mass spectrometry.

Keywords: Monolithic detector; Mixed-signal electronics; Time-of-flight.

1 INTRODUCTION

The outstanding time resolution and monolithic nature of the proposed detector, combined with the high granularity, the low material budget and the reduced assembly procedure and production cost, will represent a ground-breaking instrument for a very large spectrum of applications.
For ionizing radiation detection, for example:

- Time-Of-Flight (TOF) mass spectrometry;
- Time-Of-Flight Positron Emission Tomography (TOF-PET) or TOF-X-ray imaging;

Applying the same detector to photonics will allow full fill factor and low dark noise, which will have great impact in:

- Quantum cryptography and communication
- Quantum optics
- Material science (e.g. Fluorescence lifetime spectroscopy)
- Biology (e.g. Flow cytometry)

The key breakthrough of the project is the implementation of a buried avalanche region allowing an unprecedented time resolution of 2 ps, breaking the Landau-noise limit of present detectors [1] and improving by an order of magnitude the best resolutions measured so far. This novel sensor needs to be integrated with fast electronics, capable of accurately measuring the time of arrival of the pulses coming from the substrate. A low-noise, low-jitter front-end based on IHP Silicon-Germanium HBT (Heterojunction Bipolar Transistor) is used to acquire the signal, coupled with a fast Time-to-Digital Converter (TDC), featuring low-power and robust multi-chip calibration capabilities, allowing the use of the detector in complex large-area systems.

During the ATTRACT phase 1 we submitted a number of prototypes in order to validate every block of the detection system. A fully featured pixel detector with a 12 by 12 matrix of hexagonal pixels is currently under test and it shows promising preliminary results. Two separate architectures for a fast TDC were developed and submitted. The first prototype was received and a test setup is being produced, while the second one will be back from the foundry in September. Finally a batch of wafers with the buried gain structure is currently being produced. Unfortunately the development of a thick-epitaxial layer growth process not yet available at IHP proved difficult and required a second run as the initial quality was not satisfactory. In parallel the production of the wafers by an external company is also being investigated.

2 STATE OF THE ART

The best time resolution for Minimum Ionizing Particles (MIPS) presently achieved with silicon sensors without internal gain is 46 ps [2] obtained by our group with a monolithic detector, using low-noise SiGe HBT electronics.
Recently the adoption of a gain layer in the Low-gain Avalanche Detectors (LGAD) [3] allowed reaching a resolution of 30 ps with an internal gain of 50. This results constitutes a fundamental physical limitation of the PN-junction sensor designs, that was recently understood to be produced by the Landau noise. Moreover, the location of the gain layer in the LGADs is such that a dead area of 100 μm around each pixel is unavoidable; this circumstance does not permit to realize small pixels, and LGADs are produced with pads of mm^2 area.
Similar time resolutions have been proven in hybrid pixel detectors too [4], with more elaborate designs but at the cost of much higher costs and complexity. Moreover the need of an external sensor connected to the readout electronics limits this approach in applications where extremely thin sensors or low material budgets are needed. The 3D sensors for the TIMESPOT initiative have also demonstrated the possibility of a 20 ps time resolution [5].

3 BREAKTHROUGH CHARACTER OF THE PROJECT

The aim of the project is to go beyond the state-of-the-art in terms of timing accuracy with regards to timing accuracy in pixel detectors. While other solutions have been proposed for accurate timing measurements (some of them are presented in Tab. 1), their time resolutions are limited by the Landau noise due to the thickness of the gain region. A thin buried gain layer depicted in Fig. 1 allows only the primary electrons generated in the 1 μm electron-source region to drift toward the gain junction, enhancing the fast component of the signal while limiting the Landau noise. Added benefits are a reduced pixel capacitance due to the full depletion of the P-substrate and a more uniform weighting field as the multiplication happens far from the pixels.

Tab. 1. Comparison between the MonPicoAD detector and the state-of-the-art

	MonPicoAD	Monolithic [2]	LGAD
Time resolution	**< 5 ps**	46 ps	30 ps
Internal Gain	**50-100**	-	50
Pixel size	**100×100 μm^2**	100×100 μm^2	1 mm^2
Technology	**BiCMOS**	BiCMOS	CMOS

This novel detector will allow unprecedented developments in many applications, from basic research to industrial environments.
In high-energy physics experiments, thin silicon detectors are used with great success for accurate 3D reconstruction of the trajectory of charged particles and their production vertex. Our approach allows for true 4D reconstruction by adding accurate timing information, reducing pileup and making a clean extraction of the signals of new physics possible.

For industrial applications, we are collaborating with ID Quantique, a commercial partner with a well established market which proved to be interested in this technology for applications such as Quantum optics and Fluorescence lifetime spectroscopy. Particularly important for commercial applications is the monolithic integration of the detector, that can dramatically reduce the cost of development and production by removing the need for expensive interconnection solutions between the active sensor and the readout electronics.

Other applications include medical imaging (TOF-PET, TOF-X ray imaging) with the possibility to cover large detection areas with reasonable costs while achieving state-of-the-art accuracy.

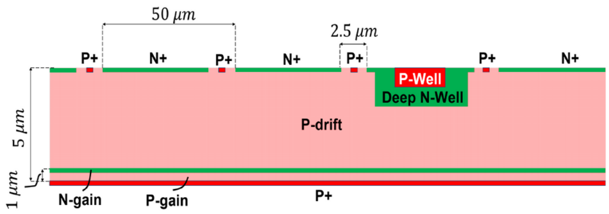

Fig. 1. Cross-section of the MonPicoAD detector, with 50 by 50 μm^2 and 2.5 μm inter-pixel distance.

4 PROJECT RESULTS

The wafer substrate with the buried gain structure was fully simulated using TCAD with different doping profiles to optimize the electric field and the gain (see Fig. 2). The geometry was chosen to make the field as uniform as possible to avoid edge effects in the areas between pixels. From these studies a specific doping was chosen to allow full depletion at 100 V (Fig. 3) and maximize the electron current density across the avalanche multiplication layer compared to the hole current density (Fig. 4).

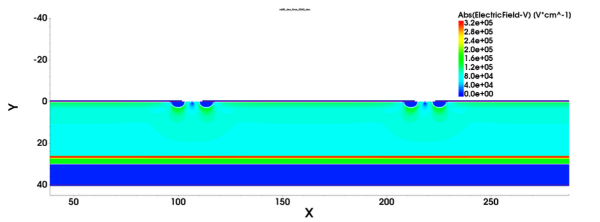

Fig. 2. TCAD simulation of the electric field across three adjacent pixels in the sensor.

The wafers are currently under production. An earlier batch showed a large number of defects due to the thick epitaxial growth, a process step not previously available at IHP, making it not compatible with CMOS processing. The next batch shows promising results, with a lower defect density.

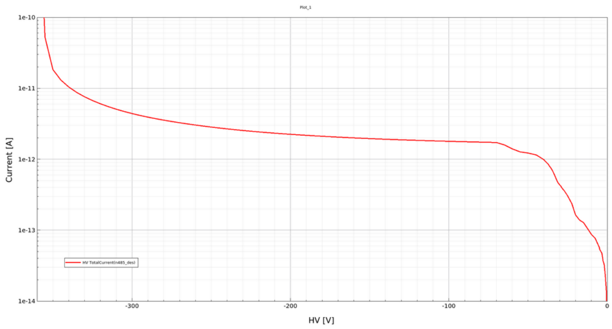

Fig. 3. TCAD simulation showing the substrate current as a function of the bias voltage. At 100V the substrate is fully depleted.

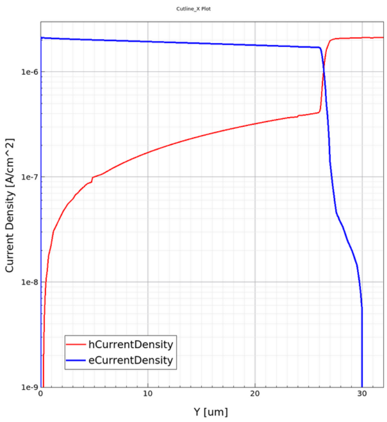

Fig. 4. Current densities for electrons and holes along the silicon substrate.

At the same time a fully featured 12 by 12 pixel matrix with four different front-end styles was designed and fabricated (a picture of the chip is in Fig. 5). The pixels are hexagonal, with an area of about 100x100 μm^2. It includes an SPI standard interface for slow control and a fast 200 Mbps link for data readout. Various circuit parameters can be tuned using on-chip Digital-to Analog converters (DACs). Time of arrival of particles can be measured with three embedded 30 ps resolution TDCs. The analog signals from a small submatrix is sent directly to output pads to be able to measure it with an oscilloscope. A preliminary analysis shows an Equivalent Noise Charge (ENC) of less than 150 electrons for power consumptions larger than 40 μW (Fig. 6) and a time jitter of 15 ps for a 1 fC input charge (Fig. 7).

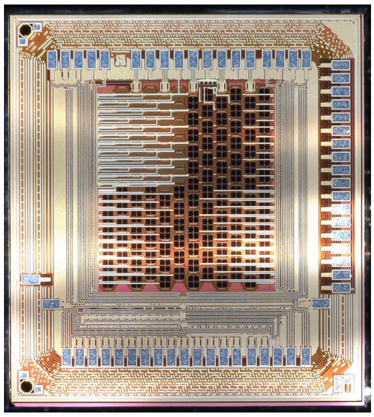

Fig. 5. Photo of the 12 by 12 pixel matrix chip.

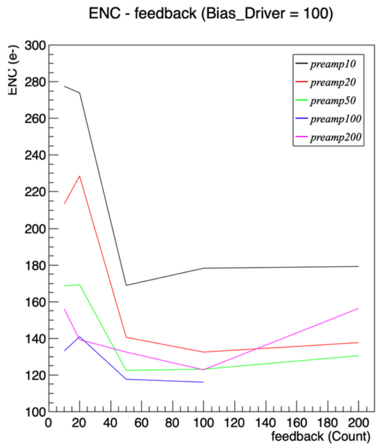

Fig. 6. Equivalent Noise Charge for different values of amplifier currents

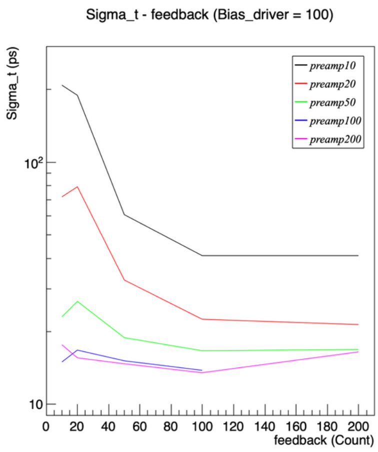

Fig. 7. Time jitter for different values of amplifier currents

Tests on this chip are currently undergoing. The digital interface works and it's possible to correctly program and readout the chip. The front-ends are operational and pulses can be seen with an oscilloscope when the detector is illuminated with a radioactive source (Fig. 8). Other two smaller chips were submitted, containing two different designs for TDCs to get to resolutions of a few picoseconds. The first one uses a longer BJT-based ring oscillator, exploiting the lower delay of the BJT gates compared to standard CMOS ones. This solution is very simple, but has the drawback of having a larger power consumption. The second chip contains a hybrid Time-to-Amplitude converter with counters to increase its dynamic range. Simulations show an accuracy of less than 5 ps with much lower power consumptions, with the drawback of needing an Analog-to-Digital converter as part of the measuring process, together with a more complex control logic. The first design was fabricated and will be tested shortly. The second one will be back from the foundry next month.

Fig. 8. Example pulse from one of the pixels connected to an output pad for a 1 fC input charge.

5 FUTURE PROJECT VISION

During ATTRACT Phase 1 a number of concrete applications and potential partners were identified to bring this technology from a lab to the market.

5.1 Technology Scaling

At the moment all the blocks of the MonPicoAD system are being produced or validated. Following this phase a fully-featured demonstrator combining all the different developments will be designed and produced, allowing testing the device in the target applications. We will closely work with commercial partners to ensure that the specifications of this detector are industrially relevant and that even the demonstrator can be used in marketable products.
The detector concept was designed to be fully compatible with existing CMOS processes from major manufacturers. While the role of IHP in the development of the buried gain layer is invaluable, the transition to mass production can be easily achieved using large-volume foundries such as TSMC or STMicroelectronics.

5.2 Project Synergies and Outreach

We are in contact with potential partners who are interested in our technology and can bring it to the market.
In the medical imaging field, members of our team (UniGE, EPFL, INFN) already have worked on silicon-based PET scanners in collaboration with medical institutes (Hôpitaux Universitaires Genève and Centre Hospitalier Universitaire Vaudois).
For light detection with picosecond time resolution, we are discussing with ID Quantique, an established company developing product in this field.

The dissemination of the results of this research will mainly be done through scientific publications and conferences. While the science behind the detector will be made public, some of the implementation details might be kept private or patented, to protect the intellectual property of our commercial partners or of a potential spin-off company.

5.3 Technology application and demonstration cases

Our picosecond resolution detector opens the way to breakthrough developments in different fields. Among the others, we believe that it will improve medical imaging techniques such as PET or X-ray leading to more accurate and more timely diagnoses, with clear benefit for public health.
Another field of application is secure quantum communication and cryptography, a critical developing technology allowing people and countries to easily employ encryption schemes robust to criminal attacks or espionage.

Light detection using our detector can be also useful in a number of biology and material science applications (flow cytometry, fluorescence lifetime spectroscopy), making it a technology that can enable other groups to further pursue their research.

5.4 Technology commercialization

For each target application, our strategy is to get to the market through companies that use or develop those technologies, such as ID Quantique. Together with them, we will leverage partners with established contacts or customer base and marketing expertise.
Once the technology is fully demonstrated, we will create a spin off company or license it to commercial partners. One of our members has a proven record having already funded three startups in Switzerland.
To go to market, we will apply for complementary public or private funds in Europe and Switzerland such as Venture Kick. In particular we are in contact with various business angels associations (e.g. A3 Angels, Business Angels Switzerland) and large companies such as Medtronic, Intuitive Surgical and Mediso.

5.5 Envisioned risks

The main risks for the ATTRACT Phase 2 concern the timeline of the future prototypes. The production of the wafers with internal gain was already delayed during this

year (partly due to the COVID-19 crisis) and the design could require an iteration to optimize the electric characteristics, pushing the date forward.
To minimize this risk the work was parallelized as much as possible, allowing the development of different blocks independently, reducing the impact of a delay in the design of a single part of the system.

5.6 Liaison with Student Teams and Socio-Economic Study

Due to the extremely technical natures of the research, students will not be able to contribute directly to the development of the project. Nevertheless, events such as "hacaktons" and collaboration with student teams from outside of the project can prove invaluable to discover new disruptive applications for our technology, which might not be obvious to a team with a more homogeneous background. To facilitate this we will have students as one of the targets of our outreach efforts and we will organize at least one student event in the framework of CERN IdeaSquare.

During ATTRACT phase 2 we will also carefully evaluate the socio-economic impact of our technology. This will be part of the market study and results will be made public if possible, including interviews with potential customers.

6 ACKNOWLEDGEMENT

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7. REFERENCES

[1] W. Riegler and G. Aglieri Rinella, "Time resolution of silicon pixel sensors," JINST, vol. 12, pp. P11017, https://doi.org/10.1088/1748-0221/12/11/P11017, 2017.
[2] L. Paolozzi et al, "Time resolution and power consumption of a monolithic silicon pixel prototype in SiGe BiCMOS technology", arXiv:2005.14161
[3] C. Allaire et al., "Beam test measurements of Low Gain Avalanche Detector single pads and arrays for the ATLAS High Granularity Timing Detector," JINST, vol. 13, pp. P06017, https://doi.org/10.1088/1748-0221/13/06/P06017, 2018.
[4] X. Llopart, "Intrinsic time resolution of 3D-trench silicon pixels for charged particle detection", https://indico.cern.ch/event/591299/contributions/2423187/attachments/1393307/2123191/Timepix4_specs.pdf
[5] L. Anderlini et al, "Timepix4: Specs & Plans", https://arxiv.org/abs/2004.10881