A customized 110nm CMOS process for large-area radiation detection and imaging

Lucio Pancheri[1,2*], Thomas Corradino[1,2], Coralie Neubüser[2], Chiara Ferrero[3,4]
on behalf of the ARCADIA collaboration

[1]Università di Trento, Trento, Italy, [2]TIFPA-INFN, Trento, Italy,
[3]Politecnico di Torino, Torino, Italy, [4]INFN Torino, Torino, Italy
*Corresponding author: phone: +39 0461 281532, e-mail: lucio.pancheri@unitn.it

Abstract

This contribution presents a customized 110nm CMOS process tailored for the fabrication of pixel sensors on fully-depleted High-Resistivity (HR) substrates for radiation imaging applications. The test devices integrated in the first two fabrication runs, having three different values of active thickness, 48µm, 100µm and 200µm, are described, and the main results obtained from their electrical and functional characterization are summarized.

Introduction

Efficient charged-particle and X-ray direct detection require thick semiconductor sensors, and the mainstream solution for a wide range of applications are hybrid pixel detectors [1]. CMOS-integrated Monolithic Active Pixel Sensors provide a cost-effective alternative, but their efficient implementation requires a customization of the process and several trade-offs in detector performance [2-3]. Combining low-capacitance sensing node with thick active substrates and fast charge collection is a particularly challenging task, for which several approaches have been proposed so far [4-5]. This work presents a process specifically modified to tackle this problem, and discusses the main features of the proposed integrated sensors, summarizing the most significant results obtained so far.

Process customization

The process was specifically developed for the detection of charged particles for biomedical (proton Computed Tomography), High-Energy Physics (HEP) and space applications, but its characteristics make it also suitable for the efficient detection of X-rays in the energy range from a few keV to 15keV.
Since the applications require large active pixel areas, typically ranging from 100s cm^2 to several m^2 in large HEP experiments, one of the drivers of this development was the cost-effectiveness of the technology. The approach presented here was developed starting from a commercial 110nm CMOS process with several customizations. A n-type high resistivity active volume, which can be fully depleted with a sufficiently high bias voltage applied at the backside, was used to enable fast charge collection and efficient radiation detection. A p+ region is present at the bottom of the active volume, and a deep pwell implantation at the front side is used to avoid the collection of signal electrons by the nwell hosting pMOS transistors. Figure 1 shows the simplified cross section of a pixel array implemented in this modified process.
Two engineering runs were fabricated in 2021 and 2022 in the framework of the ARCADIA project, funded by INFN, and wafers from a third run have been delivered by the foundry in the first months of 2023. In the reticles, several active pixel designs were included, together with passive test structures for the qualification of the process (Figure 2). To comply with different application needs, 3 different process splittings have been developed (Figure 3), and devices with 3 different active thicknesses, 48µm, 100µm and 200µm, have been produced using the same mask set. For the 48-µm thick devices, a p+ substrate with high-resistivity n-type epitaxial layer was used as starting material, while in the other two cases the starting material was a high-resistivity n-type wafer, that was backside processed after the completion of the front-side. A back-side p+ implantation followed by a laser annealing was used to create a shallow junction at the backside. In the 200 µm version, p+ regions surrounded by guard rings were lithographically defined.

Sensor design

Several test devices, composed of arrays of pixels with different pitches (from 10µm to 50µm), with the pixel sensors connected in parallel, were included in the design in order to measure the electrical and functional characteristics of the sensors independently from the electronics. As a main demonstrator for the technology, a 512x512 active pixel array with 25µm pitch was developed (Figures 4 and 5). The demonstrator, designed for charged-particle tracking, features an event-driven readout architecture, and the pixels include the analog and digital circuitry needed to amplify, discriminate, store and transmit the address of the hit event. Several additional test designs, consisting in active pixel arrays with smaller area, microstrip arrays and electronic circuits test structures were also fabricated using the same reticle.

Electrical and functional characterization

The passive pixel test structures were used for the electrical and electro-optical characterization of the sensors. Using a 1060-nm picosecond pulsed laser to excite the optical response from test pixels, an excellent correspondence between measurement results and TCAD simulations was obtained (Figure 6). The time needed for the complete collection of the photogenerated charge varies from a few ns for 10-µm pixels to 30-40ns for 50-µm pixels. The tail in the current signal is mainly due to charges generated at the corner of the pixels, where the lateral drift field is lower (Figure 7). Nevertheless, the charge collection is fast enough for the majority of applications and to ensure a good tolerance to non-ionizing radiation damage.

The cluster size distribution with Minimum Ionizing Particles has been studied using a combined TCAD-Monte Carlo approach, where the 3D electric field maps computed in TCAD are imported into a Monte Carlo simulation software, that computes the statistical interaction of charged particles with silicon (Figure 8). In pixels with 25µm pitch, the high electric field in the substrate is sufficient to limit the maximum cluster size to a group of 4 pixels in most cases, when particles with perpendicular incidence are considered (Figure 9).

A summary of the most relevant parameters for sensor operation, extracted from text structures, are shown in Tables 1 and 2. These results demonstrate that the proposed process can provide sensors with fast charge collection and small capacitance, with a dark current density suitable for most particle tracking and high-energy radiation imaging applications.

Acknowledgments

The research was carried on inside the framework of the ARCADIA project funded by the Istituto Nazionale di Fisica Nucleare, CSN5, Italy. We would like to thank LFoundry for the support.

References

[1] N. Wermes, "Pixel detectors... where do we stand?" Nucl. Instrum. Methods Phys. Res. A, Vol. 924, pp. 44–50, 2019.

[2] W. Snoeys et al., "PIN detector arrays and integrated readout circuitry on high-resistivity float-zone silicon," IEEE Tran. Electron Devices, Vol. 41, No. 6, pp. 903-912, 1994.

[3] R. Turchetta et al. "A monolithic active pixel sensor for charged particle tracking and imaging using standard VLSI CMOS technology," Nucl. Instrum. Methods Phys. Res. A, Vol. 458, pp. 677–689, 2001.

[4] H. Pernegger et al., "First Tests of a Novel Radiation Hard CMOS Sensor Process for Depleted Monolithic Active Pixel Sensors," J. Inst., Vol. 12, P06008, 2017.

[5] S. Lauxtermann, V. Vangapally, "A Fully Depleted Backside Illuminated CMOS Imager with VGA Resolution and 15 micron Pixel Pitch," Proc. IISW 2013, paper 7.18.

[6] K. D. Stefanov et al., "Fully Depleted, Monolithic Pinned Photodiode CMOS Image Sensor Using Reverse Substrate Bias", Proc. IISW 2017, paper P13.

[7] Y. Arai et al., "Developments of SOI Monolithic Pixel Detectors," Nuclear Instr. Meth. Phys. Res. A, Vol. 623, No. 1, pp. 186-188, 2010.

[8] L. Pancheri, et al., "Fully Depleted MAPS in 110-nm CMOS Process With 100—300 µm Active Substrate," IEEE Trans. Electron. Devices 67, pp. 2393–2399, 2020.

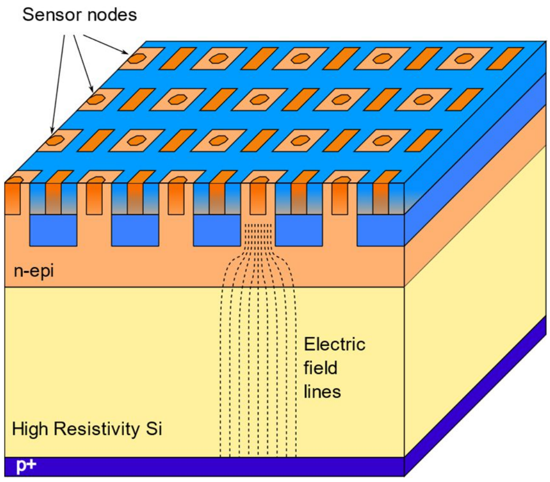

Figure 1. Schematic illustration of the pixel array, showing the sensor nodes, the surface pwell/deep-pwell regions (blue) and the isolated nwell regions (orange).

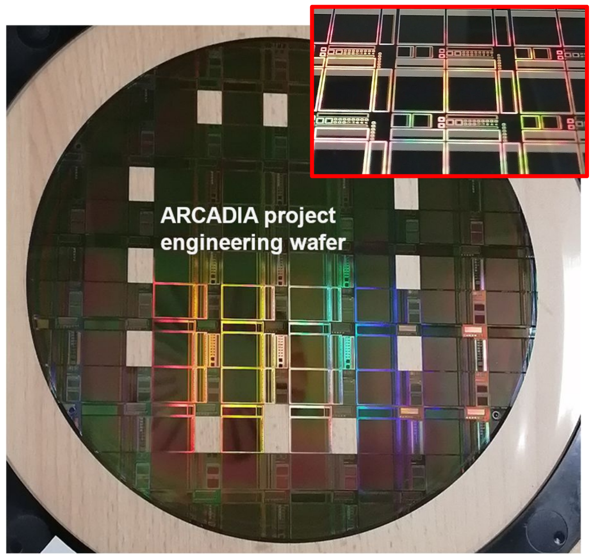

Figure 2. Image of a wafer produced in the ARCADIA project. Inset: detail of the backside of one of the wafers produced with double-sided processing.

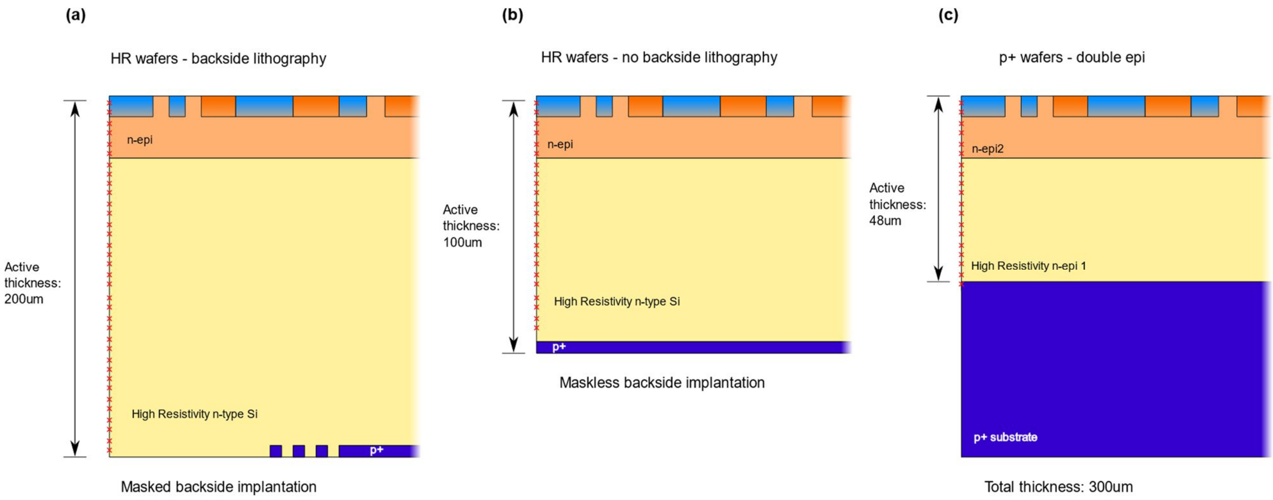

Figure 3. Cross section of the sensors produced with 3 different process splittings: a) 200µm sensors obtained with backside lithography; b) 100µm sensors with maskless p+ backside implantation; c) 48µm sensors with p+ substrate and HR epitaxial layer

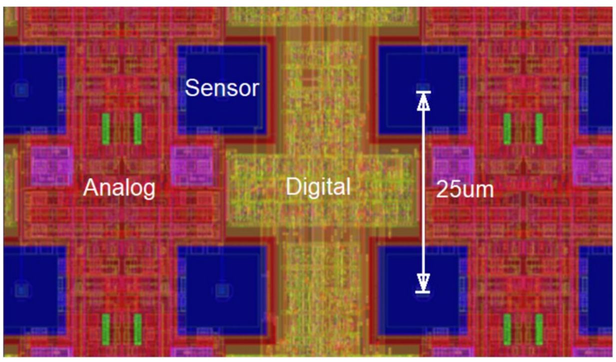

Figure 4. Detail of the layout of a group of pixels in the active 512x512 array, highlighting sensor area, analog and digital regions.

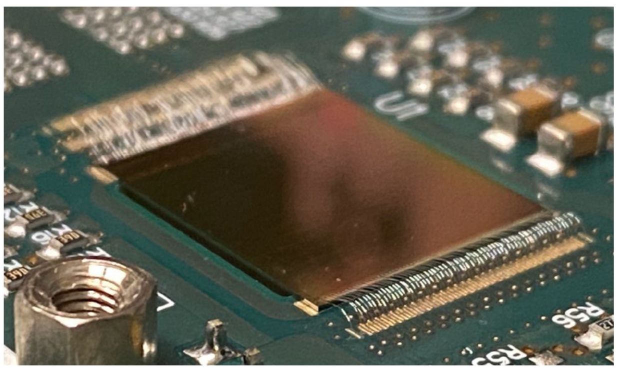

Figure 5. Image of the 512x512 active pixel array mounted on board

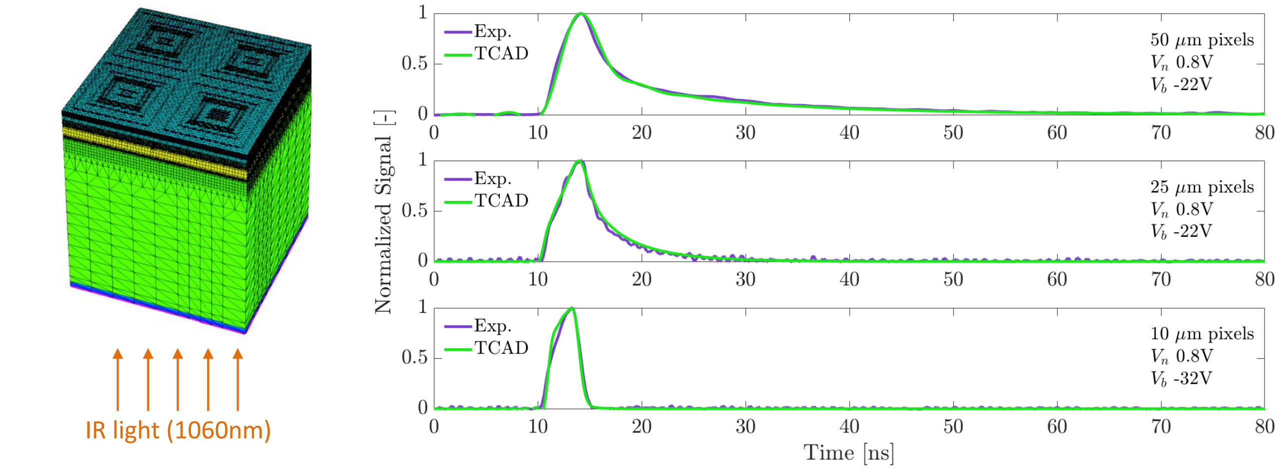

Figure 6. Optical transient response: simulated and measured on pixel test structures with fast pulsed IR laser (FWHM < 100ps, λ = 1060nm) incident uniformly on the sensor backside. In the measurements the test structures were connected to an external high-bandwidth amplifier and the simulated curves were filtered with a digital filter reproducing the characteristics of the amplifier. Measurements and simulations are shown on pixels with 3 different pitches and 100µm active thickness.

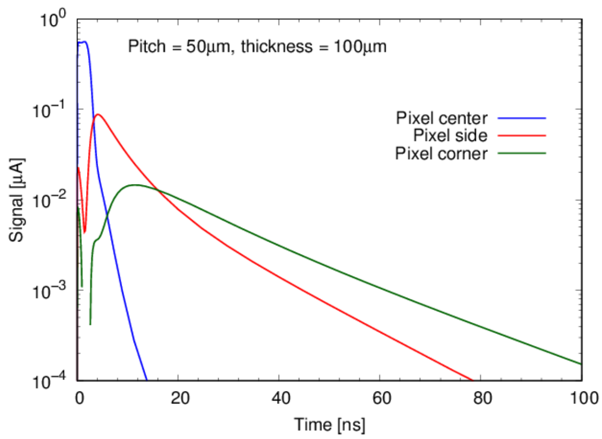

Figure 7. Simulated optical transient response with fast pulsed IR laser beam (FWHM < 100ps, λ = 1060nm) incident in different regions of the pixel.

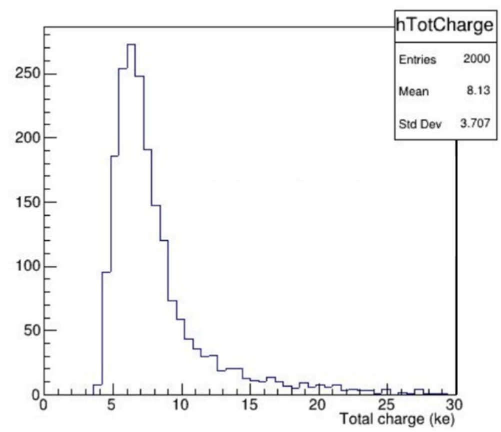

Figure 8. Simulated total charge distribution for 200-MeV muons incident on the array (100µm thickness)

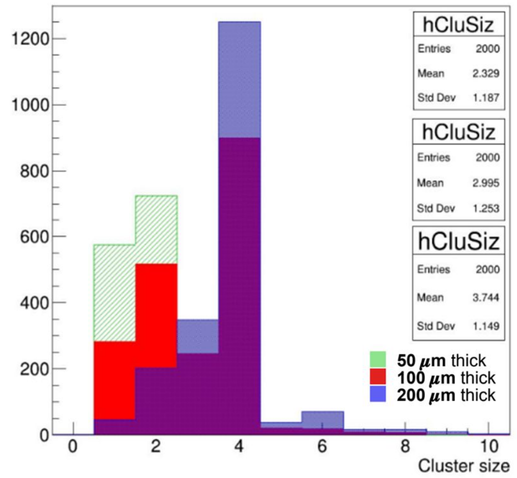

Figure 9. Simulated cluster size distribution of the 25µm-pitch sensor. In the simulations, the central pixel of a 5x5 matrix was uniformly hit by 200MeV muons with perpendicular incidence, and the threshold was set to 200e-.

Table 1. Sensor characteristics vs. wafer thickness. Ranges account for inter and intra-wafer variations

Active thickness (µm)	**48**	**100**	**200**
Sensor bias voltage (V)	25	20-35	60-100
Dark current density (pA/cm^2)	100-350	230 - 500	650 - 2000

Table 2. Sensor characteristics vs. pixel size (for 100µm active thickness)

Pixel pitch (µm)	**10**	**25**	**50**
Sensor area (% of pixel area)	36%	19%	16%
Sensor capacitance (fF)	1.9	3	12.7
Time for 90% charge collection with picosecond pulsed laser @ 1060 nm (ns)	4	10	31