Comprehensive Development of Solid-State Pixel Detectors: From Hybrid CZT to Monolithic CMOS Technologies

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MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES · CSIC · VNIVERSITAT DE VALÈNCIA · IFIC INSTITUT DE FÍSICA CORPUSCULAR · EXCELENCIA SEVERO OCHOA · IFIC PixLab Pixel Laboratory · VNIVERSITAT DE VALÈNCIA · CÁTEDRA UV-VASIC DE MATERIALES AVANZADOS PARA LA INDUSTRIA DE MICROCHIPS Y SEMICONDUCTORES

Introduction

Solid-state semiconductor detectors are at the forefront of advanced imaging, ranging from high-energy physics to applications like medical diagnostics. This work presents a comprehensive R&D methodology for the integral development of pixelated radiation detectors, branching into two main configurations:

- Hybrid Detectors: Utilizing high-Z sensor materials like Cadmium Zinc Telluride (CZT) bonded to readout electronics, ideal for high-efficiency X-ray imaging.
- Monolithic Detectors: Integrating both the sensing volume and readout circuitry into a single silicon chip, offering reduced material budget and high spatial resolution.

Hybrid Detectors

THE HYBRIDIZATION BOTTLENECK

- Hybrid pixel detectors (Fig 1) require interconnecting a semiconductor sensor to the readout electronics via microscopic interconnections. This process is complex, expensive and time consuming. If a defective wafer is hybridized, the entire assembly's performance degrades, affecting production yield.

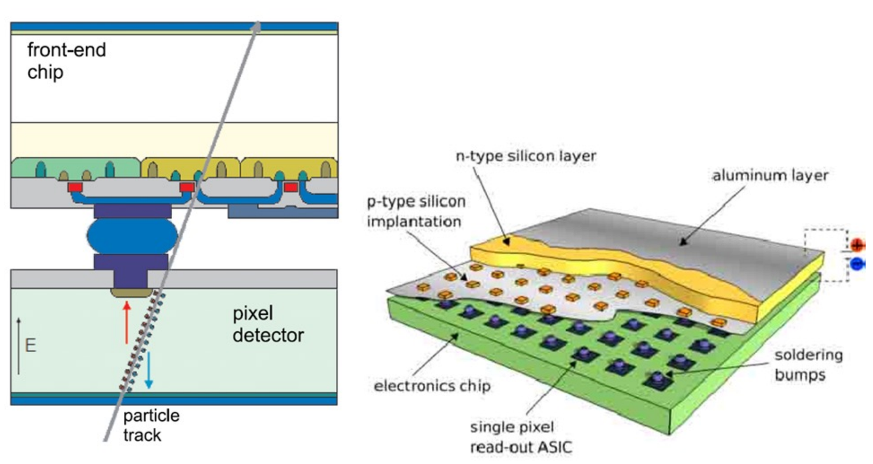

Fig 1. Hybrid detector structure

THE SENSOR MATERIAL

- Cadmium Zinc Telluride is ideal for room-temperature X-ray imaging due to its wide bandgap (1.4 - 2.2 eV) and high atomic number.
- However, its performance is often limited by intrinsic crystalline defects (Telluride inclusions, grain boundaries) that act as charge traps and increase leakage currents.[1]

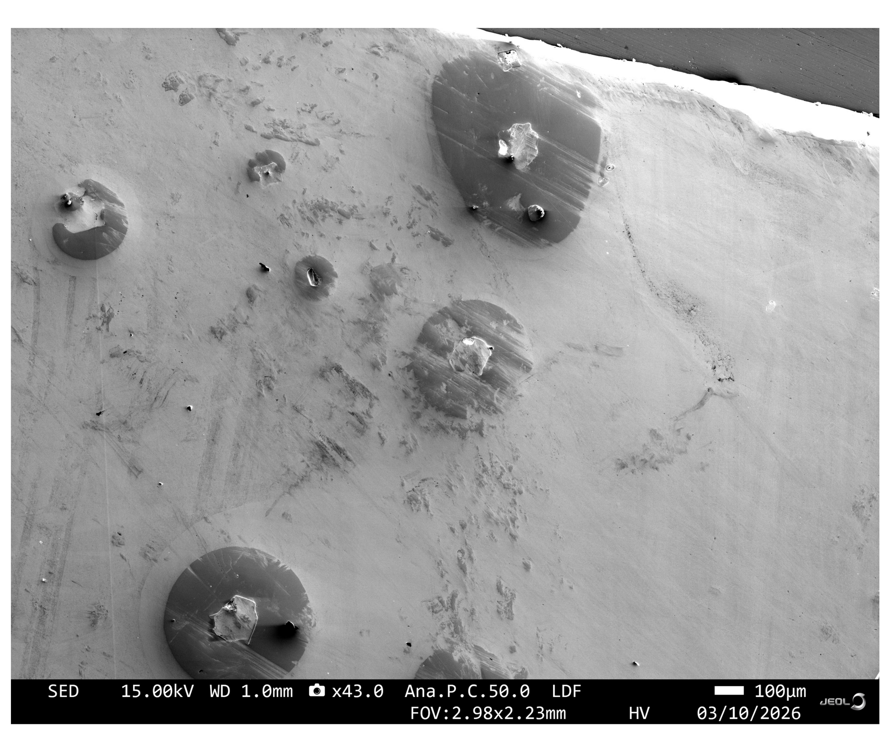

Fig 2. SEM image of CZT

WAFER QUALITY CONTROL

- To guarantee assembly's functionality and increase production yield, we developed a comprehensive non-destructive protocol to inspect base materials prior to hybridization:
  - Scanning Electron Microscopy (SEM): Assesses surface morphology and compositional contrast (Fig 2.). This is coupled with Energy-Dispersive X-Ray spectroscopy (EDX) for elemental stoichiometry and Cathodoluminescence (CL) spectroscopy to identify localized defect states.
  - Infrared (IR) Transmission Microscopy: Identifies opaque bulk defects as CZT is transparent to IR light above 850 nm (Fig 3). Cross-polarized IR imaging maps internal stress fields and lattice distortions induced by crystalline imperfections.

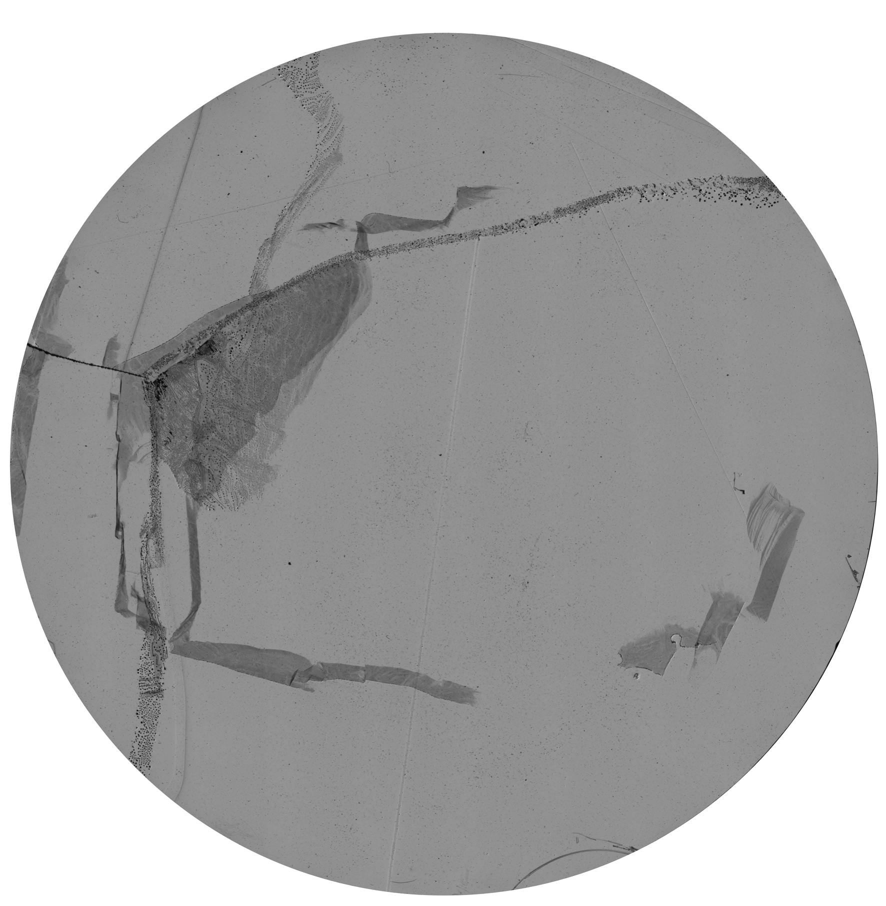

Fig 3. IR image of a CZT waffer

Monolithic Detectors

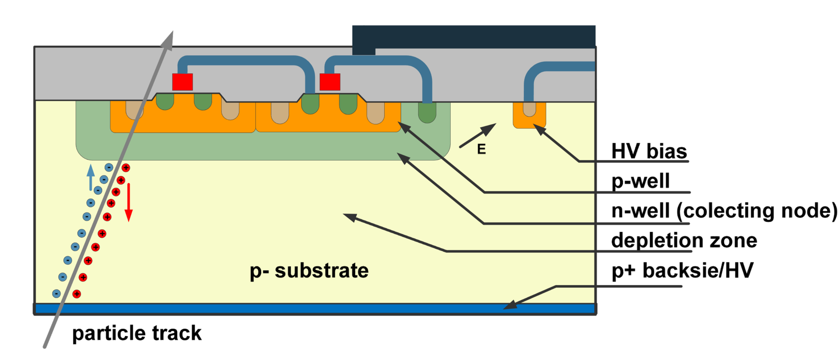

Fig 4. Monolithic detector structure

TECHNOLOGY OVERVIEW

- Depleted Monolithic Active Pixel Sensors (DMAPS) (Fig 4) integrate the depleted sensing volume and the CMOS readout electronics within a single silicon substrate. This configuration eliminates the need for expensive bonding, reducing overall material budget, assembly complexity, and sensor capacitance.
- Their low-mass configuration, high granularity and simplified assembly process make them highly suitable for next-generation inner tracking systems in high-energy physics.

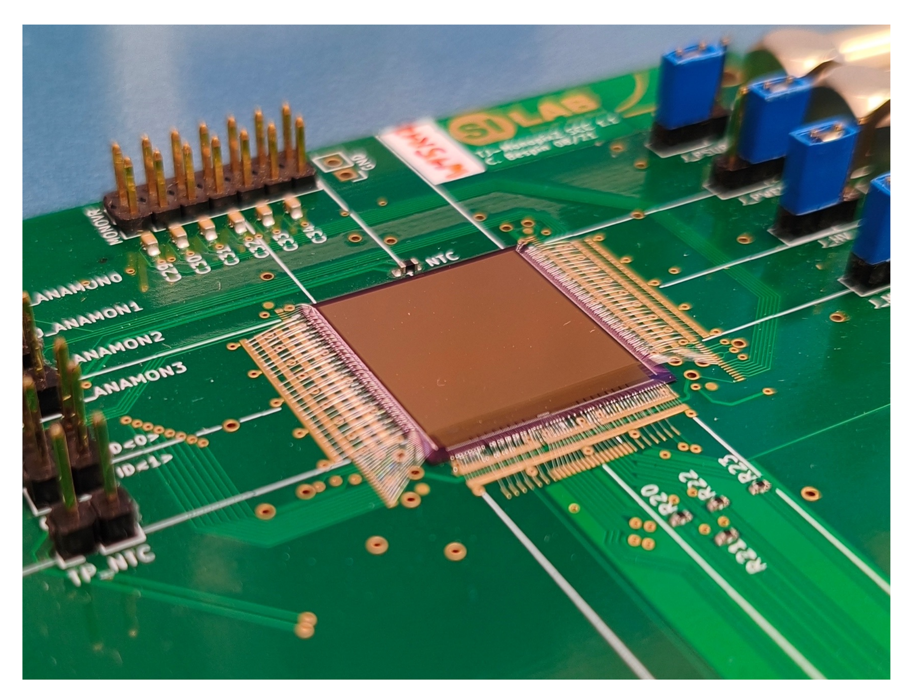

Fig 5. TJ-Monopix2 chip

TESTING PLATFORMS

- TJ-Monopix2 (Fig 5): A large-scale prototype featuring a 512x512 pixel matrix with a 33.04 μm^2 pixel pitch using Tower 180 nm CMOS imaging process. This chip features a small collection electrode design.[2]
- Obelix: An evolution designed specifically for the Belle II Vertex Detector (VTX) upgrade. It introduces an entirely reworked digital periphery, including on-chip voltage regulators, a precision timing module, and a dedicated trigger unit capable of sending hit-data to the first-level trigger system.

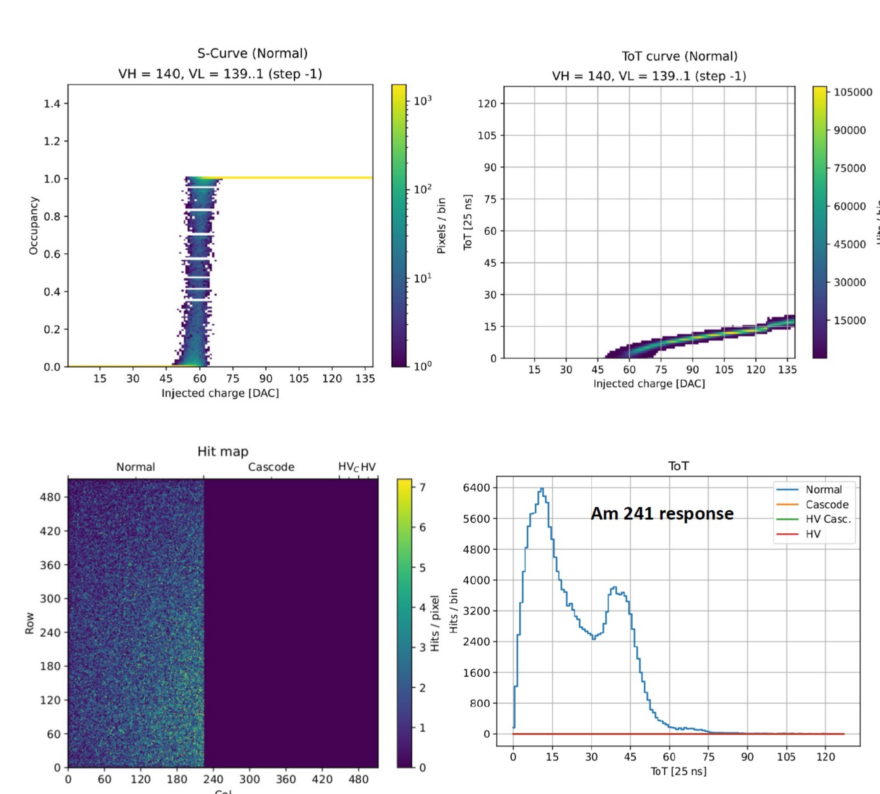

Fig 6. Characterization scans for TJ-Monopix2

CHIP CHARACTERIZATION

- Analog and digital scans for performance optimization: internal injections, laser pulses and radioactive sources (Fig 6).
- Laboratory and beam test for studies on charge collection, spatial resolution and detection efficiency.

Conclusion

- Currently, work is being done in both detector configurations:
  - Hybrid CZT validation: The non-invasive quality control system was successfully validated using SEM and IR inspection. Future work will implement Transient Current Technique (TCT), both SPA-TCT and TPA-TCT, to study charge trapping and carrier mobility.
  - Monolithic CMOS chips: The successful operation of TJ-Monopix2 is a milestone to the Obelix development validation. Future work will focus on the in-depth laboratory characterization of the Obelix chip and the development of a particle beam telescope as a future collider tracker demonstrator.

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2. Babeluk, M. (2025). Development and Testing of Depleted Monolithic Active Pixel Sensors in 180nm CMOS technology for the Belle II VTX Upgrade. PhD thesis. Vienna, Tech. U. DOI: 10.34726/hss.2025.107368